Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 56 (2014) 1143 – 1152

Physics Procedia

8th International Conference on Photonic Technologies LANE 2014

Comparative study of achievable quality cutting carbon fibre reinforced thermoplastics using continuous wave and pulsed laser sources

S. Bluemel[a,]*, P. Jaeschke[a], O. Suttmann[a], L. Overmeyer[a]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*

Abstract

Laser cutting of CFRP lightweight parts has the advantages of a contact-free, automatable and flexible processing for a prospective series production. For the development of strategies for laser cutting of carbon fibre reinforced plastics (CFRP), different scientific approaches exist to achieve a process with small heat affected zones (HAZ), and high cutting rates. Within this paper a cw laser, a nanosecond and a picosecond laser source emitting in the near infrared range have been used in combination with a scanning system to cut CFRP with a thermoplastic matrix. The influence of the scanning speed on the size of the HAZ and the corresponding tensile strength were investigated for each laser source. Furthermore, the authors compared the achievable HAZ and the effective cutting speeds of the different setups in order to evaluate the efficiency and quality of the chosen strategies. The results show that a nanosecond pulsed laser source with high average power is a good trade-off between attainable quality and cutting rate.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser cutting; CFRP; thermoplastic

1. Introduction

Carbon fibre reinforced plastics (CFRP) are of high interest for lightweight solutions due to their good weight to strength ratio. That's why they are used in more and more applications and products. In order to further increase the utilisation of CFRP, especially in automated series production, the existing processing techniques have to be

* Corresponding author. Tel.: +49-511-2788-421 ; fax: +49-511-2788-100 .
E-mail address: s.bluemel@lzh.de

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH
doi:10.1016/j.phpro.2014.08.029

improved. Regarding the cutting of CFRP parts, different process strategies are investigated using different types of laser sources. These laser sources operate either in the continuous wave or pulsed mode.

Finger et al. (2013) investigated for epoxy based CFRP the influence of increasing the average laser power $P_{L,avg}$ to values up to $P_{L,avg} = 430$ W by either increasing the pulse fluence F or the pulse frequency f_p for a picosecond laser emitting at a wavelength in near infrared range (NIR). The investigation, which was performed with an epoxy based CFRP, comes to the conclusion that for high average powers, higher pulse frequencies lead to higher ablation rates and smaller HAZ compared to same average powers achieved by higher pulse fluence. Whereas Finger et al. (2013) concluded that for high average power and pulse overlap the advantages of ultra-short pulsed lasers concerning thermal damage are reduced. With the results gained, Finger et al. (2013) achieved an effective velocity of $v_{eff} = 0.3$ m/min cutting an b = 300 µm wide kerf into a h = 2 mm thick CFRP sample. The resulting HAZ has a width between b = 70 µm and b = 250 µm from the bottom to the top of the sample. Slightly different results were achieved by another investigation. Freitag et al. (2013) investigated the development of a matrix evaporation zone for percussion drilling of thermoset CFRP with a picosecond laser emitting at a wavelength of $\lambda = 515$ nm. They show that for constant pulse energy and total energy brought into the material, lower pulse frequencies reduce the thermal damage.

Other approaches investigate the laser processing of epoxy based CFRP with nanosecond laser sources. Leone et al. (2013) used a 30 W Q-switched Yb:YAG fiber laser with a pulse duration of $t_p = 50$ ns to analyse the effects of process parameters on material removal mechanisms and the occurrence of the HAZ. Using the analysis of variance method (ANOVA), they performed a detailed analysis of the effects of certain parameters and their interaction. One conclusion of Leone et al. (2013) was that the occurrence of the HAZ is bigger using parameter sets supporting heat diffusion such as low scanning speed and high frequencies. Next to the variation of process parameters, Negarestani et al. (2010) investigated the influence of mixed reactive and inert gases on the thermal damage of the CFRP during laser cutting with a cutting head. The result was that a low volume fraction of oxygen within a nitrogen gas can improve the machining quality of the laser cuts regarding the fibre pull out. Concerning the reduction of the HAZ during gas assisted laser cutting, the statistical analysis reveal that low pulse energies at intermediate frequencies and high scanning speeds provide optimum results (Negarestani et al., 2010).

