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Procedia CIRP 74 (2018) 417–420

www.elsevier.com/locate/procedia

10th CIRP Conference on Photonic Technologies [LANE 2018]

Robot based remote laser cutting of three-dimensional automotive composite parts with thicknesses up to 5mm

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Abstract

With the intention to develop a robot based laser cutting process for automotive 3D parts with varying thickness consisting of carbon fibre reinforced plastics (CFRP), strategies of 2D investigations were adapted. The used setup consist of a fibre guided nanosecond pulsed laser with an average power of $P_L = 1.5$ kW, a 6-axis robot and a 3D programmable focusing optic (I-PFO). In a first instance strategies for the remote cutting of material with a thickness of $d = 5$ mm were developed and optimized concerning cutting efficiency and quality. In a second step the results were transferred to a robot based 3D cutting process. Main challenges are the consideration of the correct angle of incidence, the geometric constancy and the accessibility of the cutting geometry by the I-PFO for complex shaped 3D parts. Therewith, "cutting-on-the-fly" strategies were realized for automated trimming and drilling of large automotive structures.

Keywords: CFRP; cutting; robod-based;

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1. Introduction

The widespread applications of carbon fibre reinforced structures increase in automotive and aerospace industry. Consequently, the variations within the material characteristics for example of used matrix material and material thickness as well as complexity of the parts increase in the same manner.

The cutting and ablating of carbon fibre reinforced plastics (CFRP) is continuously subject to research in order to meet these demands. By doing this, the knowledge base is increased in terms of laser material interaction and influential factors on the resulting cutting quality. The general terms for the cutting of CFRP with a minimum average HAZ width are independent of the used laser source and can be summarized by the need to reduce the laser material interaction time. This can be realized in a first instance by either short pulse durations or high scanning speeds [1, 2]. Additionally, the quality of the cutting edge can be increased significantly by generating the cutting kerf with multiple passes of the laser beam at high scanning speeds instead of single pass cutting. Implementing breaks between two passes or additional cooling options, a further reduction of the HAZ width is possible [4, 5].

Cutting of thicker materials above $h > 3$ mm require, depending on the optical setup and laser source, adapted process strategies to enable a complete cut. Investigations with laser sources emitting continuous wave (cw) realized the cutting of material with a thickness of up to $h = 12.7$ mm, by adapting the process in two ways. First multiple parallel lines were applied to widen the cutting kerf, and in a next step the focus was adjusted after a certain number of repetitions [3].

Beyond that, the conversion of the gained knowledge into enhanced processes by use of handling systems and process observation in order to reach an industrial level is part of many investigations. In terms of increasing the working field by usage of handling systems, linear stages or industrial robots are common. Linear stages are often used for the positioning of planar CFRP parts within the working field of the optics. In the case of industrial robots it is more usual to attach the optic

10.1016/j.procir.2018.08.168

to the robot and to move the optic along the desired cutting geometry [6, 7].

During the processing of CFRP materials the capturing of process emissions is of high importance, especially within an industrial environment. The need for an efficient ventilation was shown by several investigations [8, 9].

2. Experimental setup

The setup used for the processing of three-dimensional automotive composite parts consists of a newly developed laser source, a 3D scanning optic, and an industrial robot to enhance the working field of the optics. The laser source is a fibre-guided thin-disk high power laser emitting high energy pulses of $E_P = 80\ mJ$ with a pulse duration of $t_P = 30\ ns$ (Table 1).

Table 1. Specifications of laser source

Laser source	TruMicro-series by TRUMPF
Wavelength λ	1030 nm
Pulse duration t_P	30 ns
Repetition rates f	5 kHz – 50 kHz
Maximum average laser Power P_L	1500 W
Maximum pulse energy E_P	80 mJ
Diameter of light conducting cable d_{LLK}	600 µm

As a scanning optic a PFO 3D by TRUMPF was used, which was updated to an I-PFO during the investigations (Table 2). The capability to adjust the focal position by $\Delta z = \pm 22\ mm$ benefits the processing of complex shaped 3D-parts, and reduces the need to position the optic within small tolerances.

