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Remote Laser Cutting Of Composites With A Fibre Guided Thin-Disk Nanosecond High Power Laser

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Abstract

Carbon fibre reinforced plastics (CFRP) are of high interest for lightweight construction within many industrial sectors. The automotive industry shows already an increasing demand for CFRP parts, but the implementation of CFRP parts is limited by the lack of automatable, reliable and cost efficient processes. In the field of laser cutting of CFRP materials, there are also different scientific approaches such as the use of nanosecond lasers with high average power. At this point, the German research project HolQueSt 3D starts dealing with 3-dimensional high power laser processing of lightweight CFRP structures in enhancing quality and quantity.

Within this paper, the authors will describe the first results achieved with a newly developed fibre-guided high power nanosecond laser. The laser emits at a wavelength of λ = 1030 nm with a pulse duration of t_p = 30 ns. The laser has an average power of P_{avg} = 1.5 kW with a maximum pulse energy of $E_{p,max}$ = 80 mJ. The laser beam was deflected by a 3D programmable focusing optic with a focal length of l_f = 255 mm. CFRP based on an epoxy resin with two different reinforcements was used for the investigations. The gained results were analysed concerning the achieved heat affected zone and the optical quality of the cutting edges. The average HAZ width b could be minimized to a value below b <40 µm for both materials. Furthermore, the maximum effective cutting velocity for selected laser parameters was determined. The maximum effective cutting speed achieved within this investigation is v_{eff} = 1.8 m/min. The results of the investigation revealed the potential of the fibre-guided nanosecond laser for industrial applications. This is in particular the case for 3D applications due to the possibility of robot based remote processes.

Keywords: cutting, composites, nanosecond laser

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1. Introduction

Endless carbon fibre reinforced composites (CFRP) have already shown their great lightweight construction potential in many applications. Hence, CFRP is of high interest for all branches of industry where, either large masses have to be moved, or weight has to be saved. Besides the field of mobility, with the huge aircraft, automotive and marine sectors and the increasing field of energy, e.g. wind turbines, pipelines and off-shore applications, CFRP is also playing an important role in the fields of sports and leisure, lightweight equipment and medical engineering. The global demand of carbon fibres and CFRP increased continuously over the last few years and it is expected to further increase within the next years (Witten et al., 2014). A current barrier for a further comprehensive dissemination of CFRP structures is the lack of additional specialized economic, quick and reliable component manufacture processes. The possibility to cut CFRP within fully-automated process chains with a constant quality and the required delivery rate at the same time is necessary to establish CFRP in industries with high standards or series production with high throughput such as aerospace and automotive. Today, cutting and trimming operations used for CFRP parts are mainly based on mechanical cutting techniques, e. g. sawing, milling, or grinding and abrasive water jet cutting, revealing respective advantages and disadvantages. Despite the fact that lasers, as thermally acting tools, may influence the fibre-matrix-structure, laser cutting using appropriate laser sources offers many advantages, such as no wear, no moisture uptake and highest feed rates. However, due to the different heat conduction properties of the matrix and the reinforcements, laser cutting could partially modify the structural properties of CFRP (Jaeschke et al., 2014).

Therefore, it is currently one main focus within different research approaches to develop process strategies minimizing the thermal damage and modification of the material properties during laser processing.

2. State of the art

Processing equipment known from the cutting of conventional materials as metals was used for former CFRP laser cutting experiments (Jaeschke et al., 2014). The increasing demand for CFRP materials and corresponding processing techniques leads to an increased effort within the laser community to find suitable processing strategies and setups for low damage laser cutting. Within the last years, different strategies were identified to reach the aim of damage free laser cutting of CFRP. In a first instance, it has been identified that laser cutting with multiple repetitions by help of a scanning head shows significant advantages comparing to contour laser cutting with a cutting head (Leone et al., 2014; Bluemel et al., 2014). The advantage of multi-repetition cutting can be explained by shorter laser-material-interaction times and the possibility of the material to cool down between two successive repetitions.

