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Joining of thermoplastic tapes with metal alloys utilizing novel laser sources and enhanced process control in a tape placement process.

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Abstract

Automated laser assisted tape placement is an additive manufacturing technology for the production of composite parts. Composite parts are common in various markets. Especially the automotive sector has a demand for lighter and stronger materials. The combination of standard sheet metal materials and fiber reinforced plastics promises to deliver enhanced properties and performances over the separate materials themselves. This multi-material combination is classically done with mechanical connections. This paper addresses a direct in-situ approach of putting carbon fiber reinforced thermoplastic tapes directly onto pre-structured sheet metal parts and shows the prerequisites needed for achieving a consolidation between both materials.

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Keywords: Automated tape placement; VCSEL; Multi-material components; Consolidation process

1. Introduction

Today more and more lightweight products made out of or with carbon fiber-reinforced thermoplastics (CFRTP) are making their way into consumer applications such as automotive parts [1]. The automotive sector is driven by topics like electro mobility, cost-reduction and lower CO2-emission. Thus, the demand for overall lighter vehicles rises up in the markets. Together with conventional sheet metals currently being the number one lightweight materials in automotive applications [2], new high performance materials are emerging. Fiber-reinforced plastics (FRP) offer many abilities and possibilities needed for new parts and designs. The excellent strength-to-weight ratio of carbon fiber reinforced thermoplastics for example allows for a great reduction in weight. Of course, currently the high costs of CFRTP is a disadvantage. Especially for the automotive sector, the joining of metal structures together with CFRTP promises new opportunities for modern product designs and more high-grade structures. Those multi-material composites enable for lower weights and higher mechanical properties with enhanced safety for passengers of a car.

The European research project ComMUnion aims to develop a novel solution for manufacturing productive and cost effective 3D metal/CFRTP multi-material components by addressing all the relevant value chain.

Nomenclature

ATP	Automated tape placement
CFRTP	Carbon fibre reinforced thermoplastics
f	Frequency
FRP	Fibre reinforced plastics
F_{Roller}	Compression force on the roller
F_{Tape}	Tape tensioning force
$F_{vol\text{-}\%}$	Fibre volume content
I_L	Intensity of laser irradiation
t_C	Cycle time
T_M	Temperature of the metal surface
T_P	Process temperature

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VCSEL	Vertical-Cavity Surface-Emitting Laser
V_P	Process speed
w_T	Width of tapea
$w_{T,max}$	Maximum width of tape
d_T	Thickness of tape
λ	Wavelength

1.1. Multi-material components – State of the art

Multi-material combinations made of high-strength steel alloys and fiber-reinforced composites are well known to the automotive market (e.g. BMW 7 series). Multi-material combinations feature better properties compared to conventional metal-only parts. The anisotropy of the multi-material part combines the advantages of both metal and composites while their joint minimizes their single disadvantages. Joining technology for such multi-material components still relies on conventional joints like bolting, screwing, pressing, gluing [3,4]. Other approached feature a resin infusion onto a fabric applied to a metal part with pins holding the fabric [19] or laminating fiber-reinforced plastic layers with metal layers [20]. Most approaches shown in literature are based on fiber-reinforced plastics with a thermoset resin [3,4,20], while thermoplastic matrix systems are gaining importance in many applications [1]. However, combining fiber-reinforced plastics with metal often leads to residual stresses in the material combination caused by different thermal expansion coefficients of the fiber, the metal and the polymer matrix [21,22,23].

1.2. Novel joining technology for multi-material components

The novel approach presented in the ComMUnion project is based on a direct bonding between a structured metal surface (Fig. 1) and a carbon-fiber reinforced thermoplastic composite, using a laser-assisted tape placement system for an in-situ consolidation between both materials. The achievable joint strength is currently under investigation.

