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Laser-remote-cutting of large-scale semi-finished carbon-fiber products using a solid state laser

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Abstract

Since carbon fiber reinforced polymers (CFRP) have excellent mechanical and weight-specific properties, and lightweight concepts become increasingly important, especially in the automotive and aircraft sector, the demand for automated, cost-efficient manufacturing processes such as laser cutting of CFRP and semi-finished products is quickly rising. This paper presents an approach of establishing a process of laser remote cutting large-scale 3D semi-finished carbon-fiber products using a high power continuous-wave (cw) laser. The result is a stable and fast process with a cutting speed up to 15 m/min. Flat and sealed cutting edges ensure a good handling as well as the possibility to drape and inject within an Resin Transfer Moulding (RTM) process.

Keywords: Macro processing, Cutting, System technology

1. Introduction

As a consequence of governmental aims to reduce carbon dioxide emissions, electrical driven cars become increasingly significant for the automotive industry. The increase in weight of those vehicles caused by necessary batteries is to be compensated by using lightweight materials such as carbon-fiber-reinforced plastics (CFRP). A higher degree in automation is a necessary condition to reduce the manufacturing costs for future high production volumes of lightweight cars such as BMW i3 (Heuss et al., 2012).

The process of laser cutting CFRP and semi-finished carbon-fiber products combines various advantages: A nearly force-free processing for an improved handling especially for non-crimped layers, wear-freeness to

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avoid high tool-wear with the consequence of unsteady cutting qualities and high tool costs, as well as significantly shorter processing times (Herzog et al., 2014).

Laser cutting of carbon fiber preforms has lately been an issue of several research groups, pursuing different approaches: minimization of heat affection using pulsed, as well as maximization of cutting speed using cw laser systems. It was shown that Nd:YAG lasers at a wavelength of 1,064nm are well-suited for processing carbon fiber fabrics, achieving better cutting qualities than using CO_2 lasers, since carbon shows a lower absorption for a wavelength of 10.6µm (Fuchs et al., 2013; Emmelmann et al., 2013 and Klotzbach et al., 2011). Two effects can generally be observed during laser cutting of fiber fabrics: Fiber swelling, investigated by Voisey et al., 2006 describes the thickening of the fibers at the cutting kerf as well as their partial fusing in this area. Secondly Mucha et al., 2013 investigated the effect of fiber bulging which is caused by the interaction between fibers and the ablated material, describing the unravelling of fibers at the cutting edge. Although fiber fusion at the cutting edges results in a good handling behavior of the preforms, it must not influence the permeability at injection processes in a negative way. Experiments by meyer, 2008 dealing with this problem showed a similar injection behavior of laser cutted preforms compared to the conventional cutting method using a cutter.

2. Process

This paper deals with a laser-remote-cutting process of large-scale 3D semi-finished carbon-fiber products. The experiments were carried out using a 6kW solid state laser. The approach of remote-cutting was realized by installing a two dimensional programmable focusing optics (PFO33) on a six-axis robot in order to cut geometries larger than the optics' working area. This configuration delivers a fast and stable cutting process with effective feed rates higher than 10 m/min and high qualities of the cutting edge. Accordingly, the laser-remote-process is a highly attractive alternative to conventional cutting methods with an enormous potential for cost savings due to its wear-freeness and high process-speed.

2.1. Experimental Setup

The laser remote process was realized by installing a 2D scanning system on a high accuracy six-axis robot (KUKA KR 30 HA) using a high-power Yb:YAG disk laser. The test specimen as well as the demonstrator were fixed and positioned on a two-axis-positioner (KUKA DKP 400).

Table 1. Specifications of laser, optics and material

Laser system		
Manufacturer	TRUMPF GmbH + Co. KG, Ditzingen, Germany	
Type	TruDisk 6001	
Wavelength	1,030	Nm
Maximum power output	6,000	W
Optical system		
Manufacturer	TRUMPF GmbH + Co. KG, Ditzingen, Germany	
Type	PFO33	
Focal diameter (measured)	172 (1kW) / 195 (6kW)	µm
Focus position	Bottom surface	

Rayleigh length	1.9 (1kW) / 2.2 (6kW)	mm
Material		
Orientation of prepreg-material	0/90/+/-45/90/0°	
Fiber system	0°/90°	TK Industries GmbH, TKI300ZN127DT
	±45°	TK Industries GmbH, TKI300B127DT
Areal weight (per layer) 0°/90°	317	g/m^2
Areal weight (per layer) +/-45°	319	g/m^2
Curing agent	EPIKOTE™ Resin 05390	
Material thickness	2.4 - 2.6	mm

2.2. Process development

Firstly laser power was increased by 500 W per step up to 6 kW to identify the necessary minimal scanning speed for a complete cut of the test specimen (figure 1), showing an approximately linear correlation between speed and laser power, resulting in energy inputs per unit length between 9.4 kJ/m at 1.5kW and 14.3 kJ/m at 5.5kW.

