Lasers in Manufacturing Conference 2015

Laser Cutting and Joining in a Novel Process Chain for Fibre Reinforced Plastics

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Abstract

Laser transmission joining and cutting are presented as the final steps of a novel process chain comprising fibre spraying, variothermal consolidation, joining and trimming of glass fibre reinforced parts to promote efficient manufacturing of light-weight components in high volume production.
The transmission joining is demonstrated up to a material thickness of 2 mm of the transparent joining partner (glass fibre / polyamide with 60 wt.-% fibre content). With this joining technique closed cross sections can be generated to increase the stiffness of the component thereby supporting lightweight design.
For the trimming, a CO_2-laser was used operating either in continuous wave mode (cw) or in pulsed mode with a pulse width of a few hundred nanoseconds and an average power >1 kW. For both operating modes appropriate process regimes were identified for GFRP cutting with a focus on cw-mode for the component production due to higher productivity. Single-pass cutting with coaxial assist gas as well as multi-pass cutting has been investigated. Also some comparisons to cutting of CFRP and to cutting with fibre laser are provided. The selected demonstration part is a seat component for trucks, which was welded with a circumferential seam and trimmed at the edge of the seam in the welded zone.

Keywords: GFRP; CFRP; laser cutting; laser joining; process chain

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1. Introduction

Innovative lightweight concepts based on fibre-reinforced thermoplastics (TP-FRP) can make a significant contribution in automotive industry to achieving a reduction of CO_2 emissions and supporting e-mobility by lightweight components. For such TP-FRP components to be used economically, however, production costs and production times still need to be reduced significantly, while the component complexity is increased.

A new automated process chain (Fig. 1) enables scrap-minimized production of load-optimized lightweight components with local adjustable properties, directly from the fibre to the laser welded and trimmed component. First, a 3D-preform is generated by mechanical cutting of a hybrid roving consisting of glass fibres and PP or PA and spraying the fibres onto a mould. The resulting near net-shape preform can be designed load optimized thanks to the high degree of orientation of the long fibres. The following process step is the variothermal consolidation. The preform, optionally equipped with inserts, is heated and cooled with rates of 10 K/s. High heating and cooling rates are reached by the variothermal tool, manufactured by a generative laser process enabling a network of channels close to the surface for optimized heating and cooling. Short flow paths and the high temperature gradients enable short cycle times. Detailed information of these production steps are given in Hopmann et al, 2014. The finishing processes laser joining and trimming are described in detail as follows.

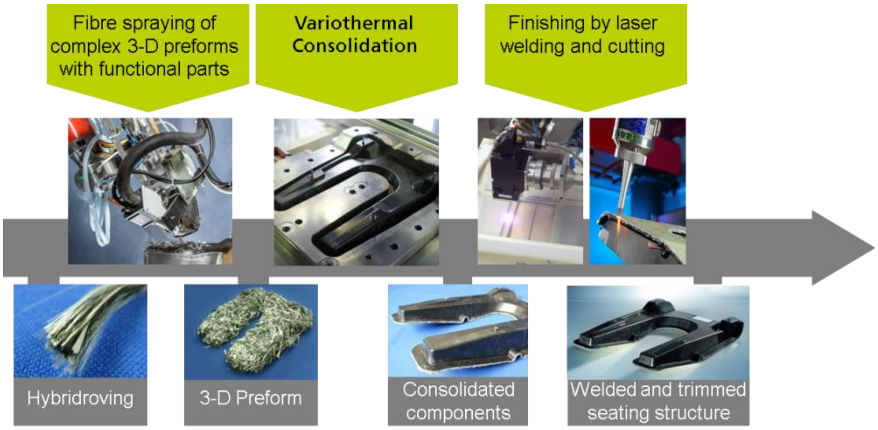


Fig. 1: InProLight process chain for 3-D thermoplastic glass fibre reinforced parts.

2. Laser joining

With laser transmission joining it is possible to design hollow structures and thus to increase the stiffness of components and to exploit the lightweight potential of thermoplastic FRP. For the joining process the laser beam has to be transmitted through one of the joining partners and absorbed by the other. For non-reinforced thermoplastic material this process is well established. For reinforced material the process parameters have to be adapted due to scattering by the glass fibres, leading to a reduction of transparency and intensity [van der Straeten, 2015]. A transmittance of at least 20 % is required for a robust welding process. Depending on the optical material characteristics and the beam shape, process windows for processing speed and laser power can be found to apply laser transmission welding with material containing 60 weight-% of fibres in 2 mm thickness. Fig. 2 shows shear strength of laser welded joints in dependence on the laser power with a constant welding speed (50 mm/s). For low laser power the shear strength is reduced, because insufficient melt volume is generated. Exceeding an optimal laser power, the matrix material is partly decomposed.

