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Laser cutting of CFRP with a fibre guided high power nanosecond laser source - Influence of the optical fibre diameter on quality and efficiency

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Abstract

For the development of a robot based laser cutting process of automotive 3D parts consisting of carbon fibre reinforced plastics (CFRP), investigations with a newly developed fibre guided nanosecond pulsed laser with an average power of $P_L = 1.5$ kW were conducted. In order to investigate the best combination of quality and process time 2 different optical fibres were used, with diameters of $d_f = 400$ µm and $d_f = 600$ µm. The main differences between the two setups are the resulting focal diameter and the maximum available pulse energy up to $E_P = 80$ mJ. In a first instance, a comparable investigation was performed with both fibres for a constant pulse overlap. For each fibre the minimum required line energy was investigated and cuts were performed, distributed over the complete parameter range of the laser source. The influences of the fibre diameter on the quality and efficiency of the cutting process are summarized and discussed.

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Keywords: laser cutting; CFRP; nanosecond; fibre guided

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1. Introduction

With the increasing demand for carbon fibre reinforced plastics (CFRP) as material for lightweight construction especially in the mobility industry, the need of efficient cutting technologies grows. Next to the conventional techniques such as sawing and milling, water jet cutting and laser cutting were also exploratory focuses in recent years. In the field of laser cutting of CFRP, a continuous research progress has led to an increasing process

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understanding and the development of new process strategies. However, laser sources are also the subject of continuous improvement and enhancements enabling, for example, higher average laser powers or high pulse energies.

First, many CFRP cutting investigations were performed with cutting heads and a contour cutting strategy. Mathew et al. (1999) stated that for contour cutting with a ms-pulsed laser that the heat affected zone (HAZ) is proportional to the pulse energy and that higher repetition rates lead to higher HAZ.

Other investigations using laser systems emitting pulses with durations in the range of microseconds came to a similar assumption. In terms of small HAZ and high effective speeds it can be summarized that high speeds, high pulse energies and short pulse durations produce the best results (Pagano et al., 2010). Realizing a multi-pass strategy with a cutting head and an axis system, investigations of (Negarestani et al., 2010) came to the conclusion that low pulse energies in combination with average repetition rates and higher scanning speeds lead to cuts with optimized quality.

The latest research is focused on the usage of galvanometer scanners for CFRP cutting. This enables multi-pass cutting with multiple repetitions at high scanning speeds to achieve complete cuts. With a further reduction of the pulse duration to nanosecond pulses, the HAZ width could be more reduced. Basic findings of further investigations still apply with new specifics due to the changing process strategies and available laser sources. Freitag et al. (2012) determined the HAZ on the surface of the material after generating grooves with different pulse energies at constant repetition rate and velocity, revealing that the HAZ width increases with increasing pulse energy and the removed volume per pulse reduces simultaneously. Leone et al. (2014) focused on the influence of scanning velocity and pulse power, where the pulse power is directly linked to the repetition rate. Summarized, he came to the conclusion that increasing scanning speeds and pulse power reduce the HAZ width. Due to the reduced repetition rate at increased pulse power this can be traced back to the reduced pulse overlap.

Laser sources emitting pulses in the range of picoseconds and femtoseconds were used for cutting investigations due to the expected high quality of the cutting edge. Finger et al. (2013) came to the conclusion that increasing the fluence at constant repetition rates increases the resulting HAZ width significantly, while increasing the repetition rate at constant fluence affects the occurring HAZ width to a lesser degree.

For the processing of complex shaped three-dimensional parts, it is necessary to combine the laser source with flexible handling systems such as axis systems or robots. It is possible to use mirror guided laser systems in combination with an axis system in order to enlarge the working field and to enable 3D processing. Full geometrical flexibility can be achieved by the combination of robot and laser scanner. The simplest way to realize this setup is the usage of a fibre guided laser source, as for mirror guided laser sources only a few special solutions concerning the beam guidance along the robot axis exist. For that reason, the influence of optical fibre diameter on the cutting process and the results is investigated.