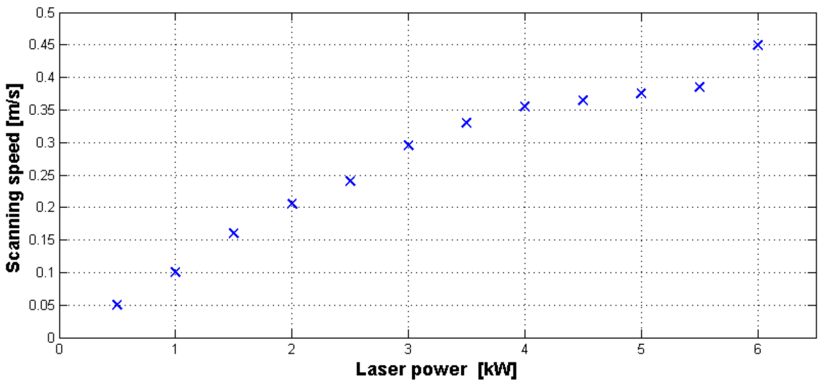

Fig. 1. Necessary scanning speed at increasing laser power

After identifying the process parameters, several investigations of evaluating the cutting quality were carried out. To quantify the effects of fiber swelling and fiber bulging, as described above, the cutting edge was microscopically investigated. Firstly, the relation between the cutting edge area (measured area of a defined length) and the initial area (product of measured material thickness and a defined length) was measured, see figure 2.

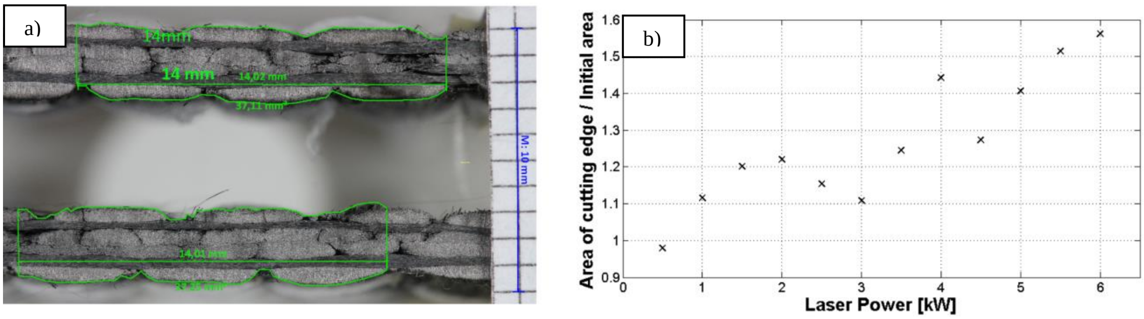

Fig. 2. (a) Measured area of the cutting edge; (b) Area of cutting edge / Initial area at different laser power

The thickness of fiber bondings with increasing laser power is shown in figure 3.

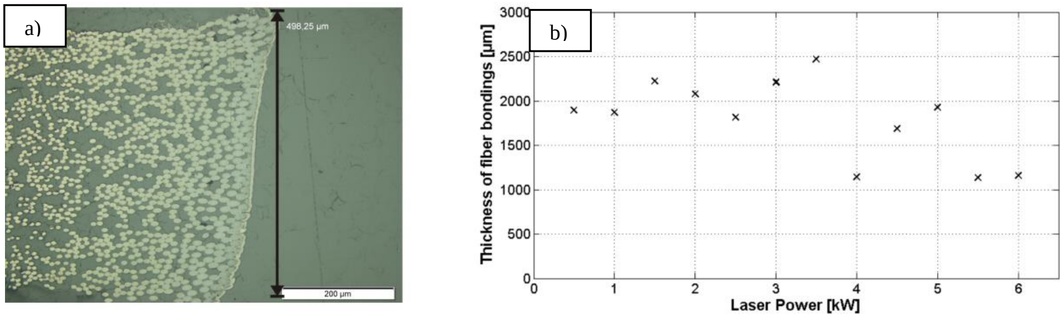

Fig. 3. (a) Fiber bonding; (b) Thickness of fiber bondings at different laser power

Due to the interaction between fibers and ablated material, the area of the cutting edge increases with higher laser powers and cutting speeds, fiber swelling slightly decreases due to the shorter thermal interaction time with increasing cutting speed (figure 4).

