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Increasing cost and eco efficiency for selective tape placement and forming by adaptive process design

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Abstract

The automated placement of continuous fiber-reinforced polymer prepregs (pre-impregnated) is a generative manufacturing technology for composites. Particularly laser-assisted tape placement of unidirectional continuous fiber-reinforced tapes provides potentials for highly flexible composite manufacturing. Whereas the single process of tape placement to generatively build up load carrying structures was already optimized in several research activities and projects, an integrated process chain approach promises further increases in cost and eco efficiency. An adaptive process design considering interdependencies between selective tape placement and a subsequent forming improves the entire process chain. Due to the knowledge of process interdependencies, the advantages of high speed placement on predetermined load carrying areas can be fully exploited. The system and process design for this adaptive manufacturing approach, the underlying assessment methodology as well as its application on a manufacturing process chain for structural composite parts are presented in this paper.

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Keywords: Selective high speed tape placement; laser-assisted tape laying; cost and eco efficiency; generative composite manufacturing; adaptive process design

1. Introduction

A remarkable potential to substitute metal components in engineering applications is provided by the use of continuous fiber-reinforced composites with a polymer matrix [1]. Continuous fiber-reinforced composites with thermoplastic matrix materials offer the ability to shape complex parts, the possibility for recycling and the opportunity to join them with thermoplastic parts due to their re-melting capabilities. These characteristics and the degree of freedom to combine novel composite manufacturing technologies with conventional thermoplastic plastic processes increase the attraction to apply these cost-intensive materials in high volume production for automotive and aerospace industries.

One remarkable process combination which offers the potential to be affordable for mass production is tailoring thermoplastic based substrates which combines the flexible composite production process of selective tape placement of unidirectional (UD) continuous fiber-reinforced thermoplastic prepregs (*pre*-im*preg*nated, *short:* tapes) with a highly productive shaping process like thermoforming [2, 3]. Thus,

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hybrid structural or semi-structural parts with the optimum performance, weight and cost profile can be produced.

Distinguished by the process and material properties the combination of shaping and selective application of tape offers a high degree of freedom to tailor the entire process chain. The shaping step of the substrate can either be used as primary shaping process followed by a tape placement process which reaches so-called in-situ consolidation [4,5] or as follow-up process enabling a faster application of tape due to post-consolidation [2,6]. Precisely these possibilities of adaptivity of the process chains without the need for major additional investment facilitate the manufactures to adjust their production depending on part complexity, design and batch size. In this way the most cost and eco efficient production strategy for the part can be realized.

The aim of the present work is to evaluate the reachable consolidation qualities of both process chains to prove that an adaptive process chain is applicable without the loss of product quality and performance. This is done by showing that the combination of fast lay-up and post-consolidation by reshaping increases the mechanical properties of a substrate in a comparable range like standard laser-assisted tape placement achieving in-situ consolidation. At the same time, it will be shown that manufacturing costs and ecological impacts will decrease for fast lay-up strategies.

Such an evaluation of adaptive process chains requires a multi-criteria evaluation as both ecological and also economic performances are important and relevant for stakeholders, legislations and decision makers whether isolated or in combination. Therefore, a software-based multi-criteria assessment is applied on this composite manufacturing chain.

Both, the process technologies as well as the underlying assessment methodology were developed in the EU-FP 7 framework research project Stellar: "Selective Tape-Laying for Cost-Effective Manufacturing of Optimised Multi-Material Components".

Nomenclature

ATP	automated tape placement
E_f	flexural modulus
EoL	End-of-Life
EU	European Union
FP 7	Seventh Framework Programme for research, technological development and demonstration
F_{roller}	consolidation force (tape placement)
F_{tape}	tape tension force
F_{TF}	consolidation force (thermoforming)
G	shear modulus
g	gauge length
GUI	Graphical User Interface
GWP	Global Warming Potential
h	specimen height
ILSS	interlaminar shear strength
KPI	Key Performance Indicator
l	specimen length
l_{tape}	tape length
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MFCA	Material Flow Cost Accounting
ODP	Ozone Depletion Potential
P_L	laser power
PA6	polymer polyamide 6
PED	Primary Energy Demand
t	specimen thickness
T_m	heating plate temperature
T_{optics}	optical cooling temperature
T_{plate}	surface temperature of molds
$T_{process}$	process temperature
ΔT	temperature difference
TF	thermoforming
UD	unidirectional
v_p	process speed
w	specimen width
φ_{laser}	laser irradiation angle
σ_{fm}	bending strength
τ	interlaminar shear strength

2. Research background

2.1. Selective tape placement

In order to establish a cohesive bond between both joining partners, the process of automated tape placement (ATP) for UD continuous fiber-reinforced tape uses the application thermal energy by using irradiation of a laser [7] or a different heat sources like hot gas torch [8] to heat up the incoming tape and substrate material while a consolidation roller applies pressure to generate the required intimate contact.

