Laser ablation of CFRP using picosecond laser pulses at different wavelengths from UV to IR

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Abstract

Laser processing of carbon fibre reinforced plastics (CFRP) has a great industrial relevance for high performance structural parts in airplanes, machine tools and cars. Through-holes drilled by nanosecond laser pulses show thermal induced molten layers and voids. Recently, picosecond lasers have demonstrated the ability to drill high-efficient and high-quality rivet through-holes. In this paper a high-power picosecond laser system operating at different wavelengths (355 nm, 532 nm and 1064 nm) has been used for CFRP ablation experiments to study the influence of different laser parameters in terms of machining quality and processing time.

Keywords: CFRP, picosecond pulses, ablation, HAZ, 1064 nm, 532 nm, 355 nm

1. Introduction

Materials used in automotive or aircraft engineering nowadays are selected to fulfil optimally the specific requirements of these industries. Carbon fibre reinforced plastics (CFRP) offer outstanding mechanical properties at extraordinarily low weight; they are going to become a preferred material for high performance structural elements in machines tools, airplanes and cars. Drilling of CFRP is often required to prepare composite parts for joining and assembling and represents one of the most important machining operations out on composites [1].

CFRP composites are heterogeneous and anisotropic materials. They usually consist of several layers of different aligned carbon fibre rovings, which contain many thousands carbon fibres with 5-10 $\mu$m in diameter and are often stitched by a textile yarn. Finally, to utilize the high stiffness and strength of the fibre rovings it is necessary to combine them with a matrix material to transfer the properties between the fibres.

Due to the abrasive character and the brittleness of CFRP the conventional drilling of rivet holes has to deal with strong tool wear, delaminating, matrix damage as well as the environmental impact caused by noise and dust. Alternative machining technologies like abrasive water jet has to cope with the water treatment, moisture absorption...
and one-side work piece accessibility.

At CFRP laser processing, however, the strong anisotropic thermo-physical properties can lead to a thermal load of the heat sensitive epoxy matrix. The size of so called heat affected zone (HAZ) correlates with the change of mechanical properties and thus the quality of CFRP parts [2]. Shortening the laser-matter interaction time has a high positive impact on reducing the HAZ [3]. However, applying of nanosecond pulses for producing of multi-millimetre rivet holes in multi-millimetre thick CFRP still leads to the molten layers and voids in the epoxy matrix of the bulk material [4]. In previous works it has been demonstrated that picosecond laser pulses considerably improve the laser drilling of 6 mm through-holes in 2 mm thick CFRP sheets [5] compared with ns-pulses of the same average power and the same wavelength at 355nm.

Figure 1. SEM of CFRP borehole machined by picosecond laser pulses (P_{av} = 9W, \tau_p = 5 ps, \lambda = 355 nm, f_p = 200 kHz) [5]

Despite the short laser matter interaction even by using ultra-short laser pulses the heat influence has to be controlled by optimized process strategies. Both by improving the path of the laser beam and the right choice of process parameters [6] the thermal damage can be minimized by avoiding heat accumulation. Thus, high-quality through-holes in CFRP without visible molten layer and without epoxy voids have been drilled by picosecond laser pulses. Figure 1 shows a SEM image of a section of the ultrafast laser machined borehole with precisely ablated carbon fibres and epoxy matrix with no visible HAZ [5]. The total processing time per borehole was 18 seconds, which is to our knowledge the best result in high quality laser drilling of CFRP.

Highest quality, increasing throughput and reducing the costs are the biggest challenges in picosecond laser machining of CFRP as a manufacturing technology. Nowadays, picosecond lasers can offer high output power and pulse repetition frequencies to optimize the process throughput. Furthermore, the fundamental wavelength can be efficiently converted by means of nonlinear optics to the visible and ultraviolet spectral range.

