Lasers in Manufacturing Conference 2015

Cutting of CFRP with short-pulsed lasers at 1 µm and 10 µm wavelength and average powers of more than 1 kW

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Abstract

Simulations of laser processing of carbon fibre reinforced plastics (CFRP) show that laser intensities of more than 10^8 W/cm² are needed to achieve thermal damage at the cutting edge of less than 10 µm (Weber et al., 2011).
Today these high intensities are mainly achieved by pulsed laser systems with pulse durations below 1 µs. Furthermore an average power above 1 kW is needed to achieve industrial relevant cutting velocities in the range of 1 m/min.
In this experimental study cutting of CFRP with two pulsed laser sources at the wavelength of 1 µm and 10 µm with an average power of more than 1 kW was investigated. The cuts were performed with fast laser scanners applying multiple passes to achieve complete separation of the processed parts. The cutting strategy was optimized in order to avoid heat accumulation from pulse to pulse and from scan to scan (Freitag et al., 2013).
The 10 µm wavelength laser source was a pulsed CO_2-laser prototype from TRUMPF with pulse duration of 170 ns and a repetition rate of 20 kHz. The peak intensity was $6{\cdot}10^8$ W/cm². The achieved thermal damage was less than 50 µm with an effective cutting speed of 0.4 m/min.
The 1 µm wavelength laser source was the IFSW-Kilowatt-Picosecond laser (Negel et al., 2014) with pulse duration of 8 ps, a repetition rate of 300 kHz, and an average power of more than 1.4 kW. The peak intensity was $7{\cdot}10^{12}$ W/cm2. The minimal thermal damage was less than 10 µm with an effective cutting speed of 0.9 m/min.
With these systems it could be shown that both short-pulsed laser systems with average powers of more than 1 kW are able to cut CFRP with industrial relevant cutting velocities. Furthermore with the correct process strategies the extent of the thermal damage is less than 50 µm.

Keywords: CFRP, laser processing, laser cutting, ablation depth, thermal damage, HAZ, short and ultrashort laser pulses;

1. Cutting of CFRP

Laser cutting of CFRP is a very promising method for large volume production of CFRP lightweight parts. To reach industrial relevant cutting velocities in the range of 2 m/min for a thickness of 2 mm, an absorbed average laser power of at least 1 kW is needed (Onuseit et al., 2015). This average power can be easily reached with industrial available cw lasers but not with pulsed laser systems with pulse durations in the ns-regime and below. These pulsed systems are needed because cutting of inhomogeneous materials like CFRP requires sophisticated process strategies due to the different

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thermophysical properties of the components. In comparison to the matrix material the carbon fibres have a much higher heat conductivity, sublimation temperature and latent heat (Pradere et al., 2009, Rolfes and Hammerschmidt, 1995). Due to this, the volume specific energy to sublimate the carbon fibres is much higher than the energy needed for decompostation and evaporation of matrix material. As long as the fibres are heated up to sublimation temperature and are sublimated, a certain amount of energy flows along each fibre due to their high heat conductivity. The matrix material which is in contact with the surface of the fibres is heaten up, in the worst case to evaporation temperature. Because of the low evaporation temperature of 800 K and the low latent heat of the matrix, the matrix is evaporated. The result is an area in the vicinity of the cutting edge without matrix material but only carbon fibres. This is the so called matrix evaporation zone (MEZ). Calculations show that the extent of this MEZ depends on the applied laser intensity (Weber et al., 2011). The higher the intensity the shorter is the time needed for sublimating the fibre. The amount of energy flowing along each fibre direction is reduced and therefore the extent of the MEZ decreases with increasing intensity.

Fig 1 shows the extent of the matrix evaporated zone as a function of the absorbed intensity. Higher intensities than 10^8 W/cm² lead to a minimum damage of less than 10 µm. These high intensities can be conveniently achieved with pulsed laser sources with pulse durations of ns or below.

