Dissertation title:

Energy transport mechanisms of pulsed laser processing of carbon fiber reinforced plastics

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Carbon fiber reinforced plastics (CFRP) have a great potential in lightweight construction due to their unique mechanical properties. However, processing of this innovative material is not yet solved satisfyingly. Mechanical cutting, milling or drilling suffer from very strong tool wear with negative effects like delamination. The laser as a well automatable, noncontact tool without wear could overcome these restrictions. However, regarding the fundamental laser process mechanisms, several open questions remain. The main topics of this thesis are fundamental investigations on the relevant energy transport mechanisms during laser processing of CFRP. Two phases can be identified: During the phase of energy deposition incident optical laser energy is deposited in the material. This absorbed energy is distributed into the surrounding material during the phase of energy distribution.

A fundamental factor defining energy deposition is the absorptance of the material at the laser wavelength. A theoretical model is used to determine the polarization-dependent absorptance for carbon fibers and CFRP. The surface of each carbon fiber is considered as multiple layers of graphite. The optical properties of the carbon fibers are estimated from the well-known optical properties of graphite. The model takes into account the round cross-section of the carbon fibers as well as multiple reflections between the carbon fibers. It is found that the total absorptance is larger than 70% for wavelengths in the ultraviolet, visible and near infrared spectrum and drops to about 40% for a wavelength of 10.6 µm (CO_2-lasers). The absorptance for light polarized perpendicular to the carbon fibers was shown to be larger than for light polarized parallel to the fibers. The additional matrix material in the case of CFRP increases the absorptance of laser radiation compared to not embedded carbon fibers. An experimental measurement of the absorptance was made with the help of a reflectometric measurement setup. The absorptance of laser radiation with wavelengths of 532 nm and 1047 nm in carbon fibers and CFRP was measured and the results confirm the predictions of the model. However, the absolute values of the measured absorptance are up to 20% larger as compared to the calculations. The theoretical model gives a conservative value for the absorptance whilst the statements made regarding the influence of different polarization orientations and wavelengths on the absorptance were confirmed.

The incident laser radiation is reflected perpendicularly to the axis of symmetry of the carbon fibers due to their circular cross section. It is shown that this distribution of optical energy leads to a widening of the ablated grooves in the range of one diameter of the carbon fibers. For process parameters that cause the formation of a matrix evaporation zone (MEZ), the influence of reflections at the cylindrical carbon fibers becomes especially visible. When laser cutting CFRP with repetitive scans, a decrease of the ablation rate can be observed at the interface between a layer where the carbon fibers are orientated perpendicular to the cutting direction and a layer where the carbon fibers are orientated parallel to the cutting direction. This temporary slowed ablation process starts to develop gradually when the kerf depth reaches the layer with the carbon fibers oriented parallel to the cutting direction. As soon as the kerf enters into the next layer with the fibers again oriented perpendicular to the cutting direction, the ablation process speeds up again. The mechanisms causing this behavior are discussed in detail in this thesis.

At the beginning of the phase of energy distribution the absorbed optical energy is converted into heat. This leads to a temperature increase of the material. At high temperatures which are usually achieved during laser processing, carbon fibers as well as the matrix material react with oxygen. This influences the process in multiple ways. Burning of the matrix material can be observed on the surface of the material, which leads to an increase of the extent of the matrix evaporation zone. For shallow grooves an increase of the groove width when ablating under standard surrounding atmosphere compared to other process gases like nitrogen was observed. This increase in width is supposed to be caused by the additional oxygen in the standard ambient atmosphere. When using a sufficiently large oxygen flow, positive effects can also be observed during multipass laser cutting of CFRP. The integral gain in processing productivity strongly depends on the final kerf depth and layer structure of the work piece. The beneficial contribution of an oxygen flow on the ablation rate is mostly noticeable in deep kerfs, where the otherwise much more efficient evaporative ablation process is strongly diminished due to the reduced laser fluence reaching the bottom of the kerf. Oxygen also enhances the maximum achievable kerf depth. The strong deformation and widening of the kerf associated with a corresponding reduction of the ablation rate is found to be typical for processing of CFRP layers with a feed parallel to the fiber orientation in standard air atmospheres. Oxygen assisted cutting allows the suppression of this problem. The extent of the MEZ inside the material was found to be insensitive to the variation of gas environments. The complete absence of oxygen, when using other process gases like nitrogen, was found to have a negative impact on the ablation process like strong smoke generation.

