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COST-EFFECTIVE HIGH SPEED PRODUCTION OF MULTI-MATERIAL COMPONENTS BY SELECTIVE TAPE PLACEMENT

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Summary: *Cost efficient production technologies for lightweight composite components are the key-enabler for a broad application. The use of laser-assisted tape placement in selected locations in existing composite structures provides the production of thermoplastic multi-material composite parts with the optimum reinforcement, weight and cost profile. Enhanced by the new manufacturing process route the weight of components can be significantly reduced as the combination of different reinforcement fibers in one single structure allows the achievement of an optimized relation between performance and weight. This is developed in the European funded FP7 Project Stellar.*

1 INTRODUCTION

Providing excellent weight and mechanical characteristics in combination with high corrosion resistance fiber-reinforced plastic (FRP) composite show remarkable potential for a substitution of conventional materials like metals for many applications. Besides applications for niche markets like specialized sports equipment [1,2], an increased use of FRP structural parts can be found in mass markets like automotive and aerospace industries.

In particular endless unidirectional (UD) fiber-reinforced tape materials allow to design multi-layered laminates and 3D structures with optimized fiber direction tailored to the load. A remarkable potential to manufacture such structural parts shows the automated tape placement process [3]. This process is capable to achieve an in-situ consolidation which does not necessarily require an autoclave post consolidation [3] but requires a sufficient tape quality [4]. Otherwise the tape placement process still often requires a subsequent consolidation step to ensure optimal consolidation quality.

The typical process principle for laser-assisted tape placement is shown in Figure 1. Thermal energy is applied by using irradiation of a laser [5, 6] or a different heat source like hot gas torch [7] to heat up the incoming tape and the substrate material while a compaction roller applies the required pressure.

However, advanced automated manufacturing capabilities cannot supply the required production speeds and the prices for these semi-finished tape materials are too high to be affordable for mass markets. Additionally homogeneous structures made out of impregnated woven fabrics in a thermoplastic matrix, so called organic sheets, using a conventional thermoforming process currently require a uniform blank thickness. As consequence the entire material thickness needs to be designed in order to resist to the highest load even if the location of load is inhomogeneous.

Selective placement of tape onto substrates following the load bearing paths offers the opportunity to enhance the organic sheet by generating a tailored blank for subsequent forming operation. As a result the production of lighter structures can be achieved. Besides the manufacturing process is more energy efficient and enables cost savings as consequence of the decreased material consumption. General investigations in the topic of using the primary process step of automated application of UD-tape onto organic sheets providing a high drapeability for subsequent forming operations have been carried out [8, 9, 10, 11].

Considering further material combinations and the variability of the order of the process steps enable the opportunity for a higher flexibility and give space for the reduction of cycle-times and material costs.

The FP7 project “Selective Tape-Laying for Cost-Effective Manufacturing of Optimised Multi-Material Components (Stellar)” aims at the development of the first manufacturing process route for the production of hybrid fiber-reinforced thermoplastic structures in order to achieve the best composition of costs, performance and weight addressing transportation and aerospace markets.

Aiming at higher cycle times fully impregnated sheets with random orientated fibers embedded into a thermoplastic matrix sourced commercially can be reshaped using the fully exploited thermoforming process. The subsequent selective tape placement onto the formed parts at the load-bearing areas with the optimum orientation aims to increase the component stiffness. Thus the combination of tape placement, being one of the most flexible composite production processes, and thermoforming, being one of the most productive processes, can be realized. This production step requires a full consolidation over the entire applied tape length to eliminate subsequent trimming operation prior to finishing and surface treatment operations.

Furthermore “Stellar” aims at the combination of a high variety of different materials tailored to the engineering application and considers also the process routes of combining random fiber sheets and endless fiber-reinforced UD using laser-assisted tape placement as primarily process step and thermoforming as reshaping step. Thus a high performance component can be produced which provides the fiber orientations according to load cases, and thereby has a high stiffness the needed ductility and the optimum of weight.

A transfer of thermoplastic composites and multi-material systems into major markets also requires material innovations. Within Stellar new tapes and random fiber sheets have been developed that enable constancies in quality and matrix materials.

The present work focuses on the tape placement process for selective reinforcement and for the combination of multi-materials in context of the achievements of Fraunhofer IPT.

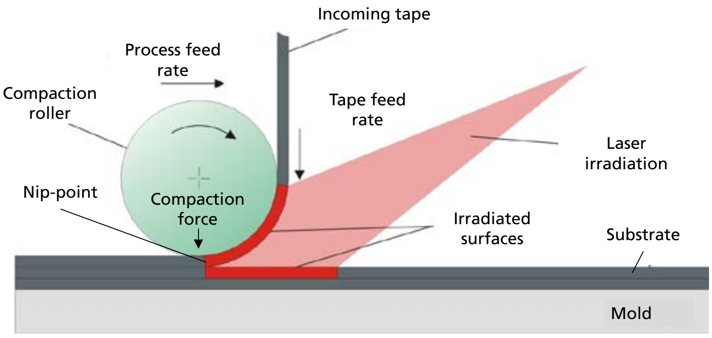

Figure 1: Principle of laser-assisted tape placement.