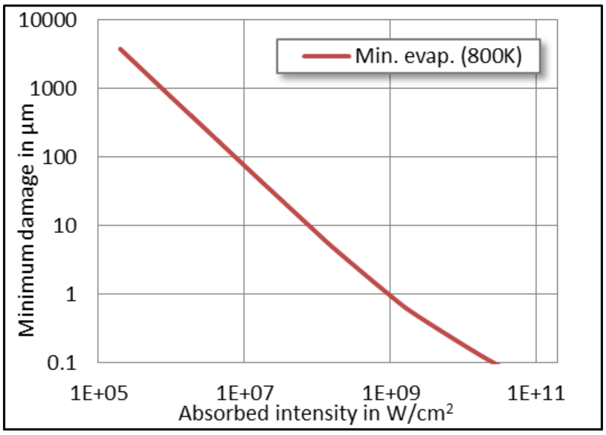

Fig 1. Calculated minimum thermal damage as a function of the absorbed laser intensity (Weber et al. 2011)

In addition to the intensity the extent of the matrix evaporation zone is influenced by heat accumulation effects. The first heat accumulation effect is the so called heat accumulation between pulses (HAP). The HAP depends on the total number of pulses (N_{Pulses}) incident at one point. The number of pulse incident at one point can be calculated by

$$N_{Pulses} = \frac{d_f \cdot f}{v}, \qquad (1)$$

where d_f is the focal diameter of the laser beam, f is the frequency of the laser and v is the velocity of the laser beam.

If the the pulse enrgy is high enough and the time between two subsequent pulses is so short that the next pulse hits an alreadey preheated surface, the heat will continuously accumulate with each following pulse and causing a steady temperature rise in the interaction region. If the matrix evaporation temperature is exceeded, the matrix evaporation zone will increase (Freitag et al. 2013, Weber et al. 2014).

The second heat accumulation effect is the so called heat accumulation between scans (HAS). For cutting with high scanning velocities to avoid the HAP effect multiple scans are necessary to cut the sample. If the cooling down time between two subsequent scans over the same position of the interacting zone is too short, the heat accumulates with every new pass and leads to additional damage (Feitag et al., 2015).

To avoid the MEZ due to heat conduction high intensities above 10^8 W/cm² are needed. In addition, the HAP and the HAS effect have to be avoided by properly choosing the process strategy. Furthermore a high average power in the range of 1 kW is needed to reach high cutting velocities.

2. Experimental setup

In this investigation two different laser sources where used:

- A CO_2-laser prototype from TRUMPF with a pulse duration of 170 ns and a repetition rate of 20 kHz (referred to as CO_2-laser in the following)
  The raw beam diameter of the laser was 14 mm and the measured focal diameter was 330 µm. The average power was 1100 W.
- A 1 µm-wavelength Kilowatt-Picosecond laser with a pulse duration of 8 ps and a repetition rate of 300 kHz (Negel et al., 2014, Feitag et al., 2015) (referred to as kW-ps-laser in the following).
  The raw beam had a diameter of 5.5 mm and the maximum used laser power was 1.1 kW.

To avoid the HAP and HAS effect the CFRP was cut in a multi-pass process with high scanning velocities above 10 m/s and additional breaks to allow a cooling down of the sample between the scans.

For both laser sources the setup consisted of the laser and a scanning unit with a F-Theta focusing lens. The laser beam was guided over the samples by the galvanic mirrors of the scanning unit.

The scanner unit which was used for the CO_2-laser had a focal length of 450 mm and a maximum possible scanning speed of 13.5 m/s. The peak intensity of the laser was $6{\cdot}10^8$ W/cm^2. The scanning velocity was chosen to 15 m/s. Therefore the number of pulses incident at one spot is calculated with formula (1) to $N_{Pulses} = 0.44$.

The scanner unit for the kW-ps-laser had a F-Theta focusing lens with a focal length of 340 mm. With the maximum possible scanning speed of 30 m/s the number of pulses incident at one spot was $N_{Pulses} = 1.2$. The calculated focal diameter was 120 µm. The peak laser intensity was $7{\cdot}10^{12}$ W/cm^2.

The contour length of the cut was 720 mm which where made with the CO_2-laser and 157 mm with the kW-ps-laser. At the experiments with the CO_2-laser a break of 20 seconds was made after 50 consecutive scans to minimize the HAS. The focal position was set on the surface of the samples. To observe the behavior of the ablation rate and the MEZ different numbers of scans were applied.

3. Experimental Results

To analyze the produced samples cross sections of the kerfs were made and the MEZ and the ablation depth was measured with an optical microscope.

