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Productive Laser Processing of CFRP

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Abstract

Laser processing of carbon fiber reinforced plastic (CFRP) is a very promising method to solve a lot of the challenges for large-volume production of lightweight constructions especially in automotive and airplane industries. Laser processes are very promising for tasks like cutting of dry fibers, trim cutting of parts after the curing process, or drilling of holes for riveting. The challenge for these processes is to reach both, the productivity and quality which is needed for large-volume production. In this paper processing with different laser sources including cw-lasers with high average power up to 6 kW and ps-lasers with average power from 30 W up to 1 kW will be compared in terms of productivity and quality for different applications. The main issue reducing the quality of laser-processed CFRP parts is the heat affected zone which results from heat conduction into the material. In the present paper, the influence of the heat affected zone on the mechanical strength of CFRP components will be discussed. It will be shown that damage-free laser processing of CFRP is possible when using high intensities above 10^8 W/cm² and avoiding any kind of heat accumulation in the processing zone. To reach this intensity it is favorable to use short and ultra-short pulsed lasers with pulse duration of several ns down to ps. However, the productivity of the process is dominated by the average laser power available which is actually below 150 W for commercial systems. Therefore it is necessary to increase the efficiency by using advanced process strategies.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

The first research on laser processing of CFRP was done in the 1980's with the first available high power lasers from (Van Cleave, 1980; Crane and Brown, 1981; Tagliaferri et al., 1985; Wehner et al., 1989). With the increasing interest in lightweight construction mainly for reduced fuel consumption in automotive and airplane industries there is a need for fast and reliable production processes mainly for large-volume production. Laser processing is a very promising technology for some of these production steps like drilling holes for riveting or trimming the outer contour of a part. But laser processing of carbon fiber reinforced plastic (CFRP) has two main challenges. First the heat affected zone (HAZ) near to the cutting edge and second the productivity of the used laser processes with minimized thermal damage.

The heat affected zone is the dominant quality reducing factor. The reason for this HAZ is the good heat conduction along the carbon fibers compared to the matrix material and the great difference in evaporation or decomposition temperature of fibers and matrix. In recent publications from (Romoli et al., 2012; Finger et al., 2013) it was shown that short pulsed laser systems with pulse durations from ns down to ps or fs are useful to reduce the extent of the HAZ. The main effect of the short pulse durations is that this kind of laser systems have the high intensity which is needed for a fast evaporation of the carbon fibers to reduce the HAZ as shown by (Weber et al., 2011). Although the heat affected zone can be suppressed with high intensities, for high productivity a high average laser power is needed. This leads to the major problem of heat accumulation especially for lasers with high repetition rates and cw lasers. The effect of heat accumulation can be separated in two different effects, the heat accumulation between consecutive pulses the so called pulse – to –pulse heat accumulation as described by (Freitag et al., 2012; Weber et al., 2012, 2014) and the heat accumulation between consecutive scans the so called scan – to – scan heat accumulation. In this case the remaining heat between consecutive scans accumulates (Freitag et al., 2014) Freitag 2015.

The productivity is mainly limited by the usable average power of the laser system. As described it is favorable to use pulsed laser systems in the ns-, or ps-regime with high intensities. Unfortunately these lasers are limited up to now to a few hundred Watts for commercial systems but the next generation of these systems is already available in the laboratories with average power above 1kW (Negel et al., 2013). These pulsed systems are necessary if a damage free processing of CFRP is needed. For high productivity it is also possible to work with already existing multi-kW cw laser systems. In this case it is not possible to avoid the HAZ completely. But with these laser systems it is possible to come to high productive cutting processes.

In this work different laser systems and processing methods will be compared concerning the productivity and the quality which could be reached with these systems.