Table 1. Optical parameters of carbon at different wavelengths [7]

| Wavelength [nm] | 355 | 532 | 1064 |
|-----------------|-----|-----|------|
| Reflectivity R [%] | 19  | 21  | 25   |
| Absorption coefficient \( \alpha [1/\mu m] \) | 33  | 20  | 14   |
| Absorption length \( l_{a} [\mu m] \) | 31  | 50  | 74   |

In order to compare the picosecond laser machining at different wavelengths Table 1 summaries the linear reflectivity R, the linear absorption coefficient \( \alpha \) and the linear absorption coefficient \( l_{a} \) at 355 nm, 532 nm and 1064 nm. The carbon fibres need 98% of the entire evaporation energy in laser ablation processes [6], therefore the optical properties of epoxy are not mentioned in Table 1. Due to the higher photon energy at 355 nm the probability of nonlinear absorption by multi-photon processes strongly increases. This should have an effect both on the ablation threshold and the depth control of the ablation process. In contrast, lower absorption can lead to more scattering of the laser radiation into the bulk material resulting in higher thermal load and thus to increasing heat
affected zones. For that reason the investigation of ablation thresholds and rates at different laser wavelengths is crucially important to understand the ablation mechanism and to optimize throughput and ablation quality. In this paper we present investigations on picoseconds laser ablation of CFRP using wavelengths of 355 nm, 532 nm and 1064 nm and average output powers up to 19W.

2. Experimental Setup

The process strategy including the processing sequence is very important in laser machining. Figure 2 shows the strategy that was carefully chosen for the ablation tests in this paper. The aim of these investigations is the optimization of drilling processes using ultrafast lasers. For that reason a circular ablation area was used for these fundamental tests. Next the processing sequence should be typical for drilling applications of large borehole diameters.

Figure 2. (a) Sketch of ablation sequence consisting of n concentric circles (here n = 5) with pulse-to-pulse separation distance spp, trench width wt, pitch as circle-to-circle separation distance, r_{min} and r_{max} as min. and max. radius of processed path, respectively; (b) Sketch of an ablated trench as a result of well chosen process parameters resulting in a well defined ablated surface

Therefore, in this report the drilling process was performed by scribing concentric circles starting from inside to outside. Figure 2 shows a sketch of the applied drilling process using n concentric circles (not to scale). Starting with smallest inner circle radius of 1 mm the maximum outer circle radius was chosen to be 3 mm. In order to fill the corresponding 2 mm trench width, 143 circles are needed. Thus in summary, one ablation layer was composed of 143 different circles. The trench width was well chosen to be larger than the fibres roving size to identify the influence of the crossover of the fibre rovings, the epoxy resin conglomerations in between, and the influence of the stitching yarn on the ablation geometry. The final depth within all experiments was achieved by removing layer by layer as illustrated in Figure 2. In this report the number of layers was constant equal to 100. During the ablation process the focal position was adapted to the correspondent ablation depth.

In summary, the process parameters were chosen to be optimal for a well defined ablation depth for any applied fluence at each applied wavelength. It should neither implicate that the applied parameter set is an optimum for each operating wavelength nor that there is only one optimal parameter set for all three laser wavelengths. But the parameter set should provide reliable results in order to compare the laser ablation at different wavelengths in respect to ablation rates and the extension of the heat affected zone in a wide pulse energy range.

The CFRP material used in this paper contains a 4 layer biaxial non crimp fabric (556 g/m²) from SAERTEX with 12k HTS fibres from Tenax. Curing with RTM6 resin was done in an autoclave. The CFRP plates were about 1.9 mm thick. All the ablation experiments in this report were performed using a high precision 5-axes laser
micromachining system (GL.5, GFH GmbH) including a picosecond laser system with 10ps pulse duration (HYPER25, Lumera Laser GmbH). All three wavelengths 1064nm, 532nm and 355nm could be used at various pulse repetition frequencies and pulse energies. Table 2 summarizes the most important laser parameters of the laser system. The combination of the high average powers and highest pulse repetition rates for all three wavelengths provide all the advantages of state-of the art ultrafast lasers. For fast beam deflection and focussing a galvanometric scanner (HurryScan II, ScanLab; F-Theta optics with 100 mm focal distance for all wavelengths) was used. For better focusing the laser beam was expanded with a ratio of 1:5 for all three wavelengths. The laser machined structures were characterized by an optical microscope (ZEISS, Axio Imager.M2m) and a chromatic confocal sensor (PRECITEC Crocodile E).