In terms of the used laser source, two different ongoing trends can be identified. On the one hand, pulsed laser sources emitting short or ultra-short pulses, and on the other hand, laser sources with high beam quality emitting continuous wave (cw) are subjects of research in order to develop laser cutting strategies (Bluemel et al., 2015; Klotzbach et al., 2011; Schneider et al., 2013).

Within this publication, the focus lies on the laser cutting of CFRP with pulsed laser sources. Nowadays, different process strategies are investigated. These strategies differ mainly in the used laser wavelength and pulse duration. One approach is the use of UV-lasers in order to reduce possible thermal damage (Wolynski et al., 2011). Although the realized HAZ in comparative studies were smaller for UV-lasers than for IR-lasers the achieved cutting speeds for the UV-laser were smaller by order of magnitude (Sato et al., 2013).

Another approach is the use of laser sources emitting ultra-short pulses in the picosecond (ps) regime. Investigations have shown that it is possible to perform cuts without detectable HAZ by use of ps-lasers.

Comparable to the laser cutting with UV-lasers the achievable cutting speeds were only in the range of a few centimetres per minute (Bluemel et al., 2014). Due to the development of new laser sources with average output powers of several 100 W up to a 1.4 kW on a laboratory scale, it was possible to increase the cutting speed. Finger et al. (2013) performed experiments with a ps-laser with average power of $P_{L,avg}$ = 430 W and a pulse duration between t_p = 1.5 ps and t_p = 7.5 ps. They were able to reach cutting speeds of v = 0.3 m/min for an epoxy based 2 mm material. A further increase of the cutting speed up to a value of v = 0.9m/min with a ps-laser was performed by Freitag et al. (2014) for a comparable material configuration using a new developed ps-laser at an average power of $P_{L,avg}$ = 1.1 kW.

Nanosecond (ns) pulsed laser sources showed also high potential to enable a flexible and automatable cutting process with low deterioration (Leone et al., 2014). For an effective industrial application the reachable cuttings speeds were often a limiting factor. Bluemel et al. (2014) came in a comparative study with a high-power ns-laser with an average power of $P_{L,avg}$ = 750 W to the conclusion that ns-laser can be a good trade-off between ultra-short pulsed lasers and cw-laser concerning the minimized HAZ and reachable cutting speed, respectively (Table 1). A further advantage of ns-laser is the availability of fibre guided laser sources enabling flexible three dimensional cutting processes.

Table 1. Exemplary effective velocities and HAZ width for chosen experiments from

Laser source	**TruMicro 7050 optimised parameter set (Bluemel et al., 2014)**	**YLS-6000 standard parameter set (Bluemel et al., 2014)**	**thin-disk multipass amplifier (Freitag et al., 2014)**
Laser Power [W]	750	4000	1100
Pulse duration	30 ns	cw	8 ps
Effective velocity [m/min]	0.82	2.4	0.9
Min. HAZ [mm]	0.0	0.57	0.0
Material	CFRP with PPS matrix	CFRP with PPS matrix	CFRP with epoxy matrix
Thickness [mm]	1.24	1.24	2

3. Experimental setup

The laser source used is a new fibre guided thin-disk nanosecond high power laser developed by TRUMPF Laser GmbH.

To increase the average output power of the thin-disk cavity-dumped laser TruMicro 7050, various new approaches have been realized. A limiting factor for scaling the output power is the circulating power inside the resonator and the limits to optical damage of optical components therein. This has been overcome by realizing more passes of the resonator through the disk, resulting in a higher roundtrip gain and a higher output coupling of the resonator (Stolzenburg et al., 2014). Along with higher pump power and a more efficient pump optic geometry, allowing an increase of the optical-to-optical efficiency, an increase of the average laser power from PL = 750 W to PL = 1500 W has been achieved. With repetition rates reaching from f = 5 kHz to f = 50 kHz, a constant pulse duration of t_p = 30 ns is independent of the repetition rate and the output laser power. The maximum pulse energy of E_p = 80 mJ is available from f = 5 kHz to f = 18.8 kHz and can be guided by a fibre with a diameter of d = 600 µm, without the appearance of nonlinear effects like Stimulated Brillouin scattering (SBS). SBS is showed as a strong reflection of light in the medium, which arises from the interaction of light with acoustic waves. The laser parameters are summarized in Table 2.