Table 2. Specifications of scanning optic

Scanning optic	PFO 3D by TRUMPF
Focal length l_f	255 mm
Working field elliptical A	102 x 174 mm^2
Z-deviation Δz	± 22 mm
Focal diameter d_f	1.2 mm

To enable the processing of larger parts, e.g. as the automotive demonstrator part with dimensions of $A \approx 1.6 \times 1.1\ m^2$, the optic was attached to a 6-axis industrial robot with a range of $l = 2.896\ m$ (Table 3).

Table 3. Specifications of handling system

6-axis robot	KR90 R2900 extra HA by KUKA
Load	90 Kg
Maximum range	2.896 mm
Repeatability	<±0.05 mm
Maximum axis speed	284 °/s*

*for the present setup a tool centre point speed of $v \leq 2$ m/s adjusted

The materials used for the investigations and process development were CFRP with either thermoset or thermoplastic matrix, with thicknesses of up to $d = 5\ mm$. A CFRP consisting of carbon fibre fabric, with a twill weave, and an epoxy matrix was used for the present investigation described below. The fibre volume content was 60 % for all thicknesses used. The demonstrator parts contain variations in the thickness of up to $\Delta d = 4$ mm within a length of just $l = 5$ mm to $l = 10$ mm which has to be considered by the process strategies.

Based on earlier investigations the parameter set shown in Table 4 was used for all experiments unless otherwise specified.

Table 4. Process parameters

Parameter	Value
Average laser Power P_L	1500 W
Repetition rate f	18.5 kHz
Scanning speed v_S	1000 mm/s
Number of repetitions n	varying with thickness
Break between repetitions t_B	500 ms

3. Results

3.1. Cutting of materials up to d = 5 mm

Cutting trials for materials with thicknesses of up to $d = 5$ mm revealed that cutting of such thick materials is possible with the present setup. Based on the known aspect ratio of 1:4, this result was expected.

In order to investigate the ablation efficiency in relation to the ablation depth, the number of repetitions n for the parameter set shown in Table 4 was increased in steps of $\Delta n = 10$ until a complete cut was achieved. For each step the reached ablation depth was determined by means of microscopic pictures of cross-sections. The results reveal that for up to $n = 60$ repetitions or a reached ablation depth of $h \approx 2.4$ mm, respectively, a linear increase of the depth per set of repetitions occurs. For increasing repetitions the slope of the ablation depth decreases but still displays a linear behaviour (Fig. 1).

Additionally, when analysing the corresponding average HAZ width b, the results show that for ablation depths over $h = 3$ mm the HAZ width starts to increase significantly, while it was nearly constant before that (Fig. 3).

Adapting the process strategy by realizing the cutting kerf with two overlapping parallel lines, named as double-line strategy, both the ablation efficiency and the resulting HAZ width can be optimized in comparison to the standard single line strategy. In terms of the ablation efficiency, the conclusion should be differentiated depending on the process strategy that was used. If the execution of the two parallel lines is defined as one repetition, the double-line strategy requires for all ablation depths fewer repetitions than the single line strategy (Fig. 1). For repetitions of $n \geq 60$ the differences in the achieved ablation depths increases up to a difference $\Delta h = 1.1$ mm. The effective cutting speed is enhanced in the same manner if between two repetitions a break is implemented for both strategies which last longer than the scanning time itself. In this case the break time is the time consuming factor, so that a reduction of the necessary repetition directly reduces the overall process time. Analysing the effective cutting speed for the case so that no breaks are required, the increase in the effective cutting speed is much less significant (Fig. 2).

While the change in the process strategy has an significant influence on the ablation efficiency for material thicknesses over $h = 2,2$ mm, the influence on the resulting HAZ width is restricted to a ablation depth of over $h = 4$ mm (Fig. 3). For greater ablation depths, the average HAZ width is smaller for the double-line strategy as well as the standard deviation.