The reduced transparency of reinforced material is compensated by a higher laser power, provoking the risk of thermal surface damage. In case of material inhomogeneities or changes in power demand due to varying speed e.g. in corners, a pyrometer is used for a closed loop power control.

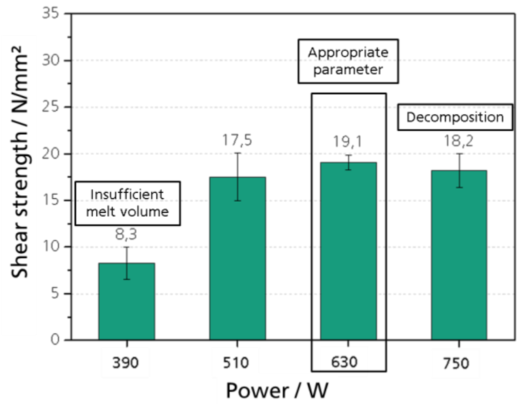


Fig. 2: Welding strength depending on laser power (feed rate 50 mm/s, material Tepex® flowcore 2mm / ~ 60 wt. % glas fibres)

3. Laser cutting

Laser cutting is the last step of the process chain and used for trimming and optional hole cutting. A CO_2-laser is used because of its high absorption in both, glass fibres and matrix material. The laser, a prototype source developed by Trumpf Laser- und Systemtechnik GmbH, provides laser radiation in cw mode up to 3 kW maximum power and in pulsed mode up to 1.5 kW average power with a pulse length in the range of 200 ns. The fibre sprayed and consolidated GFRP material is cut in cw mode, because the processing speed with cw mode is by a factor of 5 higher than in pulsed mode at the same average power. Additionally, in cw CO_2 lasers in multi-kW power range can be used. The reasons for the reduced process efficiency using pulsed radiation are energy consumption for heating up the material significantly over the melting temperature of the glass and for evaporating a high proportion of material. The resulting vapor plume leads to scattering and absorption of the laser beam above the workpiece as well as to disturbances of the cutting gas flow in the kerf.

Whereas glass with a distinct viscous melt phase benefits from an efficient coaxial cutting gas flow to eject the material, carbon fibre composites can profit from the high pulse energy of the laser in a multi-pass ablation cutting process. With an average power of 1.0 kW and a peak power of 60 kW CFRP samples (2 mm thickness, 55 vol-% fibre content, PA matrix, 0/90° woven plies) were cut with an ablation rate of 350 mm³/min (Fig. 3). The width of the heat affected zone (HAZ) is 100 µm. Scaled to the laser power, these results are in the range of ablation rates reached with ultra-short pulsed lasers up to 400 W average power [Finger 2013]. In Fig. 4 the volume specific energy for ablating carbon fibre material with different lasers in in a wide range of laser power shows that the use of a cw high power and high intensity single mode fibre laser leads to a more efficient process than provided by the pulsed sources. The volume specific energy of 74 J/mm³ needed for generating the cut kerf is based on cuts with 90 µm kerf width and a HAZ of 100 µm. In other experiments, leading to wider kerfs and a higher HAZ, less than 40 J/mm³ are needed for cutting. This is less than the specific energy needed to sublimate the carbon, which is 85 J/mm³ for carbon [Onuseit] and accordingly 51 J/mm³ for a material with a fibre content of 60 vol-%. One reason for the high efficiency is that not all material has to be sublimated, but some carbon is ejected out of the kerf as particles, as to be seen in high speed videos of the process emission. The speed of these particles was measured to more than 50 m/s (Fig. 5). Hot vapor is emitted with supersonic speed, which can be identified in the videos by periodic expansion and compression areas in the emitted jet.