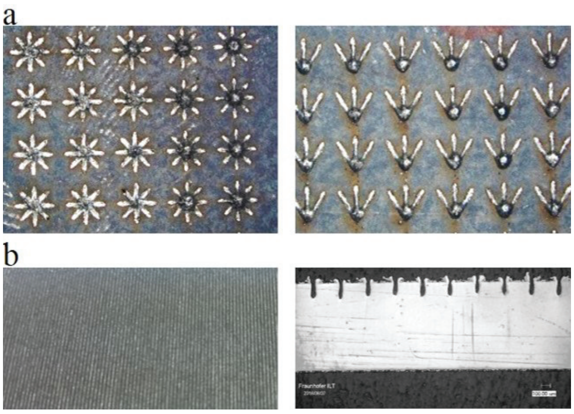

Fig. 1. Different approaches of surface conditioning. (a: Additive structure (Aimen); b: Protruding structure (left: Fraunhofer IPT / right: Fraunhofer ILT)) [16]

1.3. Process and production technology for multi-material components

Automated tape placement (ATP) of CFRTP with controlled laser-assisted heating, high-speed laser texturing and cleaning, on-line monitoring and inspection, and computational multi-scale modelling will be combined in a multi-stage robot solution for joining to provide high performance joints. Tools for quality diagnosis and decision support will be also implemented under a cognitive approach to ensure interoperability and usability.

The use of novel Vertical-Cavity Surface-Emitting Lasers (VCSEL) for the in-situ consolidated placement of CFRTP tapes onto metal alloys offers new possibilities for process controls [8]. With independently controllable emitter lines, the laser intensity can be locally varied in order to match the special properties of the metal alloy and the CFRTP tape. The novelty presented in his paper is the use of two laser sources for heating up the metal and CFRTP independently instead of just one heating source [24], with the goal of lowering the residual stresses and enhancing the bonding quality. This paper shows the potential of applying CFRTP tapes onto metal alloys utilizing novel VCSEL laser technology within a tape placement process with an enhanced process control system facing the different properties of CFRTP and metal alloys in a single process. In this paper, the focus is set onto the design of a modular automated tape placement head, an according process control system as well as the process itself.

2. Research Background

2.1. Automated laser assisted tape placement

In sense of productivity and efficiency, in-situ out-of-autoclave processes are well suited for manufacturing of automotive parts. The laser assisted automated tape placement (ATP) is a well-established production process [5,6,7]. Within the ComMUnion project, a new modular ATP head is currently being developed. This modular ATP head will be optimized for the joining of CFRTP onto metal structures and feature innovative heating sources.

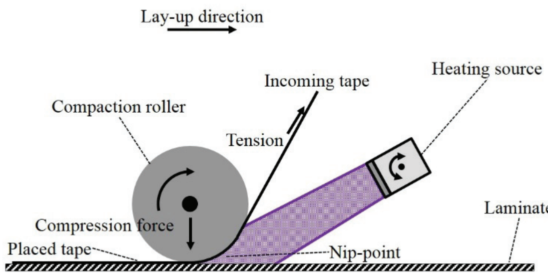

Fig. 2. Principle of an ATP process.

Due to a high variation in type and shape of automotive parts, an automated production process regularly cannot be made with a single machine. Geometries of the target part, lay-up strategies of CFRTP tapes as well as different material properties put several demands on the production equipment.

The new modular automated tape placement head will match a large variety of production parameters. The single modules include compression units, tape cutting units, tape tensioning units, robot interfaces, measurement systems as well as different heating systems, all mounted onto a universal base structure. The modularity is needed in order to be able to place small CFRTP tapes onto narrow areas of parts but also to be able to place wide CFRTP tapes onto larger areas of bigger parts. Currently, CFRTP tapes with a width of up to $w_{T,max}$=50 mm are planned to be used within the ComMUnion project.

The most critical process parameters of laser assisted automated tape placement are the process temperature in the consolidation area (Nip-point) T_P, the compression force of a compaction roller onto the tape placed onto the substrate F_{Roller} [15] and the tension applied to the tape against the lay-up direction F_{Tape} (Fig. 2) [6]. A too low temperature T_P does not melt the thermoplastic matrix and a too high temperature T_P degrades the thermoplastic matrix. The compression force F_{Roller} enables the contact between tape and substrate and widens the heated tape according to the applied force. The tape tension F_{Tape} applies a pretension to the fibers. Those parameters need to be controlled so that they stay within a specific optimum parameter range in order to receive good process results and part qualities [6]. A modular control system matching the modular ATP head is under development with the goal of making a customizable control interface with fast response times and real-time control of the process (Section 3.3).