Another common cutting strategy is laser remote cutting with cw laser sources. Cutting with a cw laser can be differentiated e.g. in using multimode or single mode lasers. Klotzbach et al. (2011) make comparable studies cutting CFRP with a vinyl ester resin using a CO_2-laser, a single mode and a multimode fibre laser with similar intensities. The studies show that using single mode fibre lasers, the maximum processing speed could be higher than for multimode lasers, whereas the benefit was not as high as expected (Klotzbach et al., 2011). It is suggested that this is due to the thinner cutting kerf and a consequently higher aspect ratio between material thickness and kerf width.

Jaeschke et al. (2014) made investigations for the gas assisted cutting of thermoplastic CFRP using a NIR multimode fibre laser with a maximum output power of $P_{L,max} = 6$ kW. The CFRP with a thermoplastic matrix had a thickness of h = 2.14 mm. For the described configuration, a maximum cutting speed of v = 13.1 m/min and a minimum width of HAZ at this speed of b = 1.2 mm was reached. It was investigated that the width of the HAZ is influenced by the cutting velocity. Furthermore, it was evaluated by correlating the HAZ with the static tensile strength measurements that a reduction in the load bearing area due to thermal influence is the main factor for a reduction in tensile strength found for laser-treated composite laminates. Further investigations for the gas assisted cutting of thermoset and thermoplastic CFRP were performed by Bluemel et al. (2012) coming to the conclusion that for increasing cutting velocities the HAZ width can be reduced to a minimum but it cannot be avoided entirely.

Many scientific approaches are evaluated for example concerning their influence on the achievable cutting quality and effective cutting speeds. Within this paper the authors compare three different laser sources fitting in these strategies with an individual best practice for each setup. This procedure enables the evaluation of the achievable quality and efficiency for one material.

2. Experimental setup

For the comparative study three different common purchasable laser sources emitting in the near infrared range were available. A cw laser, a nanosecond laser as well as a picosecond laser were used (Table 1). All experiments were performed with a laser scanner adapted to each particular laser. This results in different beam characteristics for each particular laser source. The attainable cutting speed and resulting tensile strength depending on individual parameter sets for each particular laser source were investigated. In that way the best practice for each laser source is compared with each other, which must not result in identical parameters and line energies.

For all experiments a 4-layer thermoplastic CFRP named CETEX© consisting of 1/4 satin weave fabric and a polyphenylene sulphide (PPS) matrix with a total thickness of h = 1.2 mm was used. The orientation of the layers was 0°/+45°/-45°/90° as shown in Fig. 1. All specimens were aligned under the scanner so that the main cutting direction was parallel to the warp rovings of the surface layer.

Table 1. Description of laser and process parameters.

Laser source	TruMicro 5050	TruMicro 7050	YLS-6000
Manufacturer	TRUMPF	TRUMPF	IPG
Wavelength [nm]	1030	1030	1070
Average laser power [W]	50	750	4000
Pulse duration [ns]	0.006	30	-
Pulse energy [mJ]	0.25	35.5	-
Fibre diameter [µm]	-	400	100
Focal diameter [µm]	80	736	418
Fluence [J/cm²]	4.98	8.35	-
Frequency [kHz]	200	21.1	CW
Scanning velocity [m/s]	0.058 - 1.0	0.014 – 1.0	0.04 – 1.0
Repetitions	10 - 171	1 - 73	1 - 25
Effective velocity [m/min]	0.05	0.818	2.4
Line energy [J/cm]	598.5	550	1000
Number of parallel lines	7	1	1

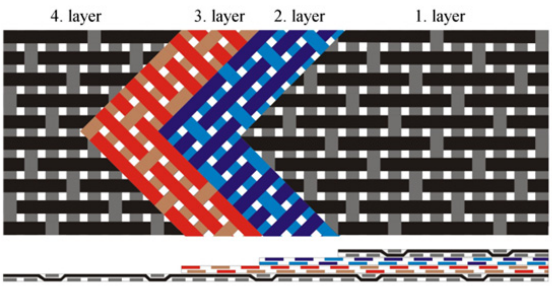

Fig. 1. Build-up of used 4-layer satin weave fabric with PPS matrix.