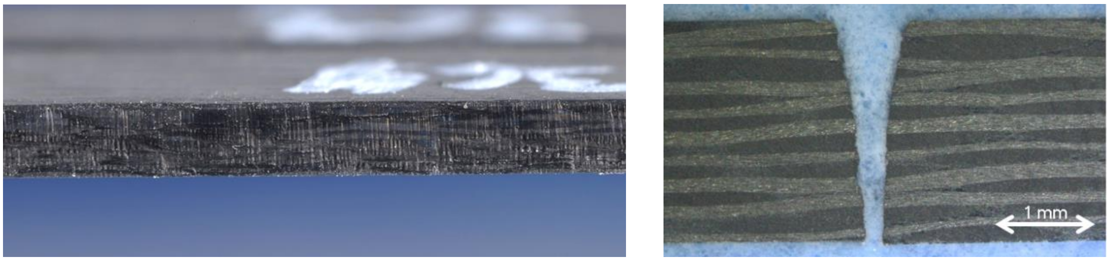


Fig: 3: Cut edge and cross section of a cut sample C/PA, 2 mm thickness, with a ns-CO_2-laser (average power 1 kW, peak power 60 kW, scan speed 240 m/min, effective speed 0.5 m/min).

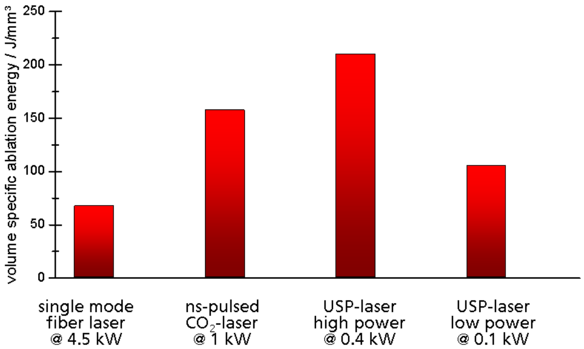


Fig. 4: Volume specific energy consumption for ablating carbon fibre composites, scaled to a fibre content of 60 vol-%.

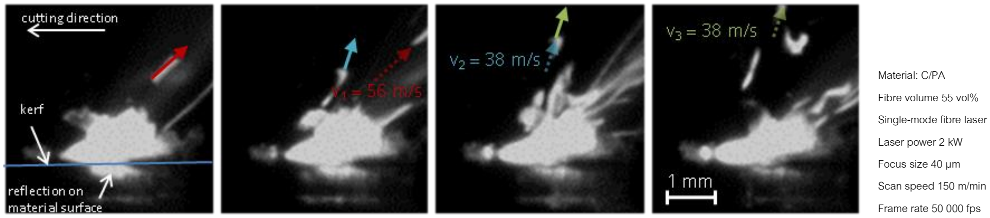
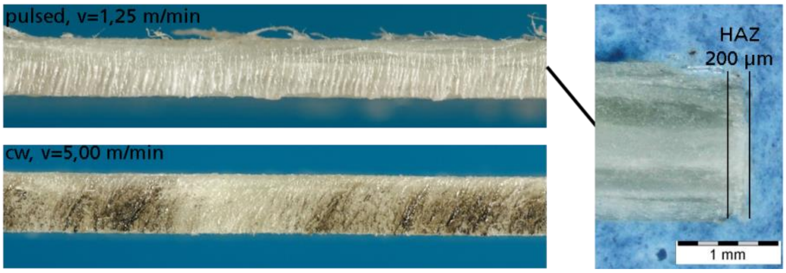


Fig. 5: High speed video of an ablation process, showing particles ejected out of the kerf.

Accepting the lower cutting speed in pulsed mode compared to the cw-mode, cutting of glass fibre composites with ns-pulses can provide a clean edge with minimal carbonized material on the edge. Fig. 6 shows a cut edge and cross section with a cutting speed of 1.25 m/min. The maximum speed for a cut with this setting (see Fig. 6 for parameters) is 3 m/min. For comparison, Fig. 6 also shows a cut in cw-mode with a cutting speed of 5 m/min, which is a speed with a similar relative surplus in laser power: the maximum speed is 15 m/min in this case.



Material:	GF/PA
Fibre content:	60 weight-%
Thickness:	1.5 mm
Laser power:	900 W
rep. rate:	100kHz
Nozzle diameter:	2 mm
Nozzle distance:	0,3 mm
Gas pressure:	3 bar
Focus position:	v_{opt}, app. 0 mm

Fig. 6: Cut edge GFRP, pulsed (top) and cw (bottom) processing.