Table 2. Laser parameters at 200 kHz

| Wavelength [nm] | 355 | 532 | 1064 |
|-----------------|-----|-----|------|
| Average power (max.) [W] | 10.2 | 14.2 | 22.7 |
| Pulse duration [ps] | 7 | 8 | 9 |
| M² | 1.2 | 1.1 | 1.3 |

3. Results and Discussion

3.1. Ablation threshold

As mentioned, the carbon fibres need 98% of the entire evaporation energy in the laser ablation process. Thus, the ablation threshold of the epoxy resin has been estimated to be an order of magnitude lower compared to the CF and will not be considered in the following.

Regarding the ablation threshold of the carbon fibres for picosecond pulses there is neither a report available nor even a verified method for the experimental determination. Usually the ablation threshold will be measured by applying a defined number of pulses striking the material surface at a single spot and measuring the ablation diameter. The number of pulses will be considered in the so called “incubation model” [9]. This approach does not represent the dynamics of the ablation process in machining grooves or concentric circles. Therefore this work takes a new approach for ablation threshold determination of carbon fibres: Machining trenches in the CFRP surface by full separating of at least one layer (not roving) of carbon fibres for increasing fluences at different wavelengths. The pulse repetition frequency was not changed (fₚ = 200 kHz).

Figure 3. (a) Microscope image of a separated CF-layer; the measurements of trench width will be analysed for ablation threshold and beam spot diameter (1/e²) determination; (b) Chart with measured trench widths for 355 nm, 532 nm and 1064 nm vs. peak fluence
Figure 3 shows a microscope image of a laser machined trench in CFRP. The carbon fibres are fully separated and the epoxy layer is completely removed by the laser beam. For the determination of the ablation threshold $H_{th,CF}$ the ablated spot diameter will be extrapolated to zero [10]. In this paper the trench width was used for this extrapolation. The results of our measurements, the ablation threshold $H_{th,CF}$ and beam spot radius $w_0$ for each laser wavelength, are summarized in Table 3.

Table 3. Ablation thresholds for carbon fibres and 1/e² spot radius at different wavelengths

| Wavelength [nm] | 355  | 532  | 1064 |
|-----------------|------|------|------|
| Ablation threshold $H_{th,CF}$ [J/cm²], incident fluence | 0.216 | 0.284 | 0.410 |
| Spot radius (1/e²) $w_0$ [μm] | 7    | 9    | 9    |

The ablation threshold of the incident laser fluence was measured to 0.216 J/cm² at 355 nm, to 0.284 J/cm² at 532 nm and to 0.410 J/cm² at 1064 nm, respectively. The results confirm the increasing laser light absorption by CFRP from IR to UV. The better the absorption the less energy is required to ablate the material. Thus, there is a better depth control and precision in ablation processes.

For the verification whether linear or nonlinear absorption plays a dominant role further investigations are required. The next approach is to determine the incubation coefficient from the incubation model. It will allow the calculation of the single-shot ablation threshold as well as the multi-pulse ablation threshold relating to the number of pulses overlapping during an optimized drilling process.

The spot diameters in these experiments were calculated to 18 μm at 532 nm, 1064 nm and 14 μm at 355 nm. For this reason ablation rates for VIS and IR can be directly compared to each other vs. fluence, average power or pulse energy in the following. The CFRP ablation results for UV should be evaluated with respect to the different laser fluence at the same laser power.

### 3.2. CFRP ablation rates and depth control

One of the most important evaluation criterions for an industrial application is the process throughput. The fundamental laser wavelength provides the maximum output power and thus presumably the highest throughput in CFRP machining. The question is if the 532 nm or 355 nm laser wavelengths can represent any technological advantage compared to the 1064 nm laser radiation in terms of ablation rates or quality.

In order to compare the different wavelengths wide trenches (see Figure 2) were machined from minimum to maximum laser output powers for each wavelength. As already mentioned, all other process parameters were optimized to get a smooth ablation surface over the full range of applied fluences and were not changed during the experiments (see Table 4).