2. Productivity

To remove CFRP it is necessary to evaporate the carbon fibers as carbon has no liquid phase below up to 100 bars (Morgan, 2005). The volume specific enthalpy of carbon

The volume specific enthalpy for evaporation of carbon,

$$h_V = \rho \cdot \left((T - T_{vap}) \cdot c_p + L_{vap} \right), \tag{1}$$

is about 85 J/mm^3 with the sublimation enthalpy, L_{vap}, of 43 MJ/kg, the specific heat capacity of c_p= 710 J/kgK, the density of ρ = 1850 kg/m3 and the high evaporation temperature T_{vap} of about 3600 K [14]. This is about a factor of forty higher than the volume specific enthalpy to sublimate the matrix material. This means that the volume specific enthalpy for the composite is in the range of 43 J/mm^3 for a composite with a typical fraction of 50 % of fibers. The required power P_p for a given feed v_f is then given by:

$$P_P = v_{feed} \cdot b \cdot s \cdot \rho \cdot h_v \,. \tag{2}$$

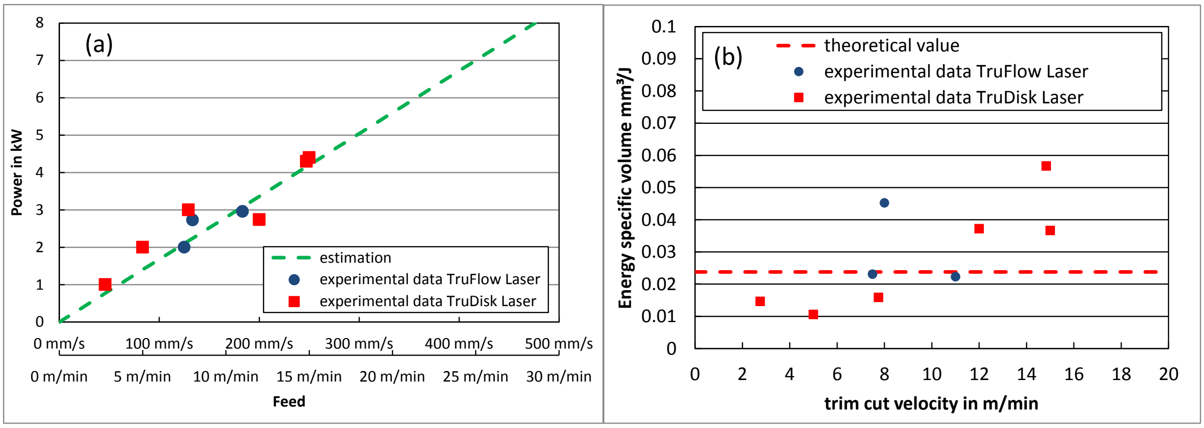

Fig. 1 (a) Estimated needed power for complete evaporation of composite compared with experimental data from cutting 2mm thick CFRP with CO_2 and Thin Disk laser with average power from 1-5 kW. (b)

For cutting of industrial relevant parts with a thickness *s* of approximately 2 mm and assuming a kerf width which is 10x smaller than the thickness (i.e. *b* = 0.2 mm) with a reasonable cutting velocity of about 10 m/min this leads to a required absorbed laser power of 3 kW if the whole kerf volume is evaporated see Fig. 1 (a) green line. This estimation fits very well to the experimental data when cutting with cw lasers in a single pass as shown in Fig. 1 (a). This estimation shows that for cutting CFRP laser sources with more than 1 kW average power are necessary to reach reasonable cutting velocities. The experiments were performed with a TruDisk5001 ThinDisk laser with wavelength λ=1030nm with a beam delivery fiber with a fiber core diameter of D_{Fiber}=100µm and with a TruFlow5000 CO_2 with radial polarization, the parameters are described in Table 1. The used material was Toray T700S-12k carbon fibers with RTM6 as matrix material. The fiber layup was quasi-isotropic [0/90, -45/+45, 90/0, 0/90, -45/+45, 90/0] with a fiber content of 50%. The deviation of the experimental data in Fig. 1 (a) is not only caused by the difference of ablated volume in comparison to the estimation with estimated width of the cutting kerf but also from differences in the needed energy to remove the volume as showed in Fig. 1 (b).