A 3D programmable focusing optic (PFO-3D) is used as scanning optic for all experiments. The PFO-3D is equipped with a collimating lens with a focal length of lf = 138 mm and an objective lens with lf = 255 mm.

Table 2. Parameters of the prototype thin-disk nanosecond high power laser

Laser parameter	Value
Maximum average laser power $P_{L,avg}$ [W]	1500
Maximum pulse energy $E_{p,max}$ [mJ]	80
Repetition rate f [kHz]	5 – 50
Pulse duration t_p [ns]	30
Fibre diameter d [µm]	600

The investigations were performed with two types of epoxy based CFRP consisting of twill weave fabric (CF-Fabric) or biaxial non-crimp fabric (CF-Biaxial), respectively (Table 3). The cuts were made perpendicular to the rovings of the fabric and in an angle of $\alpha = \pm 45$ ° to the rovings of the non-crimp fabric.

Table 3. Properties of the used epoxy based CFRP

Material parameters	CF-Fabric	CF-Biaxial
Reinforcement	Carbon fibre twill weave fabric	Carbon fibre biaxial non-crimp fabric (± 45 °)
Number of layers	4	4
Matrix	Epoxy resin (LY556 / HY917)	Epoxy resin (LY556 / HY917)
Thickness d [mm]	1.2	1.2
Fibre volume content [%]	60	60

Three different experimental series were conducted with each of the described materials. For the first series, the maximum allowed scanning velocity to achieve a cut with only one repetition was evaluated. Based on that line energy the scanning speed v_s was increased up to a maximum value of $v_s = 3000$ mm/s and the number of repetitions was increased with the same factor to keep the line energy E_L constant. In experimental series 2 the cutting length l_c was varied for three different scanning speeds v_s in order to evaluate the influence of the heat accumulation due to time interval between two passes on the HAZ width b. Thirdly, the repetition rate and therefore the fluence F was varied in a range of f = 18.5 kHz to f = 50 kHz at constant average laser power $P_L = 1500$ W.

Table 4. Summary of exemplary process parameters used for the investigations

Process parameter	Series 1	Series 2	Series 3
Maximum average laser power $P_{L,avg}$ [W]	1500	1500	1500
Repetition rate f [kHz]	18.8	18.8	18.8 - 50
Scanning speed v_s [mm/s]	20 - 3000	1000/2000/3000	1000
cutting length l_c [mm]	100	50 - 1000	100
Fluence F (at f=18.8 kHz) [J/cm²]	8.4	8.4	3.1 – 8.4
Focal diameter d_f (calculated) [mm]	1.1	1.1	1.1
Power density I [W/mm²]	1550	1550	1550

Cuts were generated for each parameter 4 times to evaluate the standard deviation of the HAZ width. Cross-sections of the cuts were prepared and afterwards, microscopic pictures were made with a microscope equipped with an integrated camera. By means of these pictures, the HAZ area A_{HAZ} was measured using a software program for digital image processing. The average HAZ width b can be calculated by dividing the HAZ area by the material thickness d (equation 1).

$$b = \frac{A_{HAZ}}{d}. \quad (1)$$

4. Results and discussion

An increase of the scanning speed v_s for constant repetition rate f and line energy E_L results in a continuous decrease of the HAZ width b (Fig. 1). Both materials show a comparable trend with a high slope for scanning speeds below v_s = 250 mm/s and slower reduction of the average HAZ width for increasing scanning speeds. However, the values of the average HAZ width b for the CF-Biaxial are constantly higher than the values for the CF-Fabric. This can be attributed to the different fibre reinforcement and orientation of the layers and, therefore, to the different heat conduction conditions during the cutting process, since the matrix consists of the same resin in both cases. It is shown that, for a cutting length of l_c = 100 mm, a heat accumulation by successive repetitions is not given for high scanning speeds and a repetition rate of f = 18.8 kHz. The average HAZ width b would increase again, if a threshold temperature would be reached due to heat accumulation.