The minimum required line energy E_l necessary to reliably achieve a cut was investigated for each of the used setups at maximum laser Power P_L. The line energy was calculated using

$$E_l = \frac{P_L}{v_{eff}} \quad (1)$$

with the average laser power P_L and the effective velocity v_{eff}. The effective velocity in turn is calculated by the parameters scanning velocity v_s, number of repetitions n, in case of a multi-pass cutting strategy, and the number of parallel lines n_l with the equation

$$v_{eff} = \frac{v_s}{n \cdot n_l} \quad (2)$$

Regarding the ratio between laser focus diameter d_f and material thickness h it could be necessary to perform a cut using parallel lines. Based on earlier investigations, two parameters of the remote cutting process have been identified to influence the occurrence of the cutting edge and the deterioration of the material. These parameters are the scanning velocity v_s and for multi-pass cuts the time difference Δt_c in which the laser spot hits the same point at the CFRP surface twice; this time is called loop time within this paper. This loop time can be calculated by

$$\Delta t_c = \frac{l_c}{v_s} \quad (3)$$

with the cutting length l_c and the scanning velocity v_s.

The cutting length for the specimens used within this paper is l_c = 320 mm which is equal to the circumference of the tensile strength specimens. The cutting length for the specimens used for the micrographs was shorter, so that a time break was implemented into the scanner program in order to achieve an identical Δt_c. Hence, the measured HAZ can be related to the determined tensile strength.

For each of the 3 particular laser sources, the scanning velocity v_s and the number of repetitions n were varied during the investigations (Table 1).

For each used parameter, micrographs of three cuts were prepared and microscopic pictures were made using a reflected-light microscope with an integrated camera. Using these pictures it was possible to measure the area of the HAZ A_{HAZ} with the help of digital image processing. The average width of the HAZ b_{avg} was then calculated by

$$b_{avg} = \frac{A_{HAZ}}{h}. \quad (4)$$

Within this paper, three different HAZ are analysed. They are differentiated by the visual appearance within the micrographs. The first zone HAZ 1 depicts a clear deterioration or lack of matrix material and fibres. HAZ 2 defines the area with clear pore formation and matrix damages due to exceeding of the decomposition temperature. A damage of the fibres cannot be observed. HAZ 3 is recognizable as an area with small porosities within the thermoplastic matrix but intact carbon fibre fabric (Jaeschke et al., 2014).

In addition to the analysis of the HAZ, the tensile strength according to the norm DIN EN 2561 was determined. To achieve a statistical relevance, 5 specimens were produced and tested for each parameter. Differing from the norm, the size of the specimen was chosen with a length of l = 150 mm and a width of b = 10 mm to increase the influence of the laser-induced HAZ on the tensile strength of the CFRP. Additionally, 5 samples were milled as reference to the laser processed samples. The samples were tensioned with a constant velocity of $v_{tension}$ = 2 mm/min and based on the failure force F and the cross-section area the tensile strength R_m was calculated by

$$R_m = \frac{F}{(b \cdot h)} \quad (5)$$

3. Results

As described before, the minimum required line energy E_l to cut the CFRP material was investigated in advance of the experiments for each particular laser setup (Table 2). The average laser power was kept at maximum power for each laser during the investigations and the scanning velocity v_s was varied to achieve the required line energy E_l. The resulting effective cutting velocity v_{eff} was the maximum achievable based on equation 1, with a minimum required line energy E_l and a constant laser power P_L. Hence, this velocity is characteristic for each of the described setups and the CFRP material used. Of the three laser sources used, the YLS-6000 is the most efficient laser for the cutting of CFRP considering only the effective velocity v_{eff} as an indicator of efficiency of the process. There are additional factors which are important for the evaluation of the suitability of a process. The dependency of the average width of the HAZ on the scanning velocity v_s as a factor influencing the visual appearance of a cut was investigated. The following analysis will show that increasing scanning velocities v_s lead to smaller HAZ. In the next step, the influence of the scanning velocity on the resulting tensile strength was also evaluated. A general correlation between HAZ and tensile strength is recognizable, relating the influence of the scanning velocity v_s to the average width of the HAZ b_{avg} and the tensile strength R_m. In conclusion, an investigation of the influence of the loop time on the HAZ is performed.

Table 2. Base value for the evaluation of the cutting process.

Laser source	TruMicro 5050	TruMicro 7050	YLS-6000
Line energy [J/cm]	598.5	550	1000
Effective velocity [m/min]	0.05	0.818	2.4

First the results of the TruMicro 5050 were analysed concerning the influence of the scanning speed on the occurrence of the HAZ. It is shown that for scanning speeds $v_s \geq 8$ m/min the HAZ 1 and HAZ 2 cannot be measured anymore. An average width of the HAZ 3 with a value of $b_{avg} = 0.15$ mm was determined. This value can be further reduced by increasing the scanning speed and accordingly decreasing the pulse overlap p_o (Fig. 2). For the maximum tested scanning velocity of $v_s = 60$ m/min no HAZ can be measured (Fig. 2). Fig. 3.c depicts a micrograph of a cutting edge gained by the described parameters.