Table 1 Parameters for experiments with cw laser

Set No.	Laser type	Wavelength λ	Focal length collimation F_C	Focal length focusing F_F	Focus diameter D_F	Power levels	Max. cutting velocity
1	TruDisk5001	1030nm	200mm	100mm	50µm	1kW 2kW 3kW	2.8 m/min 5 m/min 7.8 m/min
2	TruDisk5001	1030nm	200mm	200mm	100µm	4.3kW	15 m/min
3	TruDisk5001	1030nm	200mm	280mm	140µm	2.8kW 4.4kW	12 m/min 15 m/min
4	TruFlow5000	10600nm	–	155mm	230µm	1kW 2kW 3kW	- 7.5 m/min 11 m/min
5	TruFlow5000	10600nm	–	80mm	140µm	2.8kW	8 m/min

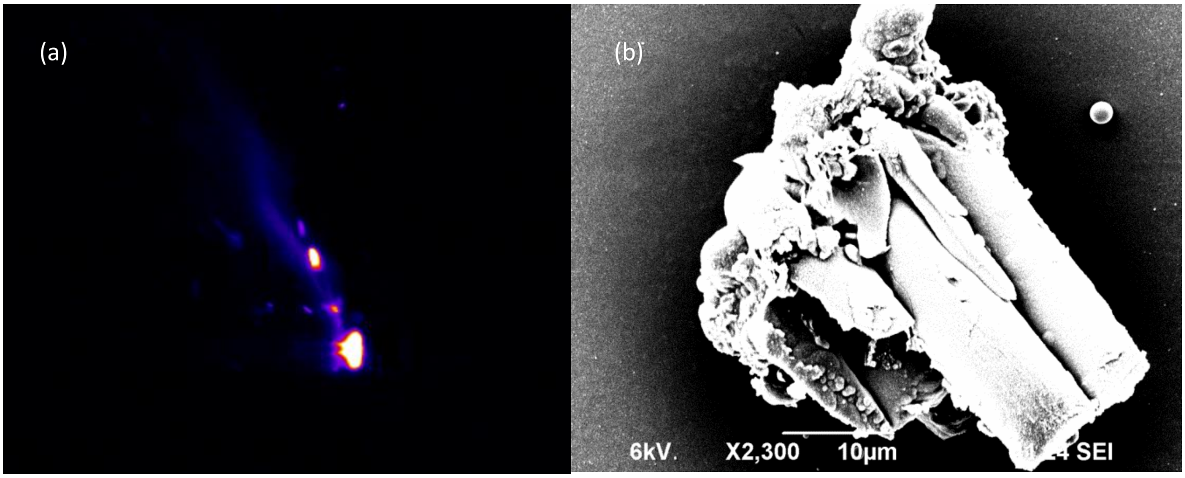

Fig. 2 (a) Picture from high speed imaging from the side of cutting process with TruDisk 5001, $P_{av.}$ 3kW, v=10m/min, parameter set No. 2 (b) SEM picture of collected particle from cutting process with TruFlow5000rad with parameter set No.4

The theoretical value of the energy specific volume is calculated with equation (1), for the experimental data the ablated volume of the cutting kerf was measured with cross sections at the trim cut velocity (fastest cutting velocity were the parts are separated). It can be seen in Fig. 1 (b) that especially for higher cutting velocities the energy specific volume is higher than calculated for complete evaporation. The reasons for this behavior could be that not the complete volume has to be evaporated. High speed imaging and collecting of particles shows that some amount of material is not removed in vapor state but as particles, see Fig.2. But nevertheless the estimation of the process speed with the volume specific enthalpy from equation (1) and equation (2) allows a prediction of the reachable cutting velocities. As mentioned above, for high speed cutting of CFRP with 10 m/min cutting velocity an average laser power of > 3 kW is needed. Unfortunately the only available laser systems with this average power are up to now cw lasers. This implies that with the low reachable intensities and the heat accumulation, thermal damage cannot be avoided. The experiments with the cw lasers shows an heat affected zone for the trim cut parameter in the range of 0.3 to 0.5 mm as shown in Fig.3 (a) and (b). To reduce the effect of heat accumulation it is necessary to increase the cutting