2. Experimental setup

The experimental setup consists of a nanosecond pulsed fibre guided thin-disk laser source and as galvo-scanner a programmable focusing optic with integrated focus-shift (PFO-3D). The laser source emits pulses with a duration of $t_P = 30$ ns at a wavelength of $\lambda = 1030$ nm for repetition rates between $f = 5$ kHz and $f = 50$ kHz. The laser source provides a maximum average laser power of $P_{L,avg} = 1.5$ kW and a maximum available pulse energy of $E_P = 80$ mJ. An optical fibre diameter of $d_f = 600$ µm (600 µm-fibre) is required in order to have the pulse energy of $E_P = 80$ mJ available. If the laser source is equipped with an optical fibre with a diameter of $d_f = 400$ µm (400 µm-fibre), the maximum available pulse energy reduces to $E_P = 35$ mJ. The differences in the available maximum laser power and pulse energy depending on the repetition rate are summarized in Fig. 1.

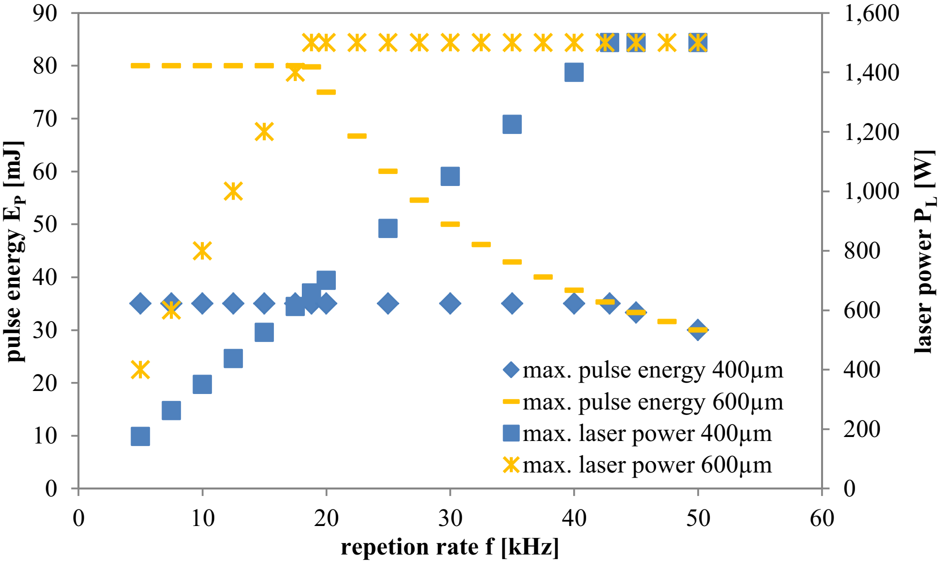

Fig. 1. Maximum laser power and maximum pulse energy depending on repetition rate and optical fibre diameter.

The PFO-3D is equipped with an f-theta lense with a focal length of $l_f = 255$ mm, resulting in a focal diameter of $d_{focal} = 1.2$ mm for the 600 µm-fibre and of $d_{focal} = 0.8$ mm for the 400 µm-fibre. In both cases the resulting beam profile is a round top-head profile with a homogenous energy distribution.

An epoxy based carbon fibre reinforced plastic (CFRP) with 4 layers of biaxial non crimp fabric, resulting in a thickness of $d = 1.2$ mm, was used for the investigations. All cuts were made at an angle of $\alpha = \pm 45°$ in relation to the fibres. Doing this, the excess heat will be conducted away from the cutting kerf into the material and dependencies of process parameters on the HAZ are more distinctive.

The main part of the investigations deals with the different optical fibres used and the achievable HAZ width for different pulse energies and repetition rates. Furthermore, the achievable fluence and the effective cutting speed were analysed. The pulse overlap was kept at a constant value of 95.6 % by adjusting the scanning speed v_s if not otherwise specified. In addition, the minimum required line energy E_L, necessary for a complete cut, was determined and kept constant for the investigations with 600 µm-fibre and 400 µm-fibre, respectively. This is realized by the adaption of the number of repetitions. For the present investigation a minimum average laser power of $P_L = 100$ W was chosen. A summary of the used parameters is shown in Table 1.