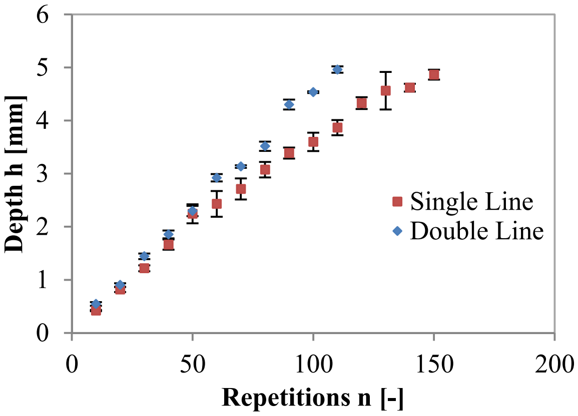

Fig. 1 Ablation depth h depending on the number of repetitions n for both processing strategies

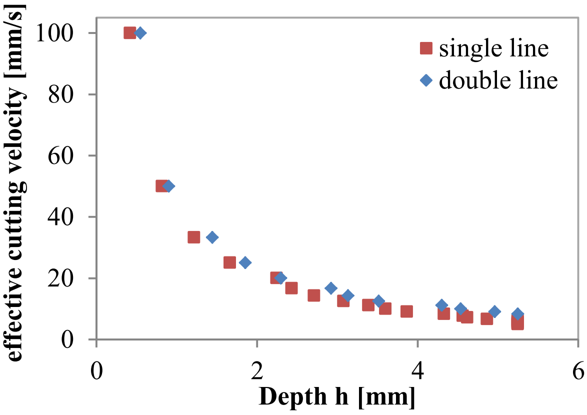

Fig. 2. Achievable cutting speed depending on the material thickness for both processing strategies

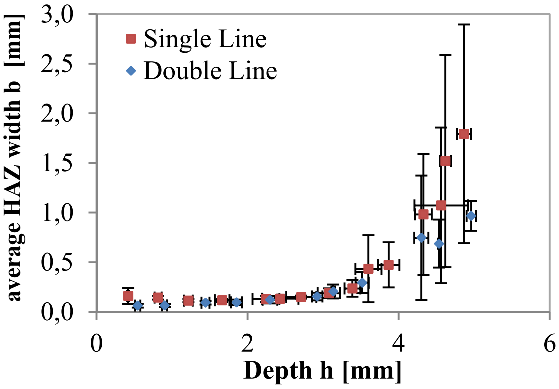

Fig. 3. Average HAZ width b depending on the ablation depth h for both processing strategy

3.2. Challenges during the processing of 3D parts

For three-dimensional parts in general, particularly complex shapes, different boundary conditions complicate the robot-based remote cutting process. These boundary conditions can be divided in boundaries driven by either the laser process or the systems engineering. For three-dimensional parts, the capturing of process emissions can be realized by adapted clamping devices with included ventilation near the processing area (Fig. 4). These complex clamping devices can limit the accessibility and thereby directly influence the process strategy suitable for an efficient trimming of CFRP parts. Another aspect is the angle of incidence during the laser cutting. Investigations showed that especially for material thicknesses over h = 3 mm the angle of incidence could influence the ablation depth, which is achievable with a certain number of repetitions, negatively. Furthermore, the angle of incidence can influence the cutting edge angle as another relevant quality criterion. Due to this, the cutting of closed contours on complex shaped surfaces can necessitate the repositioning of the optic although the contour would fit in the working field.

For complex parts in custom-made clamping devices with integrated ventilation, requiring many repositioning of the optic and the cutting of many different long contours with short break times, the most efficient strategy could be the “step and repeat cutting”. This would be the case, if the moving time of the robot is significantly longer than the laser on time.

Another possible strategy is the “cutting on the fly” strategy, where the scanning optic is continuously moved by the robot and the optic is responsible for the aligning of the scan lines. The robot speed and path have to be optimized so that all scan lines can be processed while they are positioned within the working field of the optic. The cutting of composite parts with long, flowing contours enables a continuous movement of the optic by the robot with a better ratio of laser on time to repositioning time where the laser is off. In such a case the “cutting on the fly” strategy could be the more efficient processing strategy, where the time for one “round” along the part serves as cooling time for the different cutting contour sections (Fig. 5). For the processing of this specific part the PFO was moved by the robot with a speed of up to v = 0.5 m/s while the cutting process.