2 SYSTEM IMPROVEMENT

Based on the intention to selectively reinforce existing components such as thermoformed thermoplastic FRP parts, thermoplastic injection molded parts or various fiber-reinforced blanks prior to forming operations with short cycle times the applied tape needs to be consolidated in-situ over the entire tape length during automated placement. Subsequent trimming operations to cut the non-consolidated beginning and end of an applied tape [12] extend auxiliary process times and make the process inefficient. To overcome these issues a fast cutting unit has been developed and integrated into the current laser-assisted tape placement system »Multi-Material-Head« [13]. Figure 2 shows the guillotine knife principle implemented in the cutting device that enables the compact design and is potentially feasible to cut the tape within milliseconds [14] without clamping and stopping the tape feed. The cutting force is a combination of the pneumatic force and the force resulting from the moment of inertia. Using a pressure of p = 6 bar the cutting force is F_c = 482 N and carbon fiber-reinforced (CF) poly amide 6 (PA6) containing a volume fraction of 49% and a cross-section size of 25 x 0,25 mm² as well as CF polyether ether ketone (PEEK) with a fiber volume fraction of 60% and a cross section of 12 x 0,2 mm² could successfully be cut.

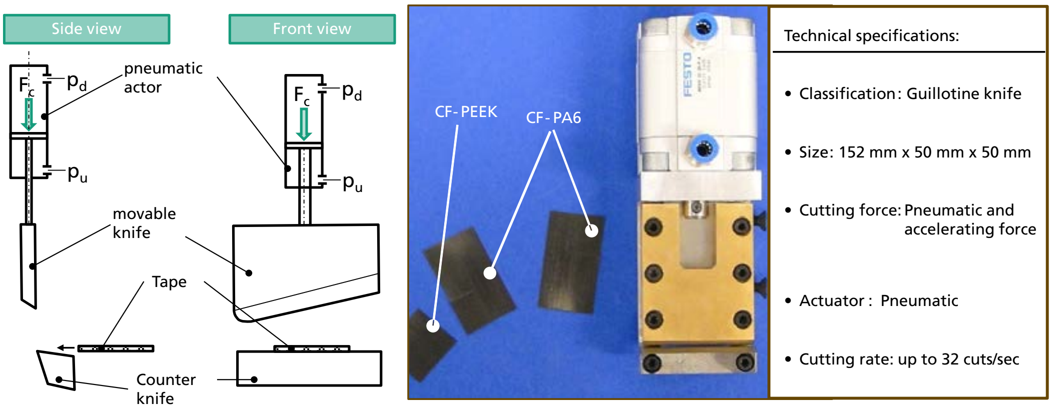

Figure 2: Guillotine cutting principle and technical specifications.

By reduction of the size of the cutting actuator the arrangement of the device inside the tape placement system facilitated the reduction of the distance between cutting point of the tape and the nip-point. Thus the tape length between nip-point and cut end can be irradiated by the laser after cut and a bonding between tape and substrate can be achieved. A qualification of the bond between substrate and cut end using the mandrel peel test [8, 9] still needs to be determined. Various process options like a post-consolidation process using the kinematics of the tape placement system and additional heat input onto the placed end of the applied tape may increase the quality.

3 EXPERIMENTAL

3.1 Influence of ply and amount of selectively placed tape layers

Driven by the intention to produce lightweight vehicles, one random fiber-reinforced substrate and one type of tape both with the technical polymer PA6 matrix were chosen for this study. Because of its potential to replace semi-structural automotive parts [15] 4,2 mm thick, black colored PA6-laminates reinforced with a randomly orientated glass fibers – glass mat thermoplastic (GMT) – supplied by QUADRANT PLASTICS COMPOSITES were used as base material. For the selective placed unidirectional carbon fiber-reinforced tapes sourced from CELANESE type CELSTRAN PA6-CF60 sliced to a width of 25 mm and 12 mm were used.

Following initial results for the combination of materials with completely different optical and thermo-physical properties using selective automated tape placement [8] the process parameter were defined. The closed-loop temperature control was set to desired values between $T_p = 240\text{-}250$ °C whilst the temperature measurement was conducted on the incoming tape as well as on the substrate using single-point pyrometers closely to the nip-point. The mold temperature T_m = 120°C was kept constantly according to [16] with a temperature difference of ΔT = 30 - 60 °C higher than the glass transition temperature of the polymer of the substrate material. The incoming tapes, applied with a process velocity of $v_{process}$ = 150 mm/s were compacted to the substrate using a form flexible compaction roller and a compaction force of F_p = 70 N. All specimens were produced using the »Multi-Material-Head« tape placement head connected to an industrial 6 axis robot and a fiber-coupled 3 kW diode laser source.