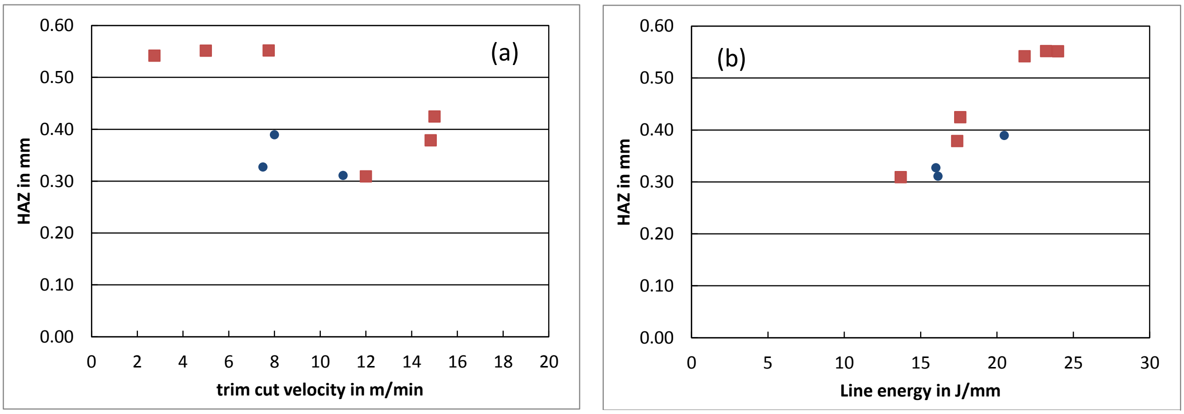

Fig. 3 Heat affected zone for cutting with TruDisk5001 (red squares) and TruFlow 5000rad (blue dots). (a) effect of cutting velocity (b) effect of line energy

velocity. With increasing cutting velocity the ablation depth decreases and it is necessary to change from a single pass process to a multi pass process to minimize the HAZ due to heat accumulation.

3. Efficient damage free processing

For damage free processing or low damage processing with a heat affected zone < 20 µm the intensity of the laser has to be above 10^8 W/cm². For this it is necessary to work with short or ultra–short pulsed laser sources with pulse durations in the ns or ps regime. Unfortunately the average laser power of industrial available laser systems with these pulse durations is up to now limited to a few hundred Watts. For an efficient cutting process of CFRP with ps lasers it is necessary to have a certain aspect ratio depth : width of the cutting kerf below 5 as shown by (Onuseit et al., 2015). To achieve such an aspect ratio over the whole cutting process it is not necessary to evaporate the complete kerf volume. The approach to reduce the power consumption is to take benefit of the thermal damage. In this case the fibers has to be evaporated at the edges of the kerf, the remaining material in the middle of the kerf can then be removed by evaporating only the matrix material. The remaining fiber fragments will be blown out by the evaporated matrix material. If the energy consumption of the matrix material is neglected the power consumption of the process will be reduced by the ratio of the width of evaporated fibers to the complete kerf width as shown in Fig. 4 (a).

The experiments to test this strategy were made with a TruMicro 5250 with pulse duration of approximately 7 ps and an average power of 30 W. The repetition rate was 800 kHz with pulse energy of 37.5 µJ. The wavelength of the laser was 515 nm. The laser was focused with an F-Theta lens with a focal length of 260 mm to a 27 µm-diameter spot. The processed material was the same as for the cw experiments. The distance between the two outer lines to cut the carbon fibers were set to 440 µm (center to center) to adapt the strategy properly to the needed cut geometry with an aspect ratio below five. The matrix material in the inner part of the cutting kerf was removed with three parallel lines which were processed with relatively low scanning velocity of 625 mm/s which leads to a thermal damage of > 80 µm due to the pulse to pulse accumulation. Minimum three lines were necessary to fill the inner area with this width of heat accumulation zone. The distance to the outer lines (90 µm) were kept smaller than the distance between the inner lines (130 µm). The difference between the scanning velocity of the outer lines (5000 mm/s) and the inner lines (625 mm/s) leads to different ablation depths. Therefor the outer lines were scanned 4 times when scanning once the inner part to achieve nearly the same ablation depth. The productivity of this cutting process is described with the effective cutting velocity as shown in (BILD). With this process strategy