3.1. Ablation depth

Fig 2 (a) shows the ablation depth as a function of the number of scans which was achieved with the CO_2-laser. The applied laser power was 1.1 kW and the repetition rate was 20 kHz which leads to a pulse energy of 55 mJ. The peak intensity was $6{\cdot}10^8$ W/cm^2. First there is a strong increase of the ablation depth during the first 200 scans. The ablation progress decreases with higher number of scans. To cut a 2 mm thick CFRP-sample 2000 scans were needed.

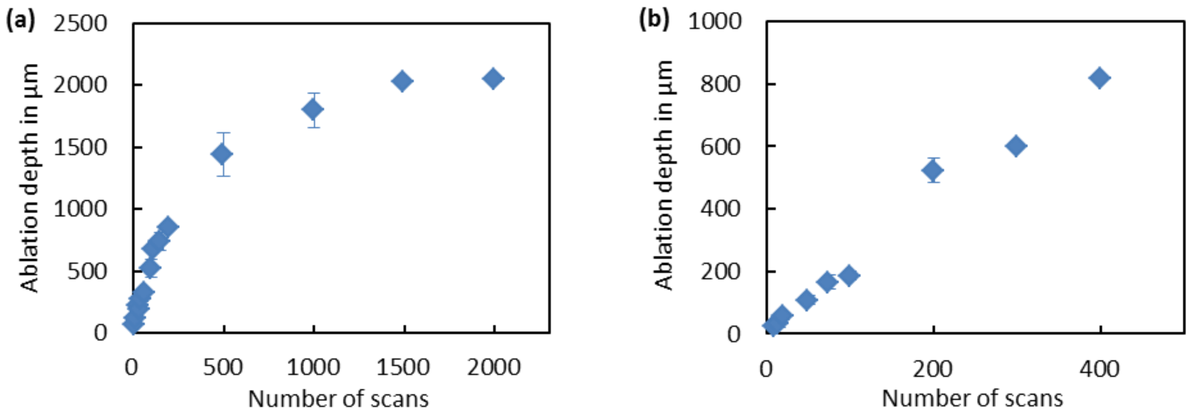

Fig 2. (a) Achieved ablation depth with CO_2-laser; (b) ablation depth for different number of scans with kW-ps-laser.

Fig 2 (b) shows the ablated depth as a function of the number of scans ablated with the kW-ps-laser. With increasing number of scans the ablation depth increases almost linearly. After 200 scans an ablation depth of 0.5 mm was achieved, with the CO_2-laser an ablation depth of 0.9 mm was achieved.

3.2. Matrix evaporation zone

Fig 3 (a) shows the extent of the MEZ for experiments with the CO_2-laser at the averge power of 1100 W. There is a slight increase in the extent of the MEZ with increasing number of scans but the maximum extent is still below 80 µm.

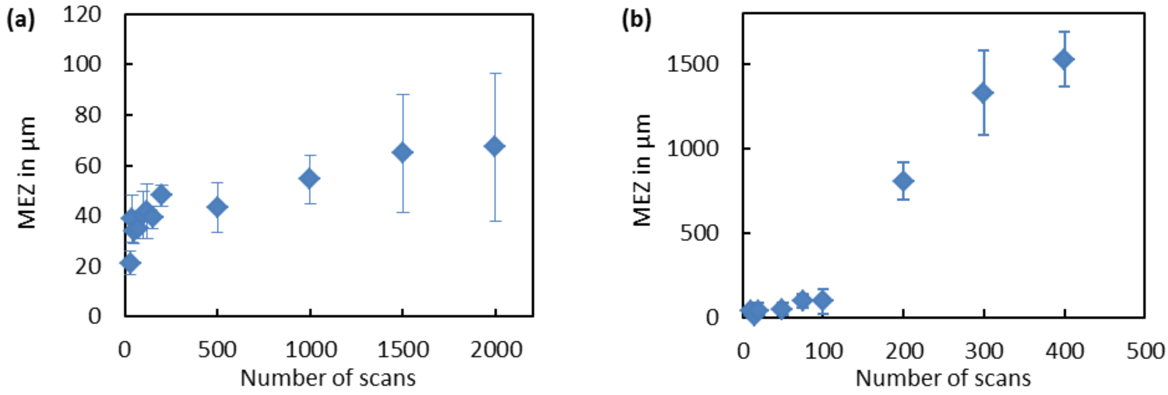

Fig 3. (a) Extent of the MEZ as a function of number of scans for the CO_2-laser; (b) extent of the MEZ as a function of number of scans for the kW-ps-laser

Fig 3 (b) shows the extent of the MEZ for experiments with the kW-ps-laser. Here no break was made after a certain number of scans. The large increase of the MEZ after 200 scans results from the HAS effect. The time between two consecutive scans is to short to cool down the cutting edge. The temperature of the cutting edge increases more and more, until the evaporation temperature of the matrix is exceeded which leads to a strong increase of the MEZ. To avoid the HAS effect the maximum number of scans has to be limited to about 100 for this contour and a break has to be implemented to keep the extent of the MEZ at the minimum value.