Each investigated parameter was performed 4 times due to statistical reasons and the cuts were analysed in terms of the expansion of the HAZ. The analysis was performed in the style of Bluemel et al. (2015) and Staehr et al. (2015).

Table 1. Summary of parameters.

	400 µm-fibre	**600 µm-fibre**
repetition rate f [kHz]	5 - 50	5 - 50
average laser power P_L [W]	100 - 1500	100 - 1500
pulse energy E_P [mJ]	10 - 35	20 - 80
scanning velocity v_S [mm/s]	176 - 1760	256 - 2560
line energy E_L [J/mm]	37	52.83
pulse overlap [%]	95.6	95.6

3. Results

The analysis of the results is done in two steps. First, the results of the 400 µm-fibre and the 600 µm-fibre are summarized concerning the parameter influence on the average HAZ width. Afterwards, the efficiency of the investigated parameter sets and optical setup is described. The dotted lines within the diagrams are polynomial curves which are used to guide the eye and to enable an easier understanding of the trends of the data points. Furthermore, the error bars shown within the diagrams bases on the calculated standard deviation.

The minimum pulse energy investigated for the 600 µm-fibre is $E_P = 20$ mJ, which is the resulting energy with $P_{L,avg} = 100$ W and f = 5 kHz. Trials with pulse energies lower than $E_P = 20$ mJ but higher repetition rates and average laser power enable no complete cut with the investigated line energy. In a first instance the influence of the pulse energy on the extent of the HAZ for different repetition rates was analysed. Based on the investigation it can be stated that for a repetition rate of f = 5 kHz, an increasing HAZ width occurs for increasing pulse energies. Although the achieved HAZ is smaller than for most of the other parameters, this trend is oppositional to all other observed repetition rates. For repetition rates between f = 10 kHz and f = 50 kHz, the HAZ width reduces for increasing pulse energies (Fig. 2). Using the 400 µm-fibre it is possible to perform cuts with pulse energies of $E_P = 10$ mJ which is half of the required pulse energy for the 600 µm-fibre. Analysing the average HAZ width depending on the pulse energy for different repetition rates it can be stated that the influence of the pulse energy on the HAZ is negligible for repetition rates f ≤10 kHz and more distinctive for higher repetition rates (Fig. 3).

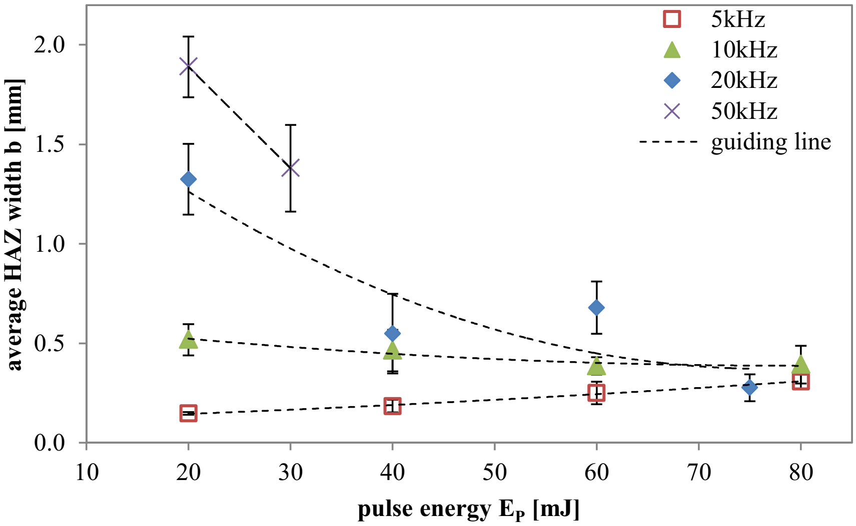

Fig. 2. Average HAZ width b depending on the pulse energy E_P for different repetition rates f using the 600 µm-fibre.