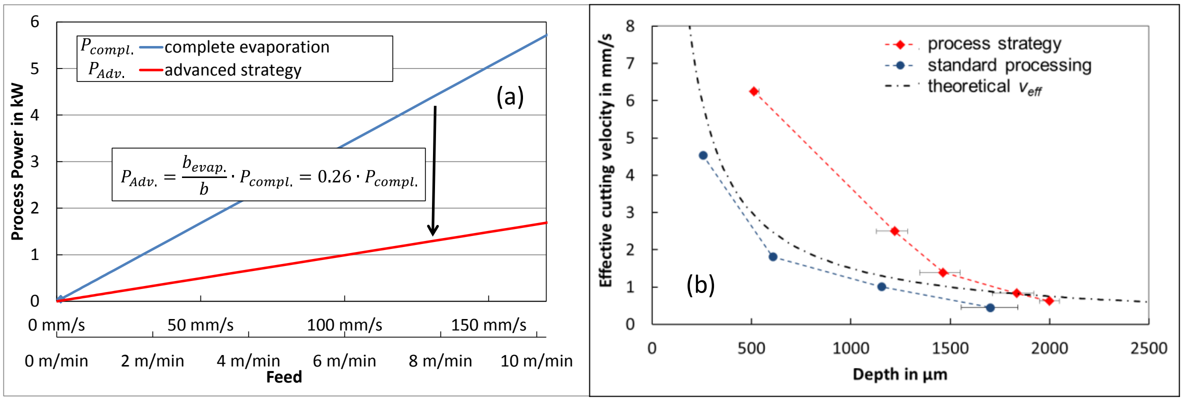

Fig. 3 (a) reduced power consumption for advanced cutting strategy $P_{adv.}$ in comparison to complete evaporation P_{comp} (b) effective cutting velocity for multi pass cutting in comparison to advanced cutting strategy

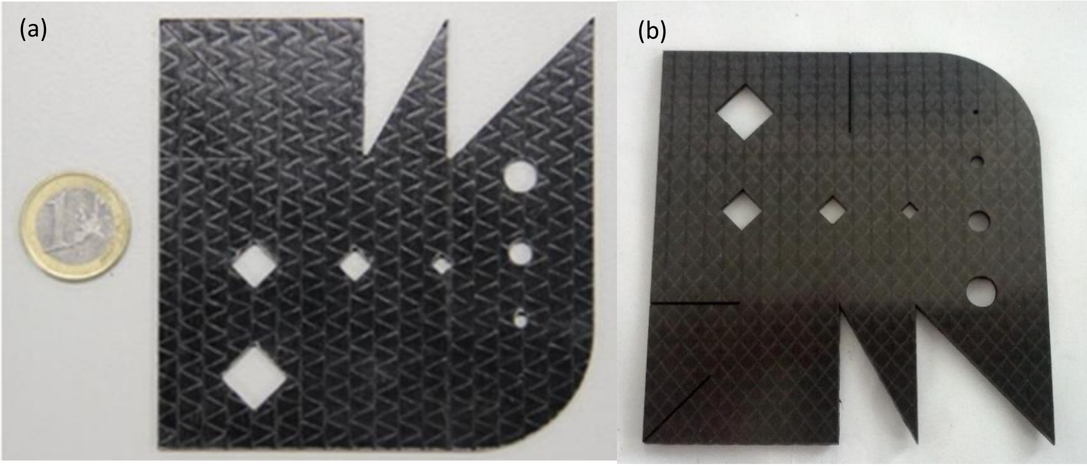

Fig. 4 Processed samples with (a) TruFlow 4500-HQ and (b) TruMicro5250.

it is possible to increase the cutting velocity at least by a factor of two by utilizing the thermal damage.