Using cw-mode for higher power and speed, either a single pass cutting or a multi-pass ablation process is possible. The process efficiency is the same in both cases, just as the HAZ, which is 300 µm for a material thickness of 4.4 mm. The multi-pass process provides a slightly cleaner edge (see Fig. 7) compared to a single-pass cut at cutting speed near the maximum cutting speed. However the single-pass is much easier to implement for processing 3-D parts and has therefore been used for producing demonstrator parts.

Multi-pass
Laser power: 3 kW cw
Scan-speed.: 100 m/min
Number of scans: 15
Effective speed.: 6.7 m/min

Single-pass
Laser power: 3 kW cw
Cutting speed: 5 m/min
Max. speed: 5<v_{max}<7.5 m/min

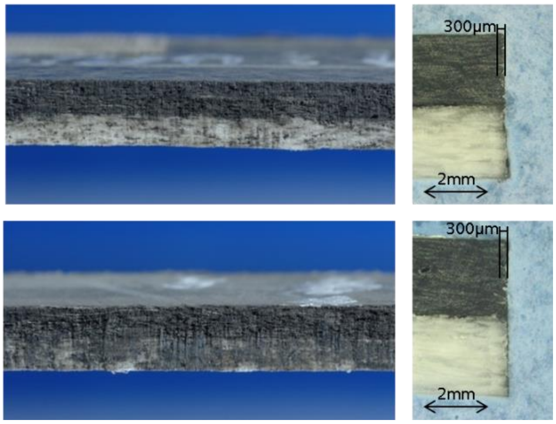


Fig. 7: Cut edges and cross sections of multi-pass and single-pass cuts in welded material of 4.4 mm thickness (GF/PA with 60 weight-% fibre content).

4. Demonstrator part: seating structure

The process chain is demonstrated by the production of a seating structure for trucks. For the two shell design a laser absorbent upper shell, thickness 3.8 mm, and a laser transparent lower shell, thickness 1.5 mm, are fibre sprayed and consolidated with a load optimized fibre orientation. The material of upper and lower shell has a glass fibre volume of 60 weight-% embedded in a polyamide matrix. The shells are joined by laser transmission welding to a hollow structure to increase the stiffness with a circumferential seam of 10 mm width (Fig. 8). For the joining a diode laser is used with a maximum laser power of 500 W. The beam is focused to a rectangular spot size of 1 mm x 10 mm. The optics is mounted on a robot and moved along the welding contour with a speed of 30 mm/s. The power is adapted to the processing speed and material condition by a pyrometer. The processing time is less than 2 minutes.

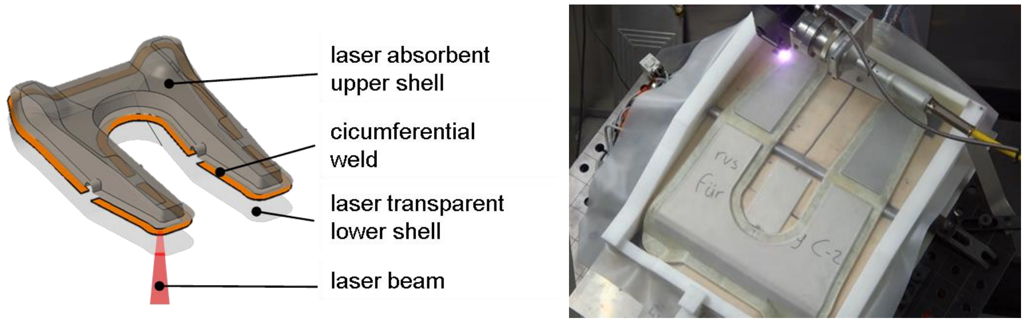


Fig. 8: Structure of the seat components (left) and welding of the components on a articulated arm robot (right).

Finally, the part is trimmed with the CO_2-laser at the edge of the weld seam generating a common cut edge without a gap between the upper and the lower shell. For highest efficiency the laser is used in cw mode, providing a maximum speed of 55 mm/s with 2.4 kW laser power as depicted in Fig. 9(a). However, for a robust processing a speed of 35 mm/s is chosen, because local agglomeration of fibres and tolerances of thickness and focus position require a reserve. With this processing speed time for trimming is app. 1.5 minutes.