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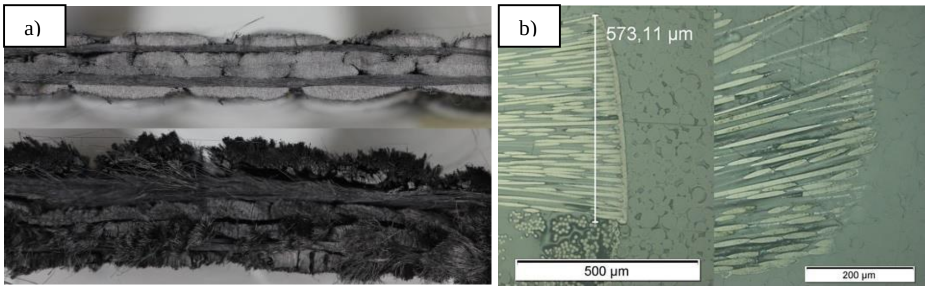

Fig. 4. (a) Cutting area of laser cutted non-crimped fabrics, laser power 1kW (top) / 6kW (bottom); (b) Fiber swelling of a 0°-layer (non-crimped fabric), laser power 0,5kW (left) / 5kW (right)

The process development yields a stable laser cutting process of non-crimped fabrics as well as preforms, generating a flat and fused cutting surface (figure 5), allowing an easy handling and transportation of the preforms.

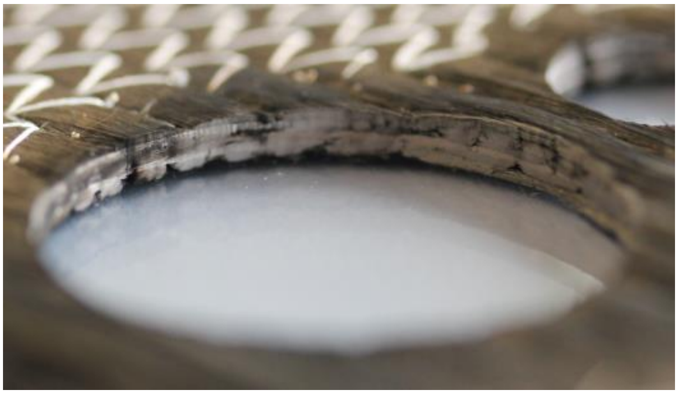

Fig. 5. Cutting edge of laser cutted preform

2.3. Finishing

Various tests have shown the drapability of laser cutted preforms as well as their suitability for an RTM-injection process, the fused cutting surfaces obviously do not prevent the flow of epoxy resin. For validating the suitability for RTM-process, preforms were cut to the final contour of an RTM-tool and then injected. The result is a flat, homogeneous laminate (figure 6).

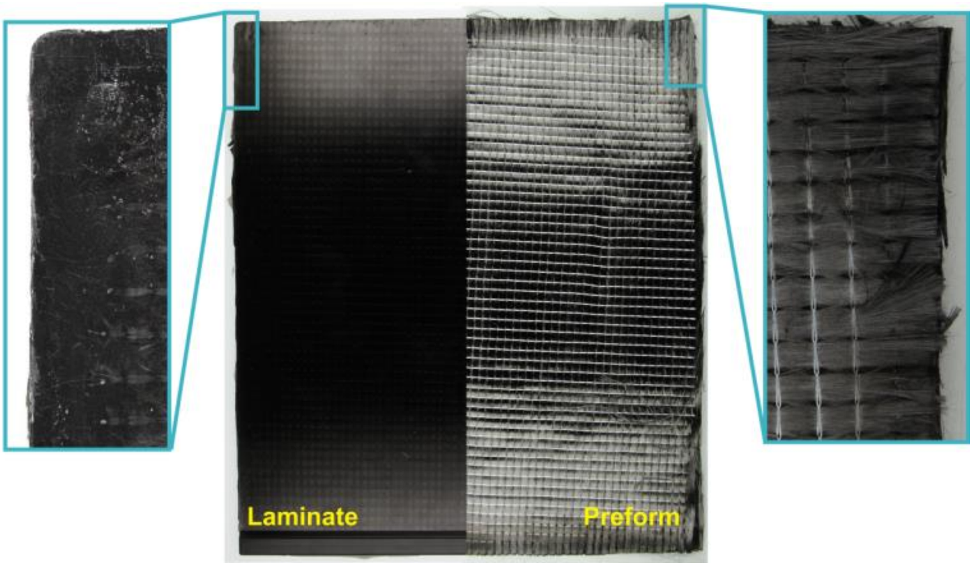

Fig. 6. Comparison of a laser cutted preform (right) and the resulting laminate after RTM infusion (left)

3. Large-scale 3D cutting

3.1. Experimental Setup

For cutting the 3D-demonstrator in shape of a caravan door, a device for fixing the preform as well as discharging process emissions was developed and fixed on a two-axis positioner. By moving the positioner and the 6-axis-robot, the optics can be positioned at the cutting contour. Process emissions are discharged on both sides. From above the cutting edge this is realized by an elliptical scan field extraction which is attached to the optics, from below by an annular extraction channel integrated into the tooling device (figure 7).