4. Comparison of different processing methods

For processing CFRP different processing methods are possible. State of the art for processing CFRP is abrasive water jet cutting or mechanical processing (drilling, milling). For laser processing different laser sources and processing strategies are possible as described above:

1. Single pass cutting with high average power cw laser
2. Multi pass cutting with high average power cw laser (small amount of passes)
3. Multi pass cutting with high average power pulsed laser (single line, multiple passes)
4. Multi pass cutting with low average power pulsed laser (parallel lines, multiple passes)
5. Multi pass cutting with additional beam rotation (single line, multiple passes)

For method No. 5 the widening of the cutting kerf was done with a beam rotation optic GLTrepan from GFH instead of using multiple parallel lines. The diameter of the beam rotation was set to 215 µm and the

Method	Description
Milling	f=24000rpm, v=2.8m/min
Water jet	Pressure 3500bar; Abrasive 350g/min; v = 2.5m/min
TruFlow 4500-HQ single pass	λ= 10600nm;$P_{Av.}$= 4kW; D_F= ;v_{single}=17 m/min; N_{Passes}=1; cw
TruDisk 6001 multi pass	λ= 1030nm;$P_{Av.}$= 6kW; D_F= ;v_{single}=60 m/min; N_{Passes}=4; cw
Multi Pass Amplifier	λ= 1030 nm; $P_{Av.}$= 1 kW; D_F= ;v_{single}=30 m/s; N_{Passes}=2100; t_P<10 ps; f_{Rep}=300kHz; E_P~3.6 mJ
TruMicro 5050 adv. Strategy	λ= 1030 nm; $P_{Av.}$= 50 W; D_F=61 µm ;v_{single}=5 m/s and 0.63 m/s; N_{Passes}=2400; t_P<10 ps; f_{Rep}=200 kHz; E_P=250 µJ
TruMark 6350 UV	λ= 355nm;$P_{Av.}$= 5W; D_F=57µm ;v_{single}=0.2 m/s; N_{Passes}=2500; t_P=12 ns; f_{Rep}=30kHz; E_P~150µJ
TruMicro 5250 with GLTrepan	λ= 515nm;$P_{Av.}$= 8W; D_F= ;v_{single}=2 m/s; tP=6 ps; f_{Rep}=200kHz; E_P~40µJ