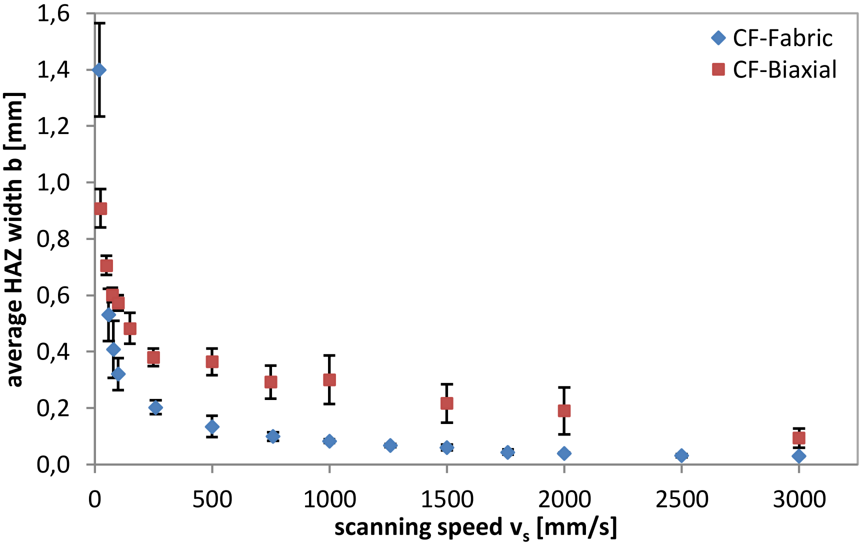

Fig. 1. Average HAZ width depending on the scanning speed for constant line energy.

In the second experimental series, the cutting length was increased for the constant parameter set described in Table 4. For both materials, an increase of the cutting length reduces the HAZ width; this effect is most distinctive for cutting length smaller than l_c = 250 mm. Furthermore, the results agree with the trend in Fig. 1, where higher scanning speeds v_s lead to smaller HAZ. Fig. 2 depicts the results of the second experimental series for the experiments using CF-Fabric, exemplary. The CF-Biaxial results, which are not shown here, have a trend and curve progression similar to CF-Fabric´s.

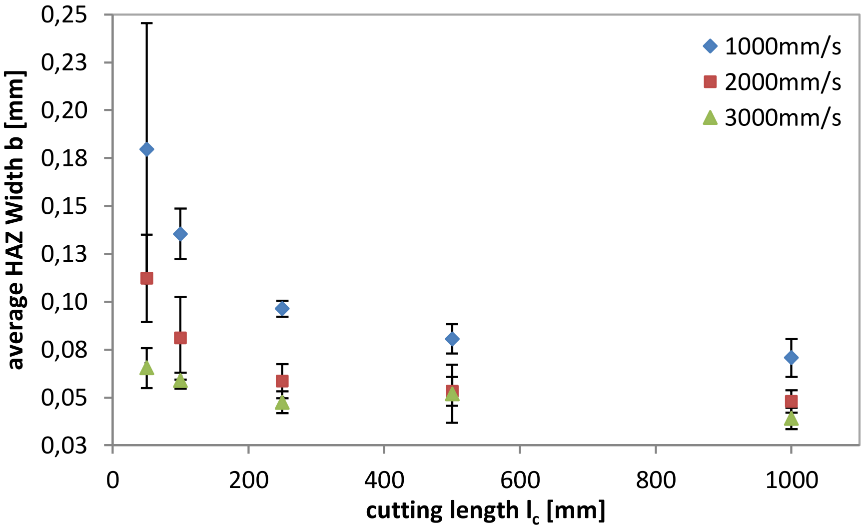

Fig. 2. Average HAZ width CF-Fabric depending on the cutting length for three different scanning speeds.