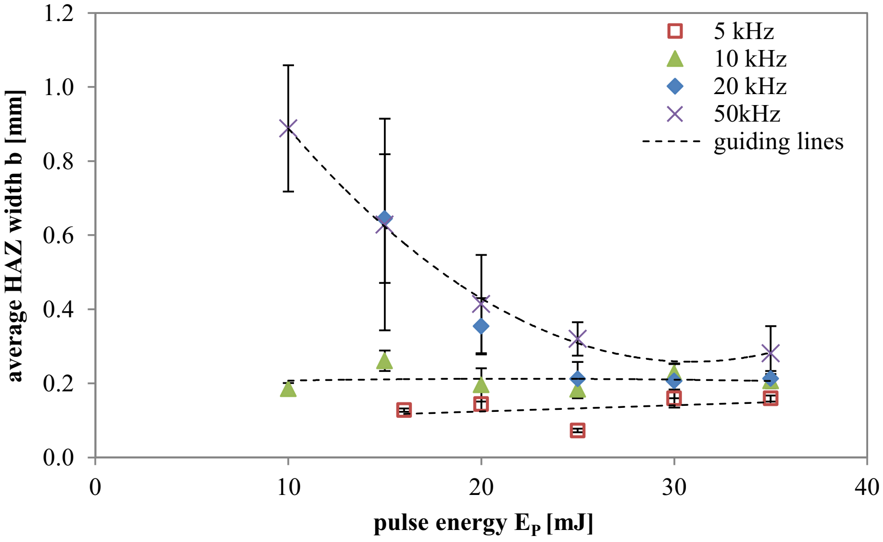

Fig. 3. Average HAZ width b depending on the pulse energy E_P for different repetition rates f using the 400 µm-fibre.

For increasing repetition rates the width of the HAZ increases as well, which correspond generally, in terms of the influence of the repetition rate, with the results of earlier investigations of pulsed laser cutting (Bluemel et al., 2014; Finger et al., 2013). Within this investigation the dependency is more distinctive for pulse energies below $E_P = 60$ mJ for the 600 µm-fibre (Fig. 4), or pulse energies below $E_P = 30$ mJ in case of the 400 µm-fibre (Fig. 5).

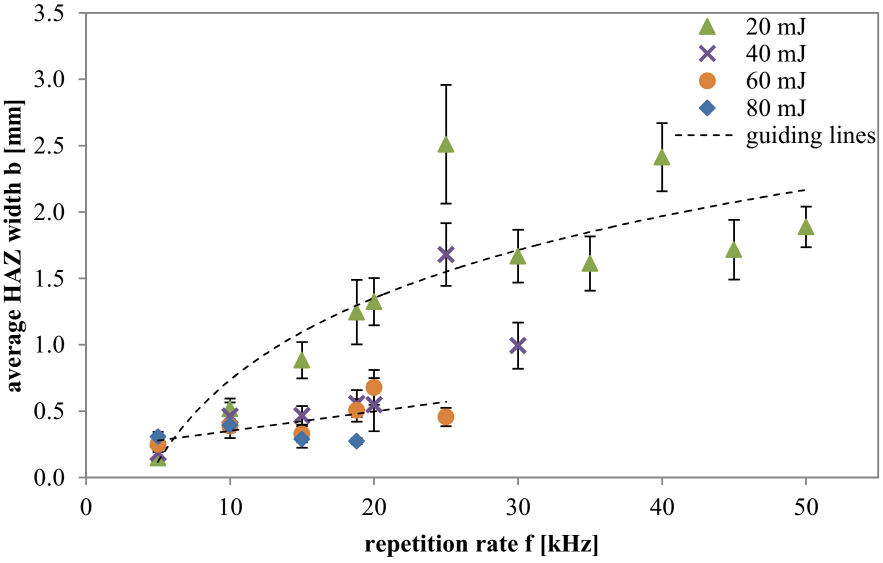

Fig. 4. Average HAZ width b depending on the repetition rate f for different pulse energies E_P using the 600 µm-fibre.