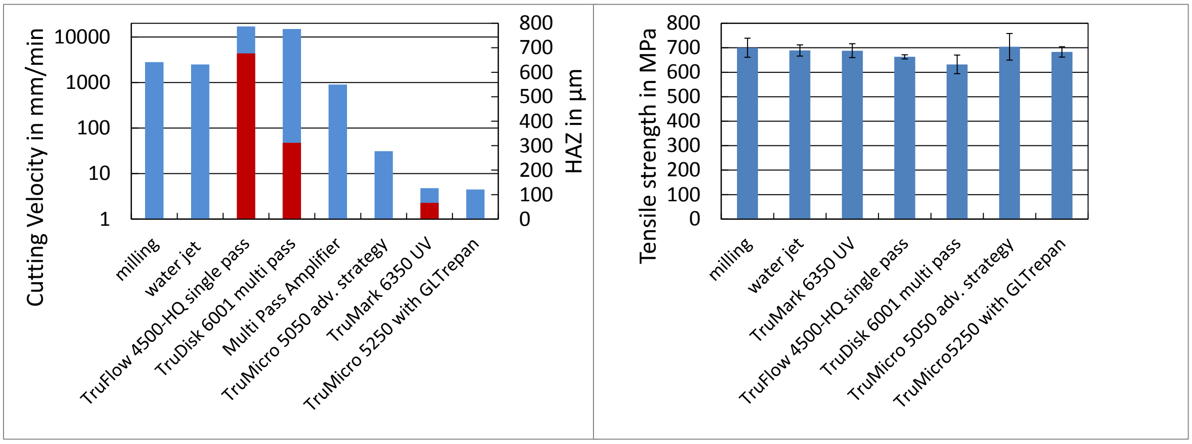

Fig. 5: (a) Cutting velocity of different processing methods. The cutting velocity is scaled logarithmic due to the large different between low average power pulsed laser and cw laser (b) results of open hole tensile testing taking into account the Airbus standard AITM1.0007

beam movement in cutting direction was done with an additional galvanometer scanner. The comparison of these different processing methods was done with standardized sample geometry with different tasks, large contour cutting with different edge angles and small contour cutting for round and rectangular holes with different size. The sample geometry is shown in Fig. 5. To investigate these different processing methods more in detail the different processing strategies were tested with different laser sources as and parameters shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** and compared to the state of the art milling and water jet. The processed material was the same as for the other experiments mentioned before. In case of the Multi Pass Amplifier the cutting velocity was not demonstrated with the sample geometry shown in Fig. 5 due to the prototype setup of the laser as described in (Freitag et al., 2014 Freitag et al., 2015). To compare the productivity of the different processing methods Fig. 6 (a) shows the used cutting velocities for the outer cutting contour for the different samples. In this case the fastest possible cutting velocity with acceptable quality was used for the processing of the samples. It can be seen that there is a difference of approximately two orders of magnitude between the laser processing with low average power pulsed laser sources and the milling and abrasive water jet cutting. With increased average power with the Multi Pass Amplifier this difference is reduced to only a factor of two and will be reduced further in future work. If a certain amount of thermal damage is acceptable the cutting velocity can be increased by using cw laser sources at least by a factor of 5 compared to water jet cutting and milling.

The influence of the laser processes on the static tensile strength was tested exemplary for riveting applications the specimen geometry according to Airbus standard AITM1.007. It can be seen in Fig. 6 (b) that there is no significant difference between the processing methods, the variability of the values is in the range of the variation of the sample material. The influence of the HAZ on the mechanical properties was also investigated by (Herzog et al., 2008; Jaeschke et al., 2011; Harada et al., 2012; Jung et al., 2012; Riveiro et al., 2012; Bluemel et al., 2014; Stock et al., 2014). And it was shown that the influence of the HAZ is mainly in the range of the reduction of the tested area due to this HAZ. This is in most cases a minor effect because the HAZ is in the range of 0.3 to 0.5 mm.

5. Conclusion

Damage free laser cutting is possible and with the power scaling of USP laser systems to more than kW average power and the actual state of the art for cutting velocities with milling and water jet cutting can be reached. In addition to this high speed laser cutting of CFRP with more than 10m/min with cw lasers is an alternative to conventional cutting technologies, especially if a certain amount of thermal damage is acceptable with regard to the fact that the effect in tensile strength tests is quite low.

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References

Bluemel, S., Jaeschke, P., Suttmann, O., Overmeyer, L., 2014. Comparative Study of Achievable Quality Cutting Carbon Fibre Reinforced Thermoplastics Using Continuous Wave and Pulsed Laser Sources. Physics Procedia 56, 1143–1152.

Crane, K.C.A., Brown, J.R., 1981. Laser-induced ablation of fibre/epoxy composites. Journal of Physics D: Applied Physics 14, 2341.

Finger, J., Weinand, M., Wortmann, D., 2013. Ablation and cutting of carbon-fiber reinforced plastics using picosecond pulsed laser radiation with high average power. Journal of Laser Applications 25.

Freitag, C., Hafner, M., Onuseit, V., Michalowski, A., Weber, R., Graf, T., 2012. Diagnostics of basic effects in laser processing of CFRP, in: Proceeding International SymposiumLaserProcessing CFRPComposites.