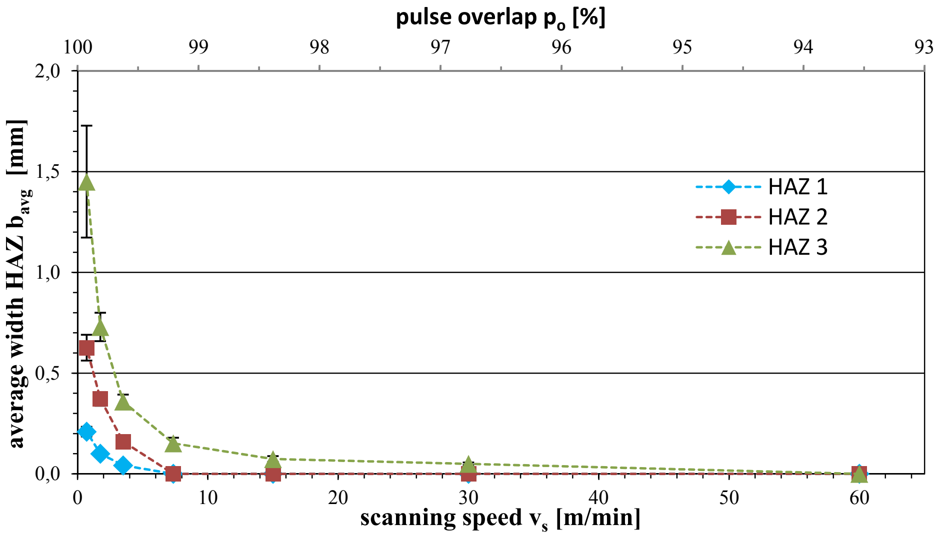

Fig. 2. Average width of HAZ depending on the scanning speed and pulse overlap using a TruMicro 5050 picosecond pulsed laser.

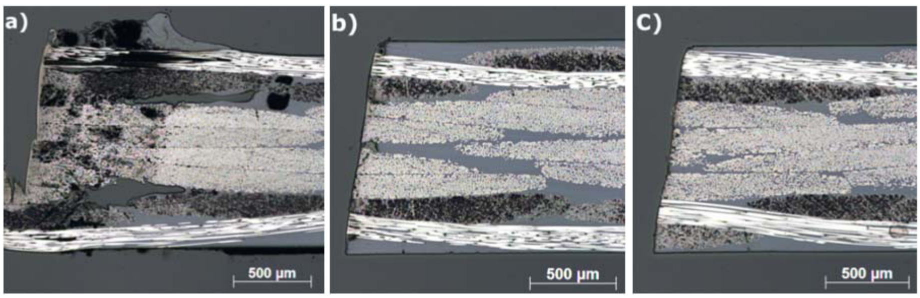

Fig. 3. Micrograph of cuts with the TruMicro 5050 at a scanning speed of a) $v_s = 0.7$ m/min b) $v_s = 15$ m/min and c) $v_s = 60$ m/min.

Observing the results achieved with the TruMicro 7050, a continuous decrease of the HAZ for increasing scanning speed v_s was seen (Fig. 4). In contrast to the previous results, at the maximum tested scanning speed of $v_s = 60$ m/min, a HAZ with an average width of $b_{avg} = 0.14$ mm for the HAZ 3 was measured (Fig. 4). Fig. 4 shows a clear decrease of the HAZ 3 with an absence of explicit deterioration of matrix and fibres (HAZ 1), for scanning velocities of $v_s \geq 14.7$ m/min. The visual appearance of the cutting edge for specific scanning velocities v_s is depicted in Fig. 5. The micrograph of the cut performed with a scanning velocity of $v_{eff} = 60$ m/min shows only small porosities along the cutting edge (Fig. 5.c).