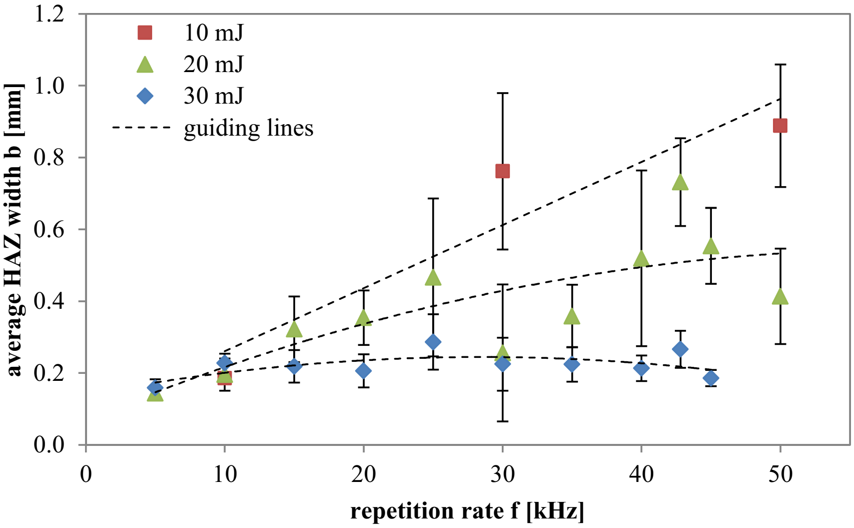

Fig. 5. Average HAZ width b depending on the repetition rate f for different pulse energies E_P using the 400 µm-fibre.

The different focal diameters for the fibres used resulted in a difference in focal area of $A_{f,400} = 0.5$ mm² for the 400 µm-fibre and $A_{f,600} = 1.13$ mm² for the 600 µm-fibre, which is a factor of 2.25. Due to that big difference comparable fluences can be achieved with both fibre setups despite the lower pulse energy for the smaller fibre. For that reason the previous results were analysed in terms of the achievable fluence and its influence on the results. Fig. 6 depicts the available repetition rates depending on the fluence for both fibre diameters. Additionally, parameter combinations resulting in a HAZ width $b \leq 300$ µm are marked in a different colour than parameter combinations with bigger HAZ. It is possible to achieve cuts with a threshold HAZ width of $b = 300$ µm in a wide range of repetition rates for a fluence over $F = 0.05$ J/mm². Furthermore, it is possible to go below the threshold HAZ width at higher repetition rates with a smaller focal diameter. For lower fluences good results can only be achieved for repetition rates below $f = 10$ kHz.