Especially the use of lasers as a heating source puts very high requirements on the process control system [6, 9, 10, 11, 12]. With the capability to rise the power up to several kW of laser power with power densities of several I_L=100 W/cm² and process speeds of over V_P=1.000 mm/s of tape throughput, fast control loops with cycle times below t_C=10 ms are necessary in order to keep the process temperature within a +/- 10 K limit. Currently the cycle time is limited by the measurement speed of sensors. Uncooled thermal sensors with a reasonable detection wavelength in a range of λ=8-14 µm (Wavelength of the laser irradiation λ=980 nm) are capable of acquiring data with a refresh rate of about f=100 Hz. Thermal imaging cameras are ranging at about f=70 Hz while having the advantage of enhanced process control and inspection capabilities due to digital image processing [9].

2.2. Challenges of processing multi-material components with automated tape placement

While processing of CFRTP tapes on thermoplastic-based substrate materials (e.g. other tapes) is state of the art, the challenge presented in this paper is the placement onto metal surfaces. As depicted in Fig. 2, a laser beam focused partly onto the incoming tape and party onto the substrate around the nip-point is a standard application in a laser assisted ATP process [13]. Heat absorption, emissivity and heat dissipation of sheet metal materials need a new approach during the direct joining process.

3. Experimental setup and methodology

During the initial process study, only qualitative tests have been made. Mechanical peel tests resulting in quantitative results will be made in the near future, as there was only a small number of samples available for testing.

3.1. Heating strategy for heating up the metal

Using a laser assisted ATP process as depicted in Figure 2 is not suitable for heating up the metal substrate. The angle of the laser irradiation as well as the intensity and time could not be handled, as either the substrate was to cold or the tape was degraded due to high temperatures. Thus, the heating of the metal substrate needs to be decoupled from the heating of the incoming tape. A feasible solution is to use two heating sources as depicted in Fig. 3.

Two single VCSEL units will be integrated into the modular ATP head. One will be used to heat up the incoming tape around the nip-point while the other one heats up the metal substrate materials. The first trials have been made on a heated mould using Fraunhofer IPT's Multi-Material-Head [13] with a diode laser (Table 1) for heating the tape.

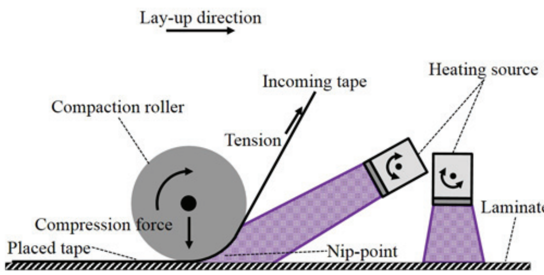

Fig. 3. Two separate heat sources within an ATP head.

For those trials, structured metal samples made of USIBOR were put onto a heated mould (Fig. 4). The fixation was done with an adhesive polyimide tape.

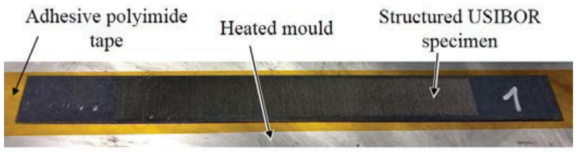

Fig. 4. Metal sample on heatable mould.

3.2. VCSEL

Figure 5 shows one of the VCSEL units to be used in the modular ATP head. One advantage of the VCSEL is the spatial control of the laser emission, as a VCSEL is made of several line arrays of micro laser diodes and each line arrays can be controlled independently. This way heating profiles can be arranged during a process.