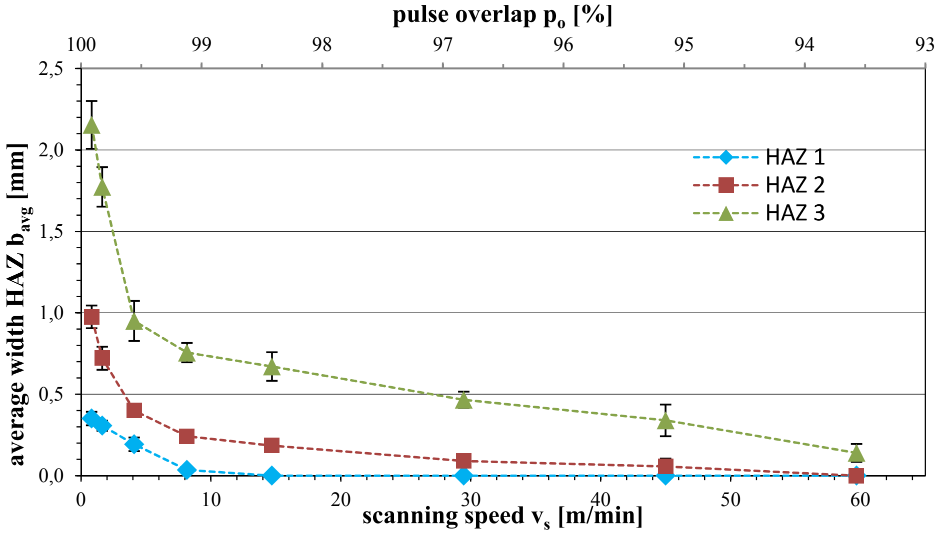

Fig. 4. Average width of HAZ depending on the scanning speed using a TruMicro 7050 nanosecond pulsed laser.

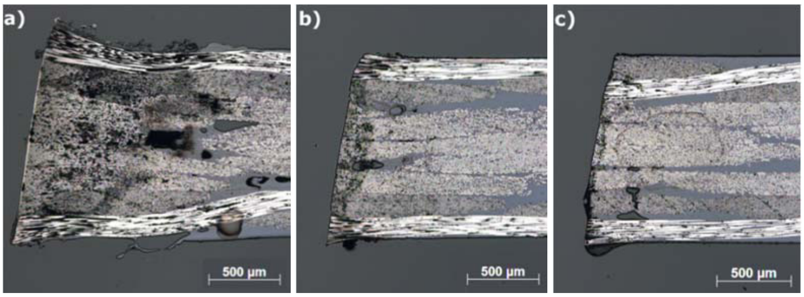

Fig. 5. Micrograph of cuts with the TruMicro 7050 at a scanning speed of a) $v_s = 0.8$ m/min b) $v_s = 14.7$ m/min and c) $v_s = 60$ m/min.

The development of the HAZ depending on the scanning speed using the cw laser YLS-6000 shows a clear difference from the trend which exists for the pulsed laser sources. For the pulsed laser sources a continuous decrease of the HAZ for increasing scanning speed is shown. Notwithstanding these results the average width of the HAZ 3 rises after decreasing to a minimum at $v_s = 9.6$ m/min again for increasing scanning speeds (Fig. 6). In comparison to that, the average width of HAZ 1 and HAZ 2 are nearly constant for scanning velocities $v_s \geq 9.6$ m/min. One explanation for the expansion of the HAZ 3 is the heat accumulation effect caused by the additional inserted heat with each repetition which does not contribute to the evaporation of the material. This accumulated heat reaches only temperatures effecting the material changes responsible for the HAZ 3, since the average width of the defined HAZ 1 and HAZ 2 stay at a constant level.

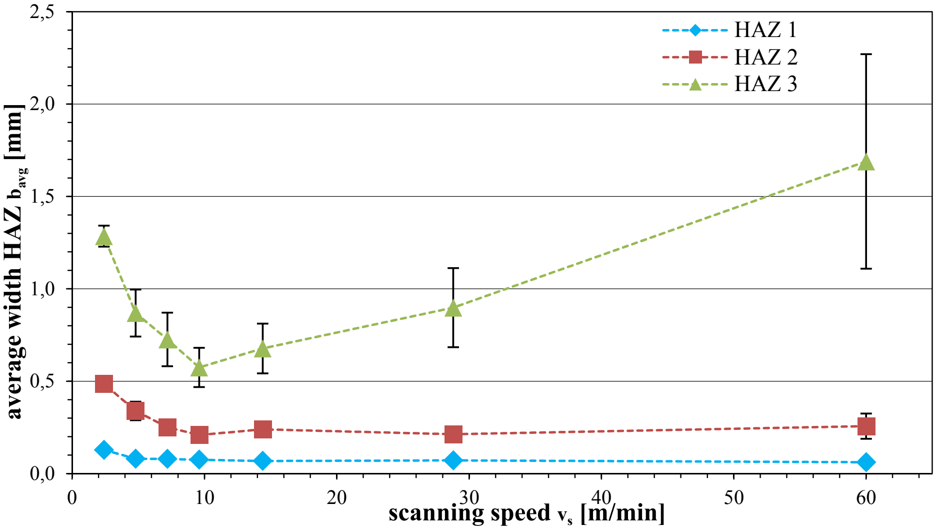

Fig. 6. Average width of HAZ depending on the scanning speed using a YLS-6000.