Figure 9(b) shows the cutting process of the bearing with a slender nozzle to allow a good accessibility to the part. Fig. 10 displays the finished demonstrator and details of the cut edge and the weld seam. The HAZ is below 300 µm and the cut edge is predominantly free of debris. The demonstrator passed all required mechanical tests including a fatigue strength test with 1 kN load and 1 million load cycles. The weight reduction compared to a steel component is 27 %.

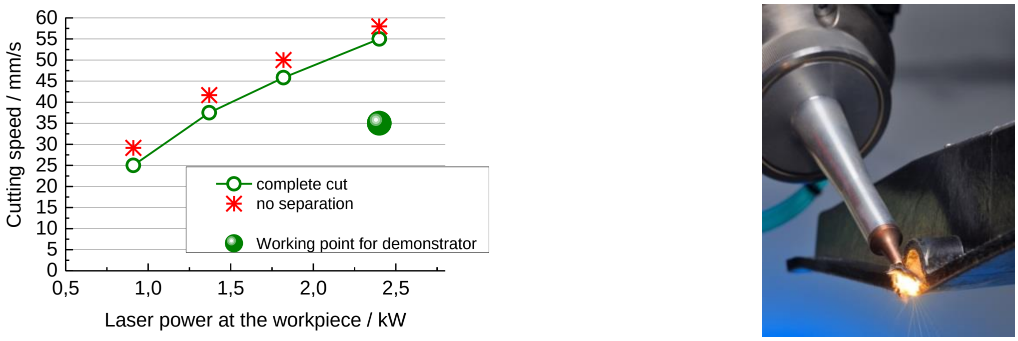


Fig. 9: (a) Cutting speed for trimming the seating structure at the welded edge of the component; (b) Cutting process with a slender nozzle for good accessibility.

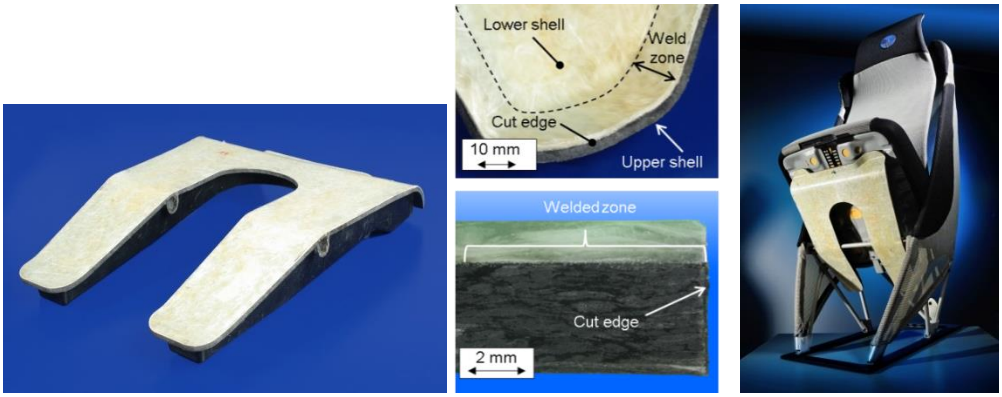


Fig. 10: left: Seating structure and details of the edges; right: Assembled seat with the demonstrator part

5. Conclusion

With the new InProLight process chain comprising fibre spraying, variothermal consolidation and laser joining and cutting the production of complex TP-FRP parts is demonstrated, employing innovative technologies for each process and providing new prospects for the design of thermoplastic FRP. Laser transmission joining and cutting reveal a high productivity with fast, wear free 3D-processes in cycle times between 1 and 2 minutes, relevant for mass production. For cutting of the GFRP components the highest productivity is achieved with a CO_2-laser in cw mode in a single-pass, gas assisted cutting process.

Using the CO_2-laser in short pulsed mode, cutting of CFRP in good quality with a HAZ in the range of 100 µm in a multi-pass process could be demonstrated. The capabilities of this process can be positioned between highest efficiency provided by high power fibre lasers and the best quality provided by ultra-short pulsed lasers.

Acknowledgements

The work has been partially funded by the German *Bundesministerium für Bildung und Forschung BMBF* in the program “Energieeffizienter Leichtbau (“InProLight”, No. 02PJ2080 / 02PJ2070) and by the European Union within the seventh framework program in the project “FibreChain - Integrated Process Chain for Automated and Flexible Production of Fibre-Reinforced Plastic Products”.

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