3.3. High-quality cuts

To achieve high-quality cuts the process parameters were set to have a minimum extent of the MEZ at high laser powers: To minimize the HAP for the high quality cut with the CO_2-laser the scan velocity was set to 15 m/s. Breaks of 20 s were introduced after 50 consecutive scans to avoid the HAS effect. The contour length of the cut was 720 mm. 2300 scans were needed to completely cut the samples. This leads to an effective cutting speed of 0.4 m/min without the breaks.

For the cut with the kW-ps-laser a scan velocity of 30 m/s was chosen and after 200 consecutive scans a break of about one minute was made to avoid the HAS. The contour length of the cut was 630 mm. 2100 scans were necessary to completely cut through the sample. The effective average cutting speed was 0.9 m/min without the breaks.

To evaluate the quality of the cuts cross sections were done to analyse the cut quality and the extent of the MEZ. Fig 4 shows cross sections of the cuts. Fig 4 (a) shows the cross section of the cut with the CO_2-laser, Fig 4 (b) with the ps-kW-laser. The width of the cut does not represent the kerf width. The quality of the kerf with an extent of the MEZ of less than 30 µm is remarkable. The kerf has a slight angle because of the angle of the laser beam with respect to the sample surface caused by the used F-Theta focusing lenses.

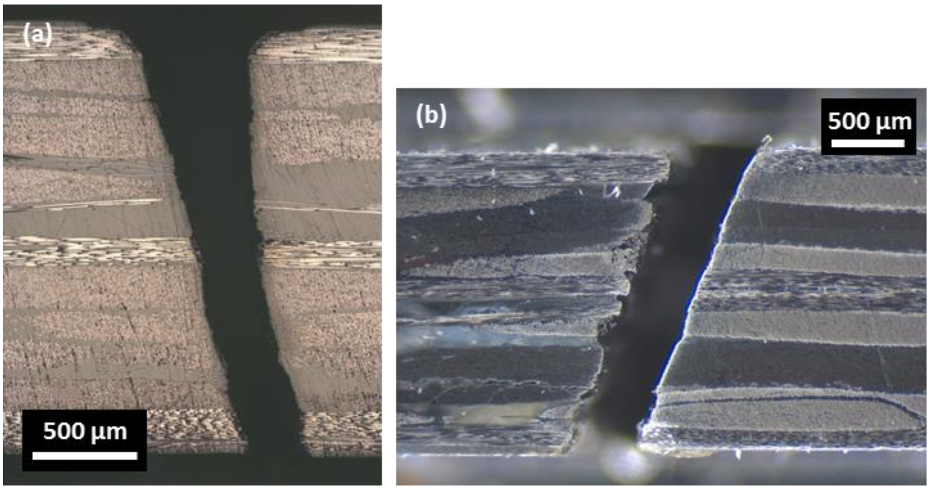

Fig 4.(a) cross section of cut with CO_2-laser; (b) cross section of cut with kW-ps-laser

4. Summary

Ablation experiments of CFRP with two different pulsed laser sources with high average power of more than 1 kW were compared. Regarding the limitations of heat accumulation between scans, heat accumulation between pulses and without additional process strategies like adjustment of the focal position and parallel processing high productivity cuts were shwon with average cutting velocities up to 0.9 m/min . The very small extent of the matrix evaporation zone of less than 30 µm confirmed that high quality cuts are possible with such pulsed laser sources with high average powers applying the correct process strategy.

Acknowledgements

These work was funded by the German Federal Ministry of Education and Research BMBF in the frame of the project ProCaV under Contract No. 13N11911 and in the frame of the project T4nPV under Contract No. 13N11787 and the Graduate School of Excellence advanced Manufacturing Engineering GSaME if the university of Stuttgart.

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