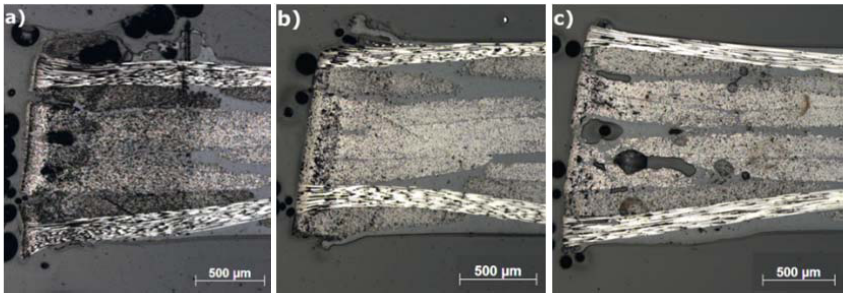

Fig. 7. Micrograph of cuts with the YLS-6000 at a scanning speed of a) v_s = 2.4 m/min b) v_s = 9.6 m/min and c) v_s = 60 m/min.

After analysing the development of the HAZ analysis, the tensile strength test was then evaluated. The milled reference samples show an average tensile strength of R_m = 543.9 N/mm² with a standard deviation of S = 13.3 N/mm². The specimens cut with the TruMicro 5050 show the highest tensile strength compared to the other laser sources used. The specimens prepared with the TruMicro 5050 have a maximum average tensile strength of R_m = 539.49 N/mm² (Fig. 8). For the results of the TruMicro 7050 and the YLS-6000, a correlation between the extent of the HAZ 3 and the maximum tensile strength is recognizable. The steeply sloping average width of the HAZ for low scanning velocities corresponds with the steeply rising tensile strength for these velocities. For the YLS-6000 it is shown that the trend for the tensile strength is inverse to the trend of the HAZ 3 (compare Fig. 6 and Fig. 8). A similar correlation between the extend of the HAZ and the static strength has been investigated by Herzog et al. (2008).

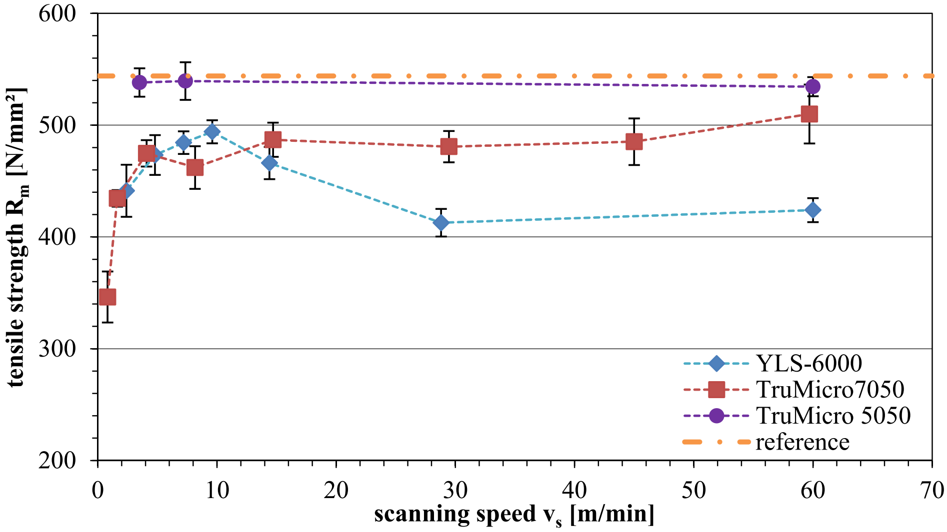

Fig. 8. Tensile strength depending on scanning speed for different laser sources in comparison to milled reference samples.