During the ablation process a part of the incident laser energy is converted into kinetic and thermal energy of the ablated material. A hot ablation plume is generated which leaves the process zone with high flow speeds. This flow of hot ablation products during laser processing of CFRP with a continuous wave laser system has been observed by means of high-speed imaging. The evaluation of the recordings revealed that compression shocks are formed in the hot stream of ablation products. The flow speed of the hot ablation products was estimated by analyzing the distance of the first compression shock to the material surface. The influence of different average laser powers on the flow speed was investigated. It was found that the ablation products leave the interaction zone with flow speeds of up to about 3.3 km/s. These high flow speeds can lead to a mechanical interaction with the surrounding work peace for example with exposed carbon fibers. Additionally hot ablation products can also have a thermal influence on the work piece. Ablation products that are generated during the laser ablation process of CFRP have a temperature between 2000 K and 4000 K. This temperature is significantly higher than the evaporation temperature of the matrix material. The additional heating of the CFRP material by hot ablation products may cause additional thermal damaging of the material. In this thesis an experiment is described that shows that the heat transportation by hot ablation products can influence the surrounding material of the work piece.

Heat conduction is a very influential energy transport mechanism. It is very high along the symmetrical axis of the carbon fibers especially compared to the heat conductivity of the matrix material which is about two orders of magnitude lower. Consequently the matrix evaporation zone has its maximum extent in direction of the carbon fibers. Investigations on the influence of different laser parameters on the extent of the MEZ become possible with high-speed imaging. In order to avoid the influence of additional process parameters like the spatial pulse-to-pulse overlap, a percussion drilling process was used. After a given processing time, the MEZ is smaller for lower average laser powers regardless on whether the power was reduced by decreasing the pulse energy or the repetition rate. However, when using the same average power, the MEZ can be reduced significantly by using high pulse energies and low repetition rates instead of low pulse energies and high repetition rates. This observation reveals the significant influence of the effect of heat accumulation on the formation of the MEZ.

When CFRP is processed with ultra-short laser pulses providing high peak intensities $>10^8$ W/cm², heat accumulation effects are the main reason for the development of a matrix evaporation zone. Two heat accumulation effects can be distinguished: Heat accumulation between consecutive laser pulses (HAP) and heat accumulation between consecutive scans (HAS). In this thesis the influence of heat accumulation on the formation of a matrix evaporation zone (MEZ) in carbon fiber reinforced plastics during multi-pass laser cutting with picosecond laser pulses is studied for a wide range of pulse frequencies (f_P=10–800 kHz) and feed rates (v=0.002–10 m/s). Three regimes of the formation of the MEZ are found and related with different heat accumulation effects: (1) a small MEZ (<2 µm) with negligible heat accumulation, (2) a moderate-size MEZ (up to a few hundred microns) determined by heat accumulation between pulses, and (3) a large MEZ (up to a few millimeters) caused by heat accumulation between scans. The dependence of the size of the MEZ on the number of scans and the scan frequency was studied to distinguish the two heat accumulation effects (between pulses and between scans), which occur on different time-scales. A diagram to illustrate the boundaries between the three regimes of the formation of the MEZ as a function of feed rate and pulse frequency is proposed as a useful tool to optimize the processing parameters in practice.

With the ongoing increase in average laser power of ultrashort pulse laser sources investigations on the scaling of the heat accumulation effects become even more important. A recently developed multi-pass thin-disk laser amplifier providing an average laser power of up to 1.1 kW at a pulse frequency of 300 kHz and a pulse duration of 8 ps has been used for these investigations. It is shown that higher feed rates and therefore smaller pulse overlaps decrease the influence of the heat accumulation between pulses on the MEZ. To completely avoid heat accumulation between pulses, the pulses have to be spatially separated. At high average laser powers the heat accumulation between scans is a very important influencing factor on the MEZ formation when using a multi-pass process. This effect can lead to a burning of the matrix material and therefore to vast thermal damage. A characteristic value for the scan accumulation effect is the critical number of scans above which the extent of the MEZ starts to increase very rapidly. The critical number of scans is proportional to the feed rate divided by the average laser power squared.

The findings about the energy transport mechanisms were applied to demonstrate high-quality processing of CFRP with high average laser powers. A rectangular shaped CFRP part was cut with 1.1 kW of average laser power (with 8 ps of pulse duration and 300 kHz of repetition rate). In cross sections of the cut a matrix evaporation zone with a maximum extent of 20 µm can be observed. In most parts no thermal damage is visible. In total about 2100 scans at a feed rate of 30 m/s were necessary to completely cut the material which gives a process efficiency of 28%. The effective average cutting speed was 0.9 m/min. The cutting kerf is inclined by about 11° which results from the F-Theta focusing optics. The thesis is concluded with propositions for a further increase of the process efficiency and a possibility to influence the inclination angle of the cutting kerf.