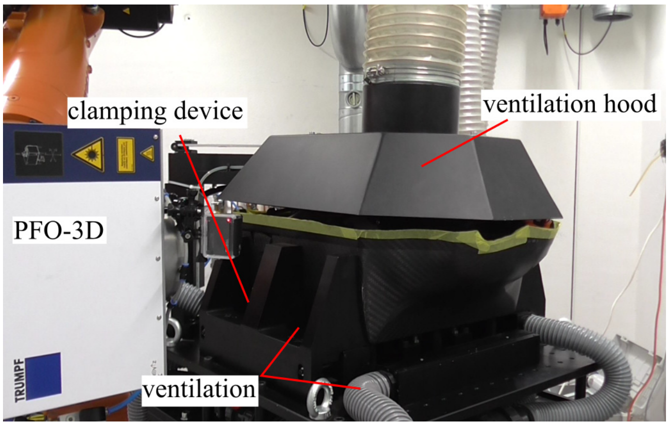

Fig. 4. Process setup for demonstrator part processed via the step-and-repeat strategy

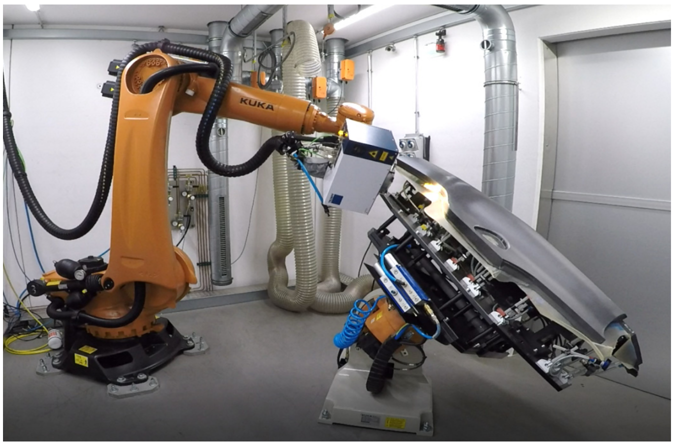

Fig. 5. Cutting-on-the-fly process of demonstrator part

4. Conclusion and outlook

We have demonstrated processing of CFRP material with a thickness of up to h = 5 mm. Our investigations reveal the efficiency of the performed cutting strategies and the influence of the ablation depth on the HAZ. For material thicknesses over h = 3 mm special precautions must be taken in order to reduce the resulting HAZ width. Cuts with a HAZ of less than b = 100µm can be realized, if longer breaks between subsequent repetitions or even additional cooling are applied (Fig. 6). Although it is possible to cut h = 5 mm material with the setup with a single-line strategy, the cutting edges possess a cutting edge angle of up to $\alpha = 10$ °. This has to be taken into account, when deciding if the setup is suitable for the desired tasks.

In terms of the best strategy for the processing of larger 3D parts, two strategies and their corresponding boundary conditions were discussed. In summary, it can be stated that for more complex shaped parts with complex clamping systems and many short contours, the “step-and-repeat” processing method can still be the strategy of choice. At the same time, the setup is capable of performing the cutting-on-the fly processing, meeting the required geometrical accuracy and quality. This strategy is best suitable for CFRP structures where a continuous robot movement without overly large changes in orientation of the optic can be realized.

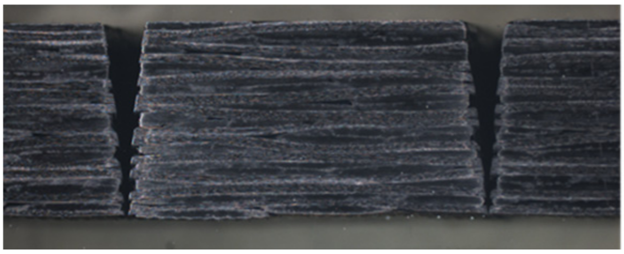

Fig. 6. cross-section of a cut through h = 5 mm material with single-line strategy

Acknowledgements

The authors 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 all project partners for their contribution and support.

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