Table 4. Constant laser and process parameters for all wavelengths

| Process and laser parameters | 143 | 14   | 1000 |
|------------------------------|-----|------|------|
| Number of concentric circles $k$ | 143 |      |      |
| Pitch [μm]                   | 14  |      |      |
| Pulse-to-pulse separation distance $s_{pp}$ [μm] | 7   |      |      |
| Feed rate $v$ [m/s]          | 1.4 |      |      |
| Min. radius $r_{min}$ [μm]   | 1000|      |      |
| Max. radius $r_{max}$ [μm]   | 3000|      |      |
| Number of ablation layers $n$ | 100 |      |      |
| Pulse repetition rate $f_p$ [kHz] | 200 |      |      |
First of all, the ablation depth within the trenches and the ablations rates were measured in dependence on the laser average power. Due to the heterogeneity of the CFRP composite the depth of the trenches was measured at different locations within the ablated areas. The error bars represent the differences between the average ablation depth and the minimum depth (negative error bar) and maximum depth (positive error bar), respectively. The ablation rates were calculated by the average ablation depth for each laser average power.

In Figure 4 the ablation depths and ablation rates vs. the peak fluence (unfilled symbols) and vs. average laser power (filled symbols) are presented for all three laser wavelengths. The ablation depth and rate increases approximately linear with increasing laser average power and there are no remarkable saturation effects visible. The slight differences in ablation thresholds and optical properties of carbon fibres for the different wavelengths have no significant influence on the ablation rates. All three laser wavelengths show very similar ablation depth applying the same pulse energy and laser power up to \( Q_p = 50 \, \mu \text{J} \) (\( P_{av} = 10 \, \text{W}, \, H_{peak} = 40 \, \text{J/cm}^2 \)). Due to the fact that the spot diameter at 355nm was slightly smaller compared to 532nm and 1064nm the ablation depth /rate was also calculated in dependence on the laser peak fluence. By applying identical fluences there is a decrease of 25% in the ablation rates in the UV compared to the VIS and IR. The focus diameter at 355nm was probably too small because of the higher absorption coefficient and must be improved in further investigations. In regard to the ablation rates it is worth to mention that maximum rates were about 11 mm³/min at 355 nm, 12 mm³/min at 532 nm, and \(~18 \, \text{mm}^3/\text{min}\) at 1064 nm. Both the linear slope of the ablation depth and the lack of any saturation effect at higher laser power can be explained by relative high absorption lengths. For graphite the linear absorption lengths is in the range 31–74 nm at 355-1064nm compared to 10-13nm for copper at 800 nm [12]. By applying of ultra-short pulses at higher laser fluences the optical penetration depth increases to the effective penetration depth of 80 nm leading to a strong ablation regime [13] with a linear dependence of the ablation depth of the fluence [14].

In Figure 4 some steps are visible within the slope of the ablation depth vs. average power. For a better understanding of this effect Figure 5 show the maximum depth deviation (difference of minimum and maximum measured ablation depth) of the trenches vs. the ablation depth for the wavelengths 1064 nm and 532 nm.
At ablation depths of about 500 μm and 950 μm (Figure 5, encircled) the measured variations are maximal. The material thickness is 1.9 mm made up of the 4 biaxial non crimp fabric. Accordingly, there are CF layer crossovers in a region of 475 μm, 950 μm and 1425 μm. The first two layer crossovers are very close to the observed outliers. At 532 nm the depth deviations are remarkable weaker. Stronger absorption at 532 nm leads to the shorter penetration length $l_\text{Į}$ of 50 nm compared to $l_\text{Į} = 74$ nm at 1064 nm operating wavelength. Thus in summary, for highest depth control the visible laser wavelength seems to be advantageous compared to the fundamental laser wavelength.

In order to visualize the composition of CFRP and the results presented in Figure 5 a 3D-topography measurement of the CFRP sample is shown in Figure 6. The chromatic sensor is integrated in the 5-axes laser micromachining system. This setup allows topology measurements directly after laser machining without any sample reassembling. The setup parameters are shown in Table 5.

Table 5. Parameters of 3D-topography measurement

| Topography measurement parameters |  |
|-----------------------------------|--|
| Frequency [Hz]                    | 4000 |
| Axes feed rate [mm/s]             | 10   |
| Point distance (in both directions) [μm] | 25   |
| Measuring depth (axial) [μm]      | 1000 |

For the 3D-topography measurement an ablation depth close to the first and second CF-layer crossover was chosen. The corresponding 3D reconstruction of the ablated trench is presented in Figure 6 by false colour rendering. Depth details are provided by the colour scale attached to the 3D-reconstruction. The carbon-fibre roving in the centre is aligned at 45° angle to the underlying roving, which indicates the crossover between the first and the second layer starting in the final ablation plane. Darker areas (down right to the slug) show an area of deeper ablation. During the material processing of non-crimp fabric air cavities will be created in the area of roving crossovers in axial or lateral direction (relative to the sample surface). These macroscopic cavities will be filled out by fluid epoxy resin during the infiltration process. Curing in an autoclave results in local epoxy resin
conglomerations distributed inside the CFRP bulk. The 50-times lower vaporisation energy per unit volume for the epoxy matrix compared to the carbon fibres leads to highly stronger ablation of epoxy leading to the observed craters (Figure 6).