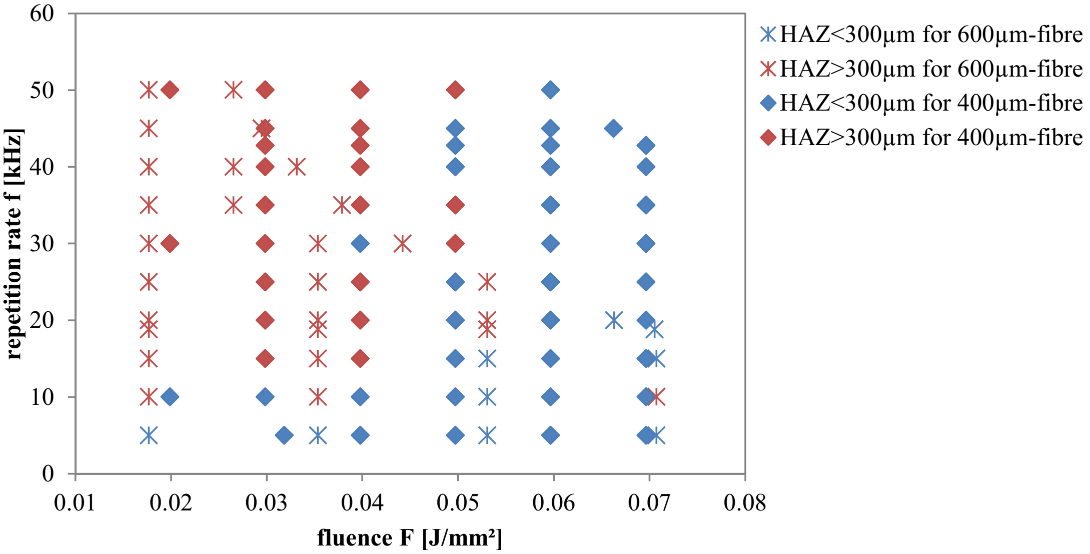

Fig. 6. Average HAZ width b depending on the fibre diameter d_f and fluence F.

Taking the parameter definitions as described in section 2 as a basis, the achievable effective cutting speeds differ clearly as expected, due to the lower necessary line energy for cuts with the 400 µm-fiber. For the 600 µm-fibre an effective speed of $v_{eff} = 28.8$ mm/s was reached, and for the 400 µm-fiber a value of $v_{eff} = 40.9$ mm/s. Depending on the parameter set it is possible with both setups to achieve a comparable fluence at an identical average laser power of $P_{L,avg} = 1500$ W. Taking into account the wider cutting kerf and therefore the higher volume of material which has to be removed, the difference in the achievable effective cutting speed can be explained. The ratio between the two effective cutting speeds is 1.42 which is comparable to the ratio of 1.5 between the two focal diameters.

Table 2 summarizes selected parameters for both optical setups. The parameters were selected by maximum achievable fluence or average power for the smallest and highest repetition rate, respectively. It can be inferred based on the present results that for equal fluence and focal diameter, the average laser power is the main factor in the achievable effective cutting speed, as an almost linear dependency between average power and effective cutting speed is present. Examining parameters with constant average laser power the effective cutting speed varies only slightly, but changing the repetition rate and therefore the fluence has a direct influence on the extent of the HAZ. Comparing the parameter sets with maximum available average power and fluence for both fibre diameters, it can be stated that the resulting HAZ width differs by 22% and the effective cutting speed by 42% between the 600 µm-fibre and the 400 µm-fibre.

Table 2. Summary of selected parameters for both fibre diameters concerning HAZ width and effective cutting speed.

400 µm-fibre	**repetition rate f [kHz]**	**average laser power P_L [W]**	**fluence F [J/mm²]**	**Average HAZ width b [mm]**	**Effective cutting speed v_{eff} [mm/s]**
	5	175	0.07	0.159	4.8
	42.8	1500	0.07	0.213	40.7
	50	1500	0.06	0.281	40.9
600 µm-fibre					
	5	400	0.07	0.307	7.6
	18.8	1500	0.07	0.274	28.5
	50	1500	0.03	1.38	28.8

4. Conclusion

Earlier studies came to the conclusion that an increasing repetition rate leads to a wider HAZ, whereas this often came along with increasing pulse overlap. This study showed that for a constant pulse overlap the influence of the repetition rate is not as distinctive for higher pulse energy or fluence, respectively. In contrast to the described investigations of Freitag et al. (2012), during this study with constant pulse overlap increasing the pulse energy barely influences the HAZ width or even reduces it for higher repetition rates. The results of the present study with the nanosecond pulsed laser also show an opposite trend to the results achieved with a picosecond pulsed system by Finger et al. (2013). While with the picosecond pulsed laser the HAZ was enlarged by increasing the fluence at constant repetition rate, for the present investigation the HAZ reduces in such a case for repetition rates $f \geq 10$ kHz.

Furthermore, with the smaller focal diameter at comparable fluence achieved with the 400 µm-fibre, it is possible to achieve faster effective cutting speeds in comparison to cuts with the 600 µm-fibre. If it would be possible to achieve higher fluence by optimizing the optical path of the 600 µm-fibre and at the same time enabling the usage of the maximum pulse energy of $E_P = 80$ mJ with a smaller spot, it should be possible to further increase the effective cutting speed and quality.

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