The selective placement of cost-intensive high performance tapes onto pre-determined areas of a thermoplastic based substrate with optimal fiber orientation prior to or after shaping operation offers the opportunity to locally strengthen the load bearing paths of a component to withstand the highest load cases. In this manner, the overall wall thickness of the substrate can be decreased [3, 9]. Additionally Brecher et al. [6] as well as Emerson et al. [10] describe the potential to locally increase the mechanical properties by selective tape placement when using semi-finished parts with comparative low mechanical properties as substrate material.

Thus, tailoring generally offers that composite structures become lighter, show benefits regarding energy efficiency and save costs because of lower material consumption [1].

Grouve et al. [2] already considered that a lay-up process achieving in-situ consolidation is not required, in case a post-consolidation process, e.g. a follow-up reshaping operation like thermoforming, is used. In respect of these findings Brecher et al. [6] aimed to speed up the lay-up process during the selective tape placement in order to achieve a higher material throughput, assuming that such a fast tape placement process would require a process chain including a follow-up process.

The present work builds on these investigations and evaluates the mechanical, economic and environmental properties of a random fiber-reinforced low performance substrate which is selectively reinforced with tape in order to demonstrate that those adaptive process designs can be beneficial.

2.2. Multi-criteria evaluation of process chains

There are various methodologies for evaluating and analyzing process chains and corresponding products in terms of economic or ecological-focused KPIs. Those methods are mostly scalable and able to assess the entire life cycle of a product system (including material extraction, production, usage and End-of-Life (EoL)) or focusing on specific life cycle phases. For ecological considerations, the Life Cycle Assessment (LCA) according to DIN ISO 14040 is well established [11]. Methods like Life Cycle Costing (LCC) or Material Flow Cost Accounting (MFCA) can be used for evaluating economic KPIs. However, distinctions of those methods are blurring [12, 13]. For performing structured multi-criteria evaluations, research was performed to integrate ecological and economic goal dimensions in general integrated approaches [14] also in the context of composites and generative technologies like tape placement [15]. The latter one is the basis for the software-based evaluation applied on the tape placement and forming presented in this paper.

3. Experimental setup and methodology

3.1. Materials

Driven by the idea to enable the introduction of thermoplastic composites into mass market applications like the automotive industry, substrate materials and tapes with a technical polymer polyamide 6 (PA6) as matrix material were chosen. Due to its potential to be applied to automotive applications such as bumper systems, large structural parts or flow molding structures, a black colored, t = 1,5 mm thick substrate material, reinforced with randomly orientated chopped glass fiber rovings (47% fiber volume fraction), was chosen. This substrate material has a flexural modulus of E_f = 11,14 GPa, determined according to DIN EN ISO 14125 [17], and an average apparent interlaminar shear strength (ILSS) of τ = 28,68 N/mm, determined according to DIN EN ISO 14130 [17] on a ZWICK/ROELL Z250 material testing machine.

For selective placement, unidirectional carbon fiber-reinforced tapes, sourced from CELANESE containing a carbon fiber volume content of 49% (type CELSTRAN PA6-CF60) and sliced to a width of w = 12 mm, were used. According to the data sheet provided by the supplier, the flexural modulus of this UD tape is E_f = 64 GPa.

3.2. Process descriptions

For the experimental work described in this paper, a single tape with a length of l_{tape} = 250 mm was placed on one side of the randomly glass fiber reinforced substrate by using the laser-assisted tape placement system *Multi-Material-Head,* which was described by Brecher et al. [18]. To evaluate specific differences concerning mechanical performances for in-situ respectively post consolidated tape on the selectively reinforced part of a component, the tape has been placed with different process speeds of v_p = 200 mm/s, 600 mm/s and 800 mm/s.

Process parameters were set according to Table 1. Whilst the laser irradiation angle was set to -1° to achieve a homogeneous heating of tape and substrate close to the nip-point, the constant laser power value was pre-determined to reach the process temperature of approximately $T_{process}$ = 240-260°C. The heating plate temperature was determined following the findings of Steyer [19] with a temperature difference of ΔT = 30 - 60 °C above the glass transition temperature of the substrate polymer.