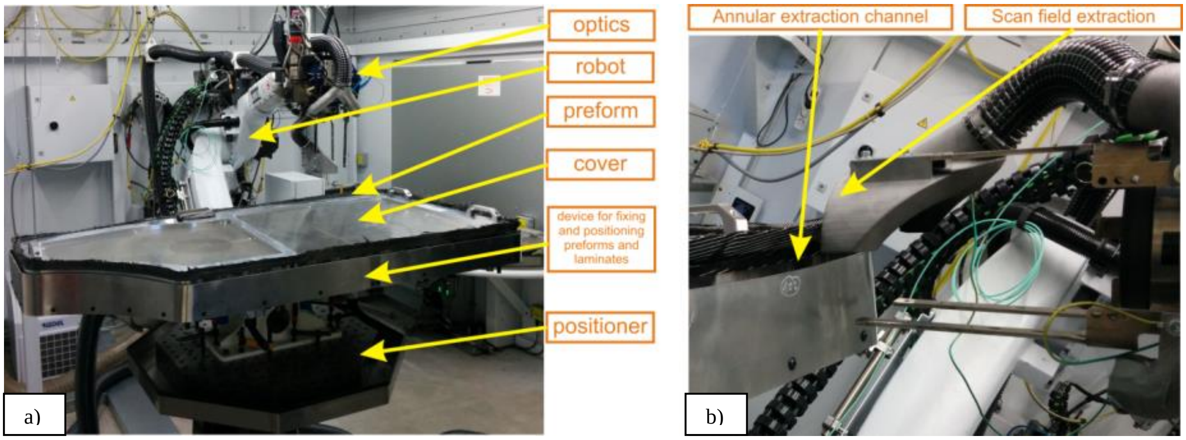

Fig. 7. (a) Experimental setup; (b) concept of emission extraction

3.2. Programming of cutting contour

The positioning of the laser scanner was realized by moving the robot, as well as rotating and tilting the positioner. Tilting the cutting apparatus is also necessary to prevent the cut-off from falling forward into the beam path of the laser. The trimming was performed by a stepwise exposure of a line of 180mm length (semi-major axis of the elliptical scan field) and moving the scanner to the following section. The programming of the contour was carried out directly on the robot. With the help of a pilot laser focus position, cutting path and connection points of intersection segments were taught manually. An on-line programming of this type is the simplest type of contour planning. The cutting path can be estimated directly on the specimen. The fact that the part of the preform standing out of the cutting apparatus slightly bends due to its low stiffness and unravels at the radiuses must be considered at programming, even if the process allows a certain defocusing. Again, the direct online-programming of the robot is advantageous. The disadvantage is the lack of path optimization and the consequential reduction of process time by shorter paths of the robot. An automatic partitioning of CAD contours does also not take place, which means extra work during the programming.

3.3. Result

The cycle time for trimming the entire demonstrator with a length of the cutting contour of 4.7m is two minutes. Cutting edges are flat and sealed, without fraying, especially on the straight sections (figure 8). Since the preforms unravel at the radiuses of the semi-finished product, it is difficult to focus the beam constantly on the surface of the entire path. The material thickness also varies at those positions. For those reasons some single filaments are standing out the trimmed part at the radiuses.

Fig. 8. Overall view of a laser cutted preform in shape of a caravan door

4. Conclusion and outlook

The trimming process for semi-finished CFRP-products with up to 15 m/min has a certain tolerance to defocusing and variations in material thickness, which is essential for a remote cutting process of semi-finished products. The results are flat, smooth and sealed edges which simplify the handling of semi-finished products, without affecting the subsequent processes such as draping and injection in a negative way. The ability to perform three-dimensional, large-scale structures by means of semi-finished products, robot controlled remote process has been shown at a caravan door.

An optimization of the cutting device can prevent the preforms unraveling at the radiuses in order to guarantee a complete separation at those positions. Furthermore, the path planning of the robot can be optimized to achieve a further reduction in process time. For this reason, future research could aim to develop a time-optimized on-the-fly process for cutting large-scale preforms. An automated segmentation of the three-dimensional CAD cutting contour could significantly reduce process speed as well as programming effort. To realize this, more theoretical investigations concerning the 3D capability of the process are necessary.

Finally a further processing of the trimmed demonstrator via RTM can prove the suitability for infusion for large-scale, three-dimensional laser-cutted semi-finished CFRP-components.

Acknowledgements

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