For experimental series 3, the repetition rate f was varied between f = 18.8 kHz and f = 50 kHz at constant average laser power P_L = 1500 W and scanning velocity v_s = 1000 mm/s. The necessary number of repetitions n was determined for each parameter set to investigate influences on the necessary line energy. The number of repetitions reduces in steps of n = 2 from n = 37 for repetition rates up to f = 20 kHz to a minimum of n = 33 for repetition rates f ≤45 kHz. Therefore, the necessary line energy varies slightly between values of E_L = 49.5 J/mm for high repetition rates and E_L = 55.5 J/mm for low repetition rates. The HAZ width b increases continuously for increasing repetition rates f, as expected (Fig. 3). Increasing the repetition rate f for constant average laser power P_L and scanning speed v_s results in a lower pulse energy E_P and higher pulse overlap, respectively (Fig. 4).

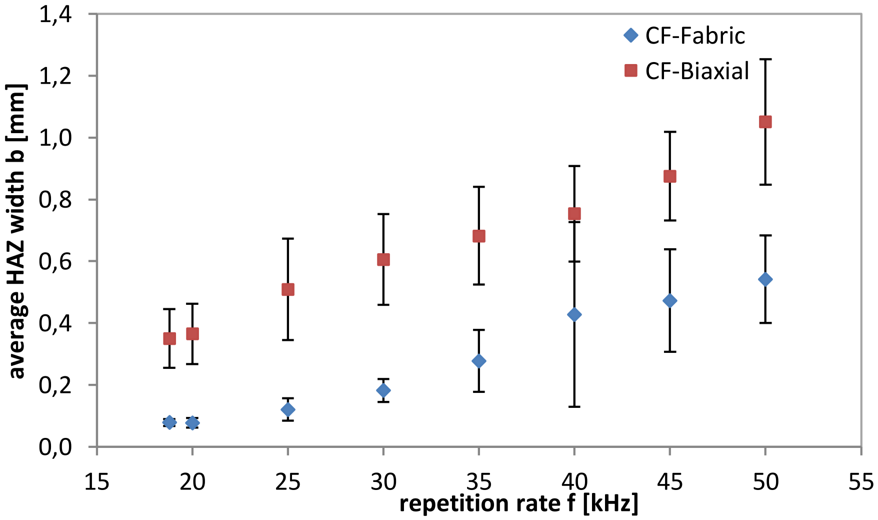

Fig. 3. Average HAZ width b depending on the repetition rate f for constant average power P_L = 1.5 kW and scanning speed v_s = 1 m/s

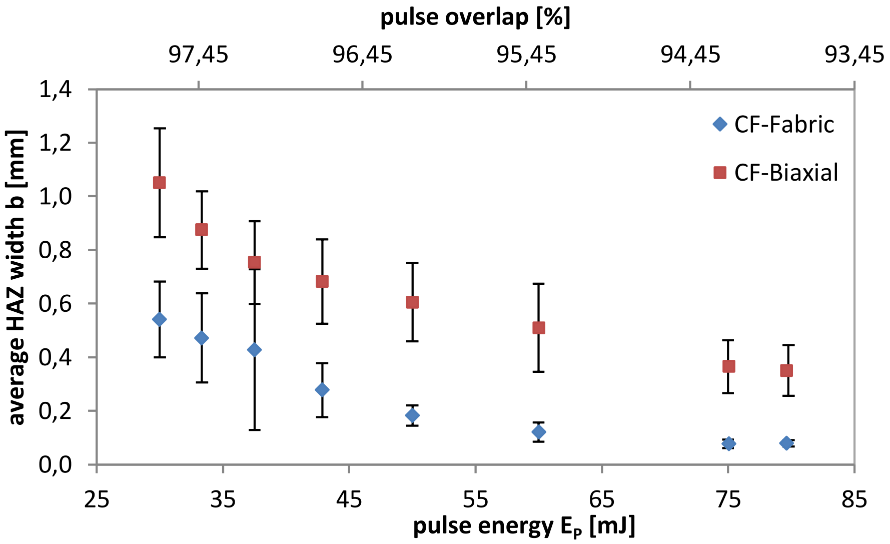

Fig. 4. Average HAZ width b depending on the pulse energy E_P and pulse overlap for constant average power P_L = 1.5 kW and scanning speed v_s = 1 m/s