Table 1: Process parameters for selective tape placement

Process parameter	Value		
Process speed v_p	200 mm/s	600 mm/s	800 mm/s
Laser power P_L	1400 W	2400 W	2800 W
Laser Irradiation angle φ_{laser}		-1°	
Heating plate temperature T_m		120 °C	
Consolidation force F_{roller}		150 N	
Tape tension force F_{tape}		0 N	
Optical cooling T_{optics}		23 °C	

Specimens of test series produced with v_p = 600 mm/s and 800 mm/s were taken after selective placement of tape and put into a thermoforming (TF) test rig, shown in Fig. 1.

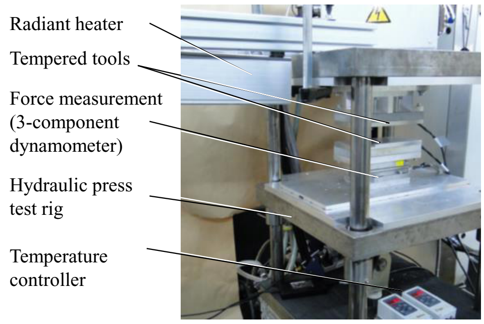

Fig. 1. Thermoforming test rig

In this test rig the specimens were heated up to process temperatures of $T_{process}$ = 240-260°C using a short wave infrared emitting radiant heater. The temperature was measured in the joint between tape and substrate. Therefore, a thermocouple was laminated in this contact during placement. Further process parameters were kept constant (see Table 2).

Table 2: Process parameters for subsequent thermoforming

Process parameter	Value
Average consolidation force F_{TF}	150 N
Average surface temperature of molds T_{plate}	74,0°C

The typical development of the temperature in the interface between tape and substrate is shown in Fig. 2.

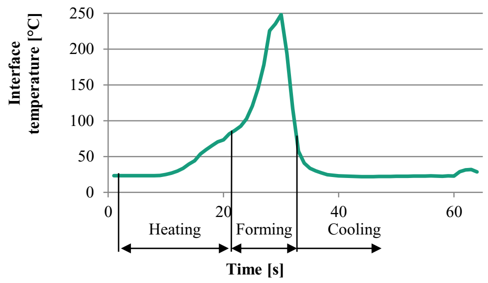

Fig. 2. Temperature development for subsequent thermoforming

Using the presented processes and settings, a fast placement speed combined with a subsequent reshaping operation as well as a direct lay-up on a complex part without subsequent thermoforming can be simulated. Particularly the process chain related influences (technical, economic, and environmental) of the placement process using adaptive process speeds can be investigated.

3.3. Testing

Specimens of following 5 test series were taken and tested using destructive test methods on a ZWICK/ROELL Z250 material testing machine:

- 200: v_p= 200 mm/s
- 600: v_p = 600 mm/s
- 600 TF: v_p = 600 mm/s + subsequent thermoforming
- 800: v_p = 800 mm/s
- 800 TF: v_p = 800 mm/s + subsequent thermoforming

The tests to be carried out were the 3-point-bending test following [16] and the 3-point-bending test on a short beam following to [17] with the aim to evaluate the resulting mechanical properties and the consolidation qualities.

Due to the mixture of materials and due to given thickness of the specimens, the testing dimensions of the specimens were adapted as shown in Table 3. These slight adaptions are tolerable according to Brecher et al. [6].

Table 3: Adapted specimen dimensions for destructive testing

Dimension	Test following	
	DIN EN ISO 14125	DIN EN ISO 14130
Specimen length l	100 mm	20 mm
Specimen width w	12 mm	10 mm
Specimen height h	1,6 mm	1,6 mm
Gauge length g	80 mm	10 mm

3.4. Assessment methodology – cost and eco efficiency

The methodology for multi-criteria evaluation includes economic and ecological KPIs. Economic indicators focus on process costs while ecological indicators have focuses on both, process-related electricity consumption as well as corresponding environmental impacts like Global Warming Potential (GWP). The methodology is based on an integrated evaluation approach developed during the Stellar project [15] and implemented in a corresponding software tool.

The goal of the study is the evaluation of cost and eco efficiency for adaptive process strategies (variation of placement speed) of the selective tape placement. Therefore, corresponding setups and specimens are evaluated in terms of manufacturing process costs, energy demands as well as influences on CO_2 emissions. Process costs are limited to machine costs (overheads), energy and personal costs. Material costs are equal for all settings and therefore excluded. For the evaluation, tape placement of l_{tape} = 250 mm was regarded (w = 12 mm, t = 0,15 mm). Ramp up and waste time (setup, run down etc.) was neglected. Depending on the adapted placements speeds, the cycle time per specimen changes accordingly.