Currently the modules are being integrated into a laser test bench, to make first process studies to obtain process parameters and geometries for the realization of the modular ATP head. Table 1 contains the technical specification of the VCSEL modules.

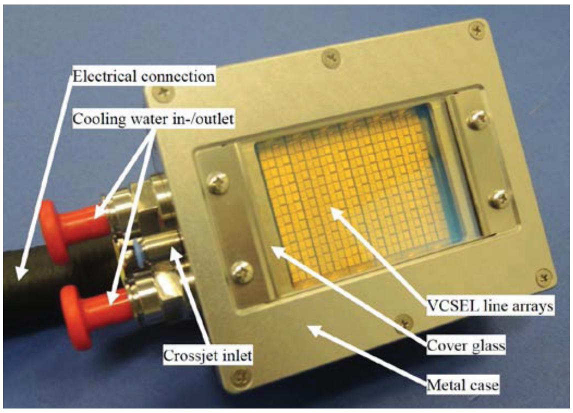

Fig. 5. VCSEL unit of the modular ATP head.

Table 1. Laser parameters of VCSEL and diode laser system.

VCSEL	Value
Manufacturer	Philips
Wavelength λ	980 nm
Number of emitters/emission zones	6 / 12
Spot size in focal plane	52 x 40 mm²
Power (max.)	2.400 W
Diode laser system	**Value**
Manufacturer	Laserline
Wavelengths λ	910 nm, 940 nm, 980 nm
Spot size in focal plane	32 x 67 mm²
Power (max.)	3.300

3.3. Enhanced process control system

In order to be able to control all of the process parameters, a modular process control system was developed. While the control of parameters like the tape tension or the compression force onto the roller can be controlled easily using fuzzy-logic or PID-controllers, the control of the process temperature is more difficult, as very fast response times and are needed. Especially if thermal imaging cameras are used, many information can be gathered by utilizing digital image processing. Fraunhofer IPT developed a software for capturing and processing digital images for controlling a laser-assisted ATP process. The software is written in C++ and uses a multi-threaded approach utilizing the C++11 parallelization capabilities. One thread is used for the communication with a thermal imaging camera, a second thread is used for data storage, a third thread manages the communication with the Beckhoff based PLC of the ATP head via ADS and a fourth thread does the digital image processing. The camera communication software module implements interfaces to different camera manufacturers with proprietary Ethernet interfaces or GigE Vision. The image processing is done by using image processing libraries like openCV [17] utilizing NVIDIA CUDA parallel computing [18].

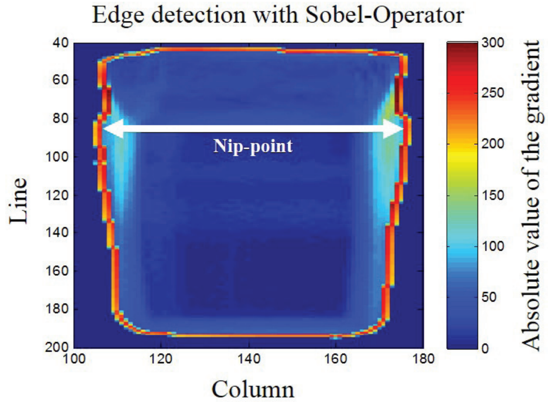

Fig.6. Detection of the position of the nip-point.

The process control software is used to acquire relevant process parameters like the temperature in the most relevant spaces, the position of the nip-point (Fig. 6) or the homogeneity of the heating. The temperature is then used to control the laser power accordingly using for instance a fuzzy-based PID controller. As the control system is build on a modular basis, depending on the process, various acquisition and control systems can be used.

3.4. Materials and process parameters

For the first trials a batch of 20 sheet metal pieces was available for process evaluation. The material properties are shown in Table 2.

Table 2. Sheet metal parts used during first process trials.

Material	USIBOR-1500
Width	30 mm
Length	300 mm
Width of structured area	26 mm
Length of structured area	200 mm
Depth of structure	~150 µm
Width of single structure	~30 µm (Top), ~50 µm (Bottom)

The properties of the tape used in the first process trials are summarized in Table 3.