Freitag, C., Wiedenmann, M., Negel, J.-P., Loescher, A., Onuseit, V., Weber, R., Abdou Ahmed, M., Graf, T., 2014. Ultra-short pulse laser processing of CFRP with kilowatt average power, in: Proceedings International CongressApplications Laser & Electro-Optics ICALEO. pp. 491–498.

Freitag, C., Wiedenmann, M., Negel, J.-P., Loescher, A., Onuseit, V., Weber, R., Abdou Ahmed, M., Graf, T., 2015. High-quality processing of CFRP with a 1.1-kW picosecond laser. Applied Physics A 119, 1237–1243.

Harada, Y., Kawai, K., Suzuki, T., Teramoto, T., 2012. Evaluation of cutting process on the tensile and fatigue strength of CFRP composites, in: MaterialsScienceForum. Trans Tech Publ, pp. 649–654.

Herzog, D., Jaeschke, P., Meier, O., Haferkamp, H., 2008. Investigations on the thermal effect caused by laser cutting with respect to static strength of {CFRP}. International Journal of Machine Tools and Manufacture 48, 1464–1473.

Jaeschke, P., Kern, M., Stute, U., Haferkamp, H., Peters, C., Herrmann, A., 2011. Investigation on interlaminar shear strength properties of disc laser machined consolidated CF-PPS laminates. Polymer Letters 5, 238–245.

Jung, K.-W., Kawahito, Y., Katayama, S., 2012. Ultra-high speed disk laser cutting of carbon fiber reinforced plastics. Journal of Laser Applications 24.

Morgan, P., 2005. Carbon fibers and their composites. taylor & Francis Boca Raton, FL.

Negel, J.-P., Voss, A., Ahmed, M.A., Bauer, D., Sutter, D., Killi, A., Graf, T., 2013. 1.1 kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses. Opt. Lett. 38, 5442–5445.

Onuseit, V., Freitag, C., Wiedenmann, M., Weber, R., Negel, J.-P., Löscher, A., Abdou Ahmed, M., Graf, T., 2015. Efficient processing of CFRP with a picosecond laser with up to 1.4 kW average power. Proc. SPIE.

Riveiro, A., Quintero, F., Lusquiños, F., Val, J. del, Comesaña, R., Boutinguiza, M., Pou, J., 2012. Experimental study on the {CO2} laser cutting of carbon fiber reinforced plastic composite. Composites Part A: Applied Science and Manufacturing 43, 1400–1409.

Romoli, L., Fischer, F., Kling, R., 2012. A study on {UV} laser drilling of {PEEK} reinforced with carbon fibers. Optics and Lasers in Engineering 50, 449–457.

Stock, J.W., Zaeh, M.F., Spaeth, J.P., 2014. Remote laser cutting of CFRP: influence of the edge quality on fatigue strength. Proc. SPIE.

Tagliaferri, V., Ilio, A.D., Visconti, C., 1985. Laser cutting of fibre-reinforced polyesters. Composites 16, 317–325.

Van Cleave, R., 1980. Laser Cutting Plastics. DTIC Document.

Weber, R., Freitag, C., Kononenko, T.V., Hafner, M., Onuseit, V., Berger, P., Graf, T., 2012. Short-pulse Laser Processing of {CFRP}. Physics Procedia 39, 137–146.

Weber, R., Graf, T., Berger, P., Onuseit, V., Wiedenmann, M., Freitag, C., Feuer, A., 2014. Heat accumulation during pulsed laser materials processing. Opt. Express 22, 11312–11324.

Weber, R., Hafner, M., Michalowski, A., Graf, T., 2011. Minimum Damage in {CFRP} Laser Processing. Physics Procedia 12, Part B, 302–307.

Wehner, M., Poprawe, R., Trasser, F.J., 1989. Cutting With The Excimer Laser, Effects Of Pulse Width And Repetition Rate On Cutting Edge Quality Of Fibre-Reinforced Polymers And Alumina Ceramics. Proc. SPIE.