The Stellar software allows direct comparisons of alternative process chain settings and requires several user inputs. Each process is economically characterized on the basis of common MFCA attributes like acquisition costs, maintenance costs, cycle time etc. It is assumed that the production systems are used in a shared utilization achieving an average utilization of 95 % in an industrial scale scenario. Inventory flows like material or energy consumptions are measured and added by specific costs. Ecological background data for environmental impacts of different matrix systems, fiber types, energy or auxiliary flows is embedded in a connected database for quantifying KPIs like Global Warming Potential (GWP; kg CO_2-Eqv.), Primary Energy Demand (PED; MJ), Ozone Depletion Potential (ODP; kg R11-Eqv.) and others. The GUI of the tool is shown in Fig 3.

In order to highlight the process-specific implications and advantages, the multi-criteria evaluation is limited to the manufacturing stage of the specimens. Prior phases (tape and substrate production) as well as subsequent life cycle stages (usage, EoL) are excluded.

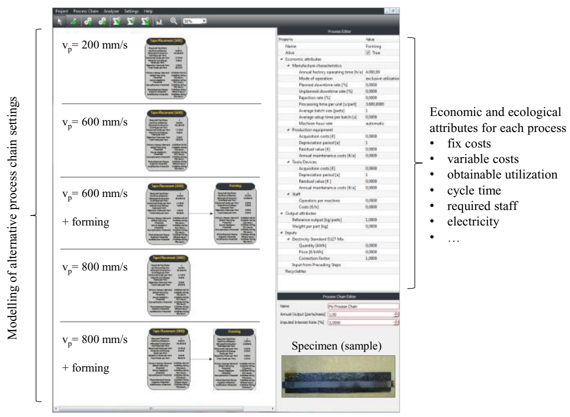

Fig. 3. Graphical User Interface (GUI) for process chain evaluation

For both process steps, relevant electrical consumers were equipped with energy data loggers and the specific power consumption was recorded while processing the specimens. Table 4 summarizes the consumers to be included.

Table 4. Relevant consumers for energetic characterization

Laser assisted tape-laying	Pressing
Laser source	Radiant heater (infrared)
Laser and optics cooling	Hydraulics
Control system	Heating plate (tool plates)
Heating plate/tool	
Robot axis	

The variation of placement speed directly influences cycle times and thereby production overheads and personal costs (fix costs – time dependent) as well as energy costs because of process-independent basic consumptions. The economic impact due to increased process speed (high speed placement) is quantified due to cost savings between the alternative tape placement scenarios, whereas $v_p = 200$ mm/s marks the baseline. Potential improvements for eco efficiency are quantified by process-related energy- and CO_2-savings for high speed placement using the presented software tool.

4. Results and Discussion

4.1. Mechanical characteristics

As Fig. 4 shows, the test results of the 3-point-bending test on a short beam underpin the expected decrease of consolidation quality indicated by a decreasing τ for increasing placement speed. Without the required time for inter-diffusion between molten polymer of tape and substrate at $T_{process} = 260$ °C, in-situ consolidation quality cannot be reached. In case the achievement of fully in-situ consolidation is required for high placement speeds, the thermal energy input needs to be increased drastically and the polymer needs to get overheated. In this case the degradation phenomena of the thermoplastic material needs to be studied in more detail in order to avoid serious damage of the matrices. However, a follow-up forming operation enables to reach as high consolidation quality as an in-situ consolidation does, even if the tape is only tacked to the substrate. The results of the mechanical investigations underpin the idea of an adaptive and high productive process design by confirming the statement of Grouve et al who claimed that the stamp forming process is sufficient to consolidate poorly consolidated thermoplastic components [2].

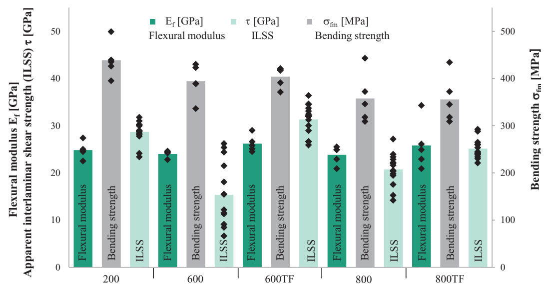

Fig. 4. Analyzed destructive testing results

Indicated by the scattering of the determined measurement values for the ILSS, the conclusion can be drawn that a combined high speed placement and follow-up thermoforming process also shows a much higher process stability than the purely high speed placement process does. Hence reliability in terms of the expected output quality can only be realized if either a slow placement process is used or the high speed placement is combined with a subsequent post-consolidation process

Fig. 4 also illustrates that the consolidation has no significant influence on the flexural modulus. Furthermore, the test results show that the bending strength decreases with an increasing placement speed. However, it needs to be stressed out that during current investigations no optimization has been performed. Further investigations and more measurements need to be carried out to evaluate the bending behavior in more detail.