Table 3. Tapes used during first process trials.

Property	PEEK-CF	PA66-GF
Supplier	Suprem	Celanese
Polymer matrix	PEEK	Polyamide 6.6
Reinforcing fiber	AS-4	E-Glass
Fiber volume content $F_{vol.\text{-}\%}$	60 vol.-%	39 vol.-%
Tape thickness d_T	0.15 mm	0.28 mm
Tape width w_T	25 mm	25 mm
Processing temperature T_P	370°C	290°C

The parameters used for the ATP production systems are depicted in Table 4. For each trial, a single layer of tape was placed onto the metal specimens, as the goal was to observe the qualitative bonding strength between metal and CFRTP.

Table 4. General process parameters.

Parameter	Value
Tape speed	150 mm/s
Compression force	150 N
Tape tension	2 N
Laser power	2200 W
Laser angle	-1.5°
Tape temperature	370°C (PEEK), 290°C (PA6.6)

Table 5. Aluminum mould used for process trials.

Parameter	Value
Material	Aluminum, flat, sanded
Length	1.540 mm
Width	540 mm
Heating zones	3, evenly distributed
Maximum temperature	450 °C

Before processing, the sheet metal specimens are fixed onto a flat aluminum mould that can be heated (Fig. 3). The parameters of the mould are listed in Table 5.

3.5. Results of PEEK-CF tape on USIBOR specimen

Starting the trials with the PEEK-CF tape (Table 3) lead to a rather weak bonding between the tape and the metal specimens. The small tape thickness of d_T=0.15 mm together with the high fiber volume content of $F_{vol\text{-}\%}$=60% and a very even fiber distribution leads to a very low amount of matrix material on the outside of the tape. Tests show that the metal structure imprints into the tape but the matrix on the outside is not enough to fill the cavities in the metal and to achieve a mechanical interlock [14].

3.6. Results of PA66-GF tape on USIBOR specimen

To overcome the limitations of the PEEK-CF tape with a very high fiber volume content, a second tape was considered for testing (Table 3). Regardless of the fiber, a very matrix rich PA66-GF tape with a rather low fiber volume content of $F_{vol\text{-}\%}$=39% was chosen. First trials with varying process parameters have been carried out. The general process parameters (system specific) are listed in Table 3. The qualitative results are depicted in Table 6.

Table 6. Qualitative Bonding Quality (Scale: --, -, o, +, ++)

Surface temperature of the metal	Bonding quality
22°C	--
75°C	--
150°C	O
160°C	O
170°C	+
180°C	++
190°C	++
200°C	+

As the number of specimens was not sufficient for statistical evaluations, the bonding quality was rated with manually peeling of the single tape of the metal specimens.

3.7. Interpretation of results

As long, as the metal surface is too cold, the heat from the tape dissipates too fast before the matrix can flow into the structured cavities in the metal surface. As the temperature raises, the bonding gets better up to a temperature between T_M=180 °C and T_M=190 °C. At temperatures above T_M=200 °C another effect was observed. The thermoplastic matrix did not cool down fast enough after placing it on the metal, resulting in a still molten matrix after the process was finished. Cutting the tape with a pneumatic driven knife induced a jerk of the tape that was high enough to shift it for some mm at the surface. Nevertheless, longer part geometries could work better, as the matrix may have longer time to flow into the cavities.

4. Conclusion and Outlook

This paper presented an overview on the goals of the ComMUnion project regarding laser assisted automated tape placement of CFRTP tapes onto structured metal surfaces. Results have shown, that the metal area where tape is to be placed onto needs to be heated up in order to achieve a mechanical bonding between the two materials. A qualitative process study highlights the bonding quality between metal and tape under different temperature conditions.

In a future work, more specimens for mechanical mandrel peel tests will be made and tested in order to quantify the influence of the metal surface temperature on the bonding strength. Trials using two VCSEL heat sources will be done in the future in order to substitute the heated mould and to enable for more efficient and faster processes.

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