In previous work it was recognized that next to the variation of the scanning speed v_c, the loop time Δt_c and accordingly the cutting length l_c also have impact on the HAZ. In order to evaluate this impact, further cuts were produced with the TruMicro 7050 varying the loop time Δt_c for a constant scanning velocity of $v_s = 8.16$ m/min and constant other parameters as defined in Table 1. The TruMicro 7050 was chosen due to its promising results for previous analysis of the tensile strength and the HAZ. Fig. 9 shows that an increase of the loop time to values up to $\Delta t_c = 3.68$ s, which corresponds to a cutting length of $l_c = 500$ mm, results in a decrease of the HAZ 3, whereas the HAZ 1 and HAZ 2 are nearly constant for loop times $\Delta t_c \geq 0.92$ s.

Using an optimized parameter set with $v_s = 60$ m/min and an increased loop time of $\Delta t_c = 0.96$ s, it was possible to produce a cut optimized concerning minimum HAZ (Fig. 10). Specimens produced with this parameter set achieved a tensile strength of $R_m = 532.8 \pm 15.4$ N/mm², which is equivalent to 98% of the values achieved by the milled reference samples.

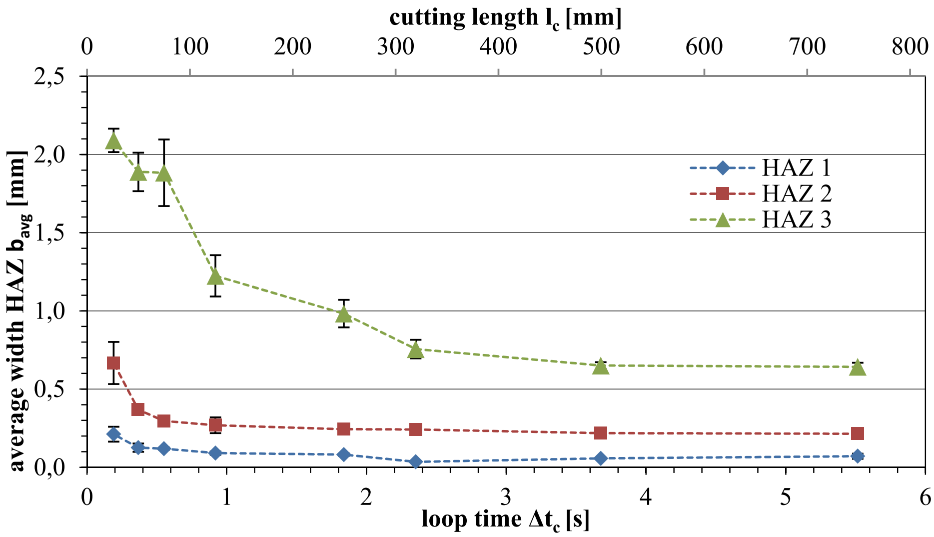

Fig. 9. Average HAZ depending on the cutting length for a constant scanning velocity of $v_s = 8.16$ m/min with the TruMicro 7050.

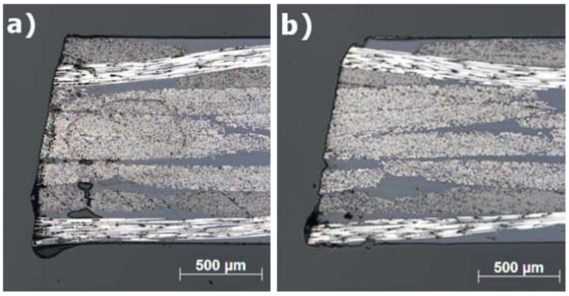

Fig. 10. Minimization of HAZ by increasing time between loops from a) $\Delta t_c = 0.32$ s to b) $\Delta t_c = 0.96$ s at a scanning velocity of $v_s = 60$ m/min.

4. Conclusion

The investigations have shown that the cw laser sources provide higher effective cutting velocities for CFRP than the pulsed laser sources. For an economic examination a preferable high throughput has to be considered as well as the quality of the cutting edge. Considering further quality characteristics such as the maximum tensile strength and the minimum HAZ, the achieved results are evaluated.

Summarizing the results of the experiments, it can be stated that the cutting tests deliver results with a wide spread of effective cutting velocities, tensile strength, and occurrence of HAZ (Table 3). Comparing these characteristics none of the investigated setups deliver a best practise for all of the characteristics at same time. There are specific optima for each characteristic.

Table 3. Summary of achievable process and quality characteristics for each used laser source.