4.2. Economic and ecological evaluation

In order to investigate potential improvements in terms of cost- and eco-efficiency, specific energy demands for both process steps were measured for the different process settings and differentiated according to the consumers involved. Exemplary results are illustrated in Fig. 5.

As the subsequent and optional forming process was performed in a test rig (lab scale) the specific consumption will differ in an industrial scale. However, it is essential to include this process for evaluating the mechanical performance and thereby showing that high speed placement can be beneficial in case there are subsequent forming processes anyway required in an industrial scale, e.g.

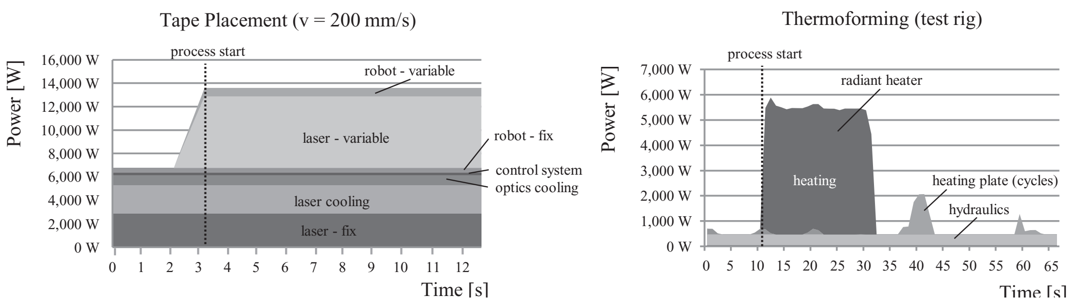

Fig. 5. Power demand while tape placement and forming in test rig

producing functional shapes etc. Main results of the economic and ecological evaluation are summarized in Table 5. The values refer to one specimen as functional unit. Process costs include machine costs (overheads), energy and personal costs.

Table 5: Evaluation for tape placement of one specimen (length: 250 mm)

Placement speed [mm/s]	Process related costs per specimen [€]	Process energy consumption [Wh]	Global Warming Potential [kg CO_2 Eqv.]
200	0,0258	37,8	0,018
600	0,0095	18,5	0,009
800	0,0071	14,2	0,007

Using adaptive process settings with high speed placement, process related costs for tape placement can be reduced by more than 70 % (comparison of v_p = 200 mm/s and v_p = 800 mm/s). Due to dominating fix costs (machine overheads, personal costs), those significant cost reductions can be reached. For all process settings, fix costs contribute more than 70 % to the process related costs.

The specific energy consumption for tape placement can be reduced by more than 60 % (comparison of v_p = 200 mm/s and v_p = 800 mm/s). The proportion of fix energy consumption (cooling, control system, fix demands of robot and laser) is 50 % for v_p = 200 mm/s. For v_p = 800 mm/s, this proportion decreases to 33 %.

The same applies for the process related Global Warming Potential which is a direct consequence of energy consumption. For this eco-indicator, a standard EU-27 electricity mix was assumed.

5. Conclusion

In this work, it could be shown that high speed placement is able to provide significant process-related improvements in terms of cost- and eco-efficiency. In case subsequent forming operations are applied, the adaptive process chain is able to achieve similar mechanical properties to standard and isolated tape placement. High speed placement as an isolated process is not necessarily able to provide sufficient mechanical performance as standard tape placement which ensures proper consolidation.

For many industrial applications, subsequent forming processes are anyway required for adding functional shapes, geometrics or edge finishing. In those cases, adaptive process design for tape placement for increasing process speeds and thereby reducing cycle times is a beneficial strategy for improving overall cost and eco efficiency.

The presented work can be seen as a proof of concept for using adaptive process settings (increased placement speed) for improving economic and ecological characteristics. This proof of concept is limited to pressing of flat plates. Further investigations on specific Use-Cases, including the consideration of interactions when forming complex shapes, should be performed in order to investigate in the suitability of this process chain design strategy for specific industrial applications. In case of required subsequent thermoforming for the specific geometries, the authors recommend to use high speed placement of UD-tapes. If those forming processes are not necessarily required, the potentials of the generative technology of tape placement in terms of flexibility and part design should be fully exploited, although the placement speed needs to be low for ensuring proper consolidation.

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