The achievable effective cutting velocity v_{eff} for the described experiments is calculated by equation 2 in order to evaluate the process performance and to enable a comparison to other laser sources.

$$v_{eff} = \frac{v_s}{n} \tag{2}$$

The effective velocity v_{eff} for the d = 1.2 mm thick material varies between v_{eff} = 1.5 m/min and v_{eff} = 1.8 m/min depending on the material and parameters.

Fig. 5 depicts a micrograph of a cutting edge for the CF-Fabric and CF-Biaxial material, respectively. Both cuts were performed with identical scanning speed v_s = 1000 mm/s, laser power P_L = 1500 W and repetition rate f = 18.8 kHz. The HAZ width b is minimized to a value of b = 0.028 mm for the CF-Fabric and b = 0.031 mm for the CF-Biaxial.

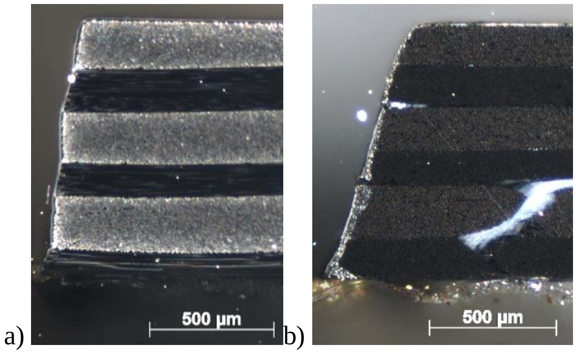

Fig. 5. Exemplary micrographs of cutting edges performed with a scanning speed of v_s = 3 m/s for CF-Fabric (a) and CF-Biaxial (b)

5. Conclusion

The present investigation has shown that the new developed fibre guided thin-disk nanosecond high power laser brings along the advantage of a fast laser cutting process at good cutting kerf quality and small HAZ. Furthermore, it can be stated that the general influence of the parameters is comparable for the different investigated material setups. However, the level of the HAZ width depends on the kind and orientation of the reinforcement. The cutting direction for the CF-Fabric was parallel to the yarn direction and, in that case, the heat is conducted in cutting direction as well as perpendicular to it. The cutting direction for the CF-Biaxial, on the other hand, was in an angle of $\alpha = \pm 45°$ and therefore the complete heat energy is conducted away from the cutting edge into the material. This is noticeable in the higher values of the HAZ width b for CF-Biaxial.

The present results are compared quantitatively to the process characteristics summarized in Table 1. This comparison enables a general estimation of the reachable quality and efficiency from a practical/industrial point of view. In comparison to the values of the TruMicro 7050 the effective cutting speed is nearly doubled with a value of up to $v_{eff} = 1.8$ m/min. Taking into account the different material thickness, the achieved cutting speed is competitive to the results with the ps-laser system. At the same time, the achieved HAZ width with values clearly below $b = 0.2$ mm and a minimum of $b = 0.03$ mm fit to industrial quality standards, for example of the automotive industry.

The presented data shows promising results for industrial applications which can be achieved by the existing setup. As the current laser is fibre guided, the next step is the transfer towards the processing of three dimensional parts using a 6-axis robot, which is currently under development. Hence, it is necessary to find solutions for occurring challenges as the combination of simultaneous movement of robot and PFO mirrors. The basic investigations within this paper and ongoing research enable the identification of adapted parameter windows for the continuous processing within the required quality standards.

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