Laser source	TruMicro 5050 standard parameter set	TruMicro 7050 standard parameter set	TruMicro 7050 optimised parameter set*	YLS-6000 standard parameter set
Effective velocity [m/min]	0.05	0.82	0.82	2.4
Max. tensile strength [MPa]	539.49	509.95	532.80	494.13
Min. HAZ 3 [mm]	0.0	0.14	-	0.57

*standard parameter set with $v_s = 60$ m/min and an increased loop time of $\Delta t_c = 0.96$ s (as described before)

Considering only the maximum tensile strength and the absence of an HAZ, the present experimental setup with the TruMicro 5050 picosecond laser and the chosen strategy would be the best choice for deterioration-free laser cutting of CFRP (Table 3). Drawbacks are the comparably slow effective cutting velocity of $v_{eff} = 0.05$m/min, which is 16 times slower than the TruMicro 7050. Furthermore, the need to cut with seven parallel lines to achieve a complete cut for the used material thickness is another drawback. Regarding the cutting speed in turn, the multi-repetition cuts with the YLS-6000 cw laser deliver the best results for an effective laser cutting process reaching effective velocities of $v_{eff} = 2.4$ m/min for the chosen setup (Table 3). This effective velocity v_{eff} is just 3 times faster than the velocity of the TruMicro 7050. At the same time, the results gained with the YLS-6000 have the biggest HAZ and the lowest tensile strength. Using the TruMicro 7050 nanosecond laser, values for the three chosen characteristic factors were achieved which are between the particular values of the picosecond and the cw process (Table 3). With an effective cutting speed of $v_{eff} = 0.8$ m/min, the TruMicro 7050 is an alternative to the cw cutting. This is especially the case taking into account the narrower HAZ and higher tensile strength achieved with the nanosecond laser in comparison to the cw laser. Furthermore, the values for the tensile strength of the TruMicro 7050 have only a small difference to the results of the TruMicro 5050.

Taking into account the development of new laser sources, such as the consideration of average laser power or beam quality nanosecond lasers with high average power could be a good trade-off for specific cutting tasks in comparison to cw or picosecond pulsed laser sources.

Acknowledgements

The authors would like to thank the Federal Ministry of Education and Research for the support within the project “3D high power laser processing enhancing quality and quantity for process reliable, automated machining of lightweight CFRP structures” (HolQueSt 3D) (FKZ: 13N12763).

Furthermore the authors would like to thank the TRUMPF Laser GmbH for the possibility to perform the investigations with the TruMicro 5050 and TruMicro 7050 at the TRUMPF application laboratory.

References

Bluemel, S., Jaeschke, P., Wippo, V., Bastick, S., Stute, U., Kracht, D., Haferkamp, H., 2012. Laser machining of CFRP using a high power laser - Investigation on the heat affected zone. Proceedings of the 15th European Conference on Composite Materials. ECCM 15. Venice. 24-28 June.

Finger, J., Weinand, M., Wortmann, D., 2013. Investigation on processing of carbon fiber reinforced plastics using ultrashort pulsed laser radiation with high average power. Proceedings of ICALEO 2013. 32th International Congress on Applications of Lasers & Electro-Optics. Miami, USA. 06.10. - 10.10.

Freitag, C., Kononenko, T., Onuseit, V., Weber, R., Graf, T., 2013. Experimental investigation of the heat accumulation effect when laser processing CFRP with a picosecond laser system. Proceedings of International Symposium on Laser Processing for CFRP and Composite Materials. International Symposium on Laser Processing for CFRP and Composite Materials. Yokohama.

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 & Manufacture, 1464–1473.

Jaeschke, P., Kern, M., Stute, U., Kracht, D., Haferkamp, H., 2014. Laser processing of continuous carbon fibre reinforced polyphenylene sulphide organic sheets--Correlation of process parameters and reduction in static tensile strength properties. Journal of Thermoplastic Composite Materials 27, 324–337.

Klotzbach, A., Hauser, M., Beyer, E., 2011. Laser Cutting of Carbon Fiber Reinforced Polymers using Highly Brilliant Laser Beam Sources. Physics Procedia 12, Part A, 572–577.

Leone, C., Papa, I., Tagliaferri, F., Lopresto, V., 2013. Investigation of CFRP laser milling using a 30W Q-switched Yb:YAG fiber laser: Effect of process parameters on removal mechanisms and HAZ formation. Composites Part A: Applied Science and Manufacturing 55, 129–142.

Negarestani, R., Li, L., Sezer, H. K., Whitehead, D., Methven, J., 2010. Nano-second pulsed DPSS Nd:YAG laser cutting of CFRP composites with mixed reactive and inert gases. International Journal of Advanced Manufacturing Technology 49, 553–566.