Figure 6. 3D-reconstruction of the chromatic topography measurement of laser machined CFRP

3.3. Heat Affected Zone (HAZ)

In addition to the throughput and depth control, it is very important to compare the HAZ at different laser wavelengths using picosecond laser systems. The question that needs to be answered is: Can the processing time be reduced by scaling laser power without losing the high quality of ultrafast laser machining? In this paper the HAZ is defined as the length of carbon fibres free of epoxy at the surface of the sample, see Figure 7.

Figure 7. (a) Sketch of the machined trench with typical shape, alignment and position of HAZ (marked in red); (b) Microscope image of the carbon fibres free of epoxy (HAZ)
Figure 7 shows a sketch of the laser machined trenches with typical shapes and positions of the HAZ in the CFRP composite. The combination of the high thermal conductivity (50 W/mK) of carbon fibres in longitudinal direction, their very high vaporisation temperature (>3500 K), two orders of magnitude lower thermal conductivity of epoxy (0.2 W/mK) and its very low vaporisation temperature (~770 K) leads to decomposition of epoxy preferred in longitudinal direction of carbon fibres [8]. Thus, if heat produced by the laser beam inside carbon fibres exceeds the critical temperature the epoxy will be vaporized preferred in longitudinal direction. In this report the removal of epoxy resin at the surface was measured to define the HAZ. Chemical analysis for the residual epoxy for checking any changes of chemical conditions will be a part of further investigations. The results of the measured HAZ for operating wavelengths 532 nm and 1064 nm are shown in Figure 8 and indicate following:

![Graph showing the relationship between peak power and HAZ for 532 nm and 1064 nm wavelengths.](image)

Figure 8. Maximum measured heat affected zone for picosecond ablation of CFRP for 532 nm and 1064 nm

First, by increasing the peak fluence or laser power the HAZ will also be increased. Furthermore, a linear dependence between pulse energy and HAZ can be assumed and confirms the assumption that a fraction of the absorbed pulse energy remains in the bulk material as heat even for applying of ultra-short laser pulses [15]. It can be explained using the well known Beer’s absorption law [16]. Any fraction of the pulse energy which is lower than the ablation threshold will heat the bulk material.

Second, the maximum measured HAZ is stronger at 1064nm compared to the HAZ at 532 nm. This can be explained by the wavelength dependence of the absorption coefficient of the epoxy resin. The epoxy matrix is optical transparent in the IR and shows higher absorption at 532 nm both for linear and nonlinear absorption mechanism. In case of IR laser machining more laser power will be scattered into the bulk material and lead presumably to more thermal load.

4. Summary and outlook

This report have presented the first systematic investigation of the wavelength influence on CFRP ablation using picosecond laser pulses in terms of quality and process throughput. All three laser wavelengths at 355 nm, 532 nm and 1064 nm show very similar ablation rates applying the same laser power up 10 W. Due to optimized process parameters for the selected geometry no remarkable saturation effects are visible for applied laser powers up to 19 W in the IR. But for highest depth control the visible laser wavelength seems to be advantageous compared to the fundamental laser wavelength at 1064nm. It has been demonstrated that the quality of CFRP ablation depends
strongly on the operating wavelength. The maximum HAZ at 1064 nm has almost been doubled compared to the HAZ at 532 nm and has shown a linear dependence on the applied laser power. Future work could include further investigations on the UV wavelength, on the focusing conditions, and on the ablation threshold by considering the incubation model.

Acknowledgements

The authors thank Torben Priess from IFB (Universität Stuttgart) for providing of CFRP sample materials. The authors wish to gratefully acknowledge the financial support provided for this study by EU/EFRE.

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