The purpose of the stated test series was the examination of the flexural behavior of the substrate material by application of various amounts of plies and different kinds of staggered plies with the use of two different widths of tape shown in Figure 3.

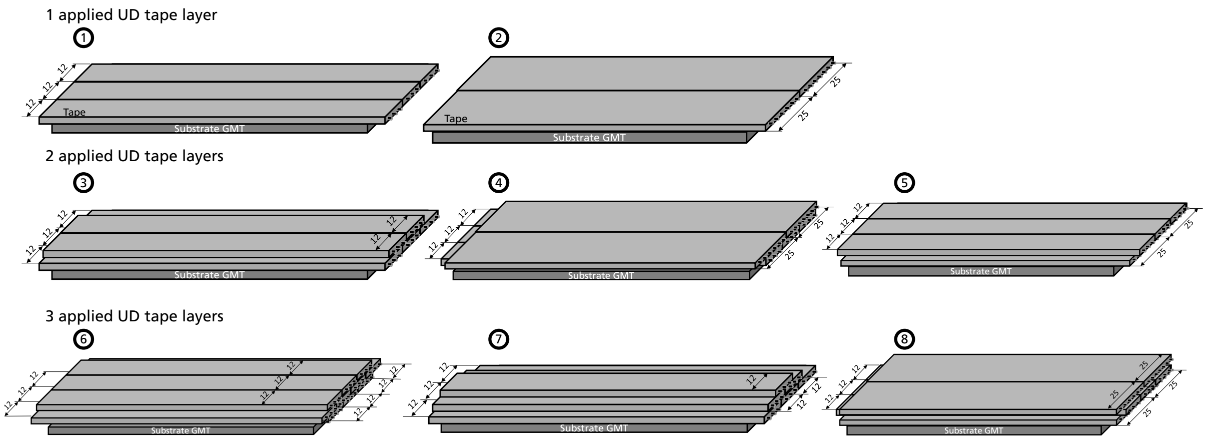

Figure 3: Staggered ply patterns for selective reinforcement investigations.

Testing of the flexural behavior in order to determine the improvement of mechanical behavior by selective reinforcement was done on a ZWICK/ROELL Z250 material testing machine following DIN EN ISO 14125. For testing the specimens were inserted with the UD reinforcement ply on the bottom side in the testing setup to ensure a primary tensile load on the stretched fibers. As the standard only defines dimensions for test specimens out of either

GMT materials or unidirectional composites but not for the combination of both, the specimen dimensions were adapted as stated in Table 1.

	length	width	thickness	Gauge length
GMT according to DIN EN ISO 14125 Class I	80^{0}_{+10}	$15^{0}_{+0,5}$	$4^{0}_{+0,2}$	$64^{\pm1}$
Unidirectional composite according to DIN EN ISO 14125 Class IV	100^{0}_{+10}	$15^{0}_{+0,2}$	$2^{0}_{+0,2}$	$80^{\pm1}$
Selectively reinforced GMT specimens	120^{0}_{+10}	$30^{0}_{+0,5}$	4,2-4,8	100

Table 1: Specimen dimensions for 3-point-bending test

The admissibility for the change of specimen dimensions and its influence during testing were determined by a comparison of measured flexural moduli of GMT using different specimen dimensions, presented in Figure 4.

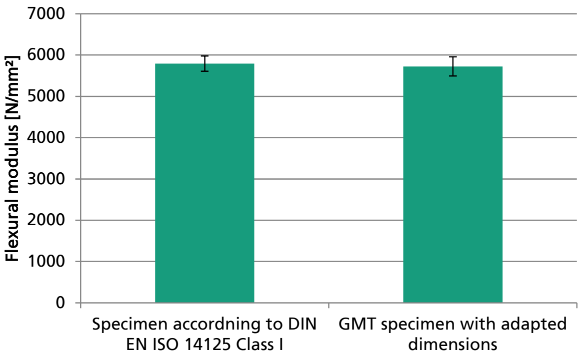

Figure 4: Influence of specimen dimensions on the analysis of the flexural modulus using 3-point-bending test

With respect to the general qualification of the bonding between substrate and applied tape the samples of each ply variation were following DIN EN 2563 test set up. An examination of the interfaces between the substrate and the applied tape was carried out in order to evaluate if the failure occurs in the joining area.

Prior to all testing the specimens, which were produced without focusing on the cut-on-the-fly process, have been manually cut out of slightly lager specimens to a rectangular size with no tape overlap to achieve homogeneous joining quality over the entire specimen and to avoid any edge start/ stop effects during testing.

3.2 High-speed tape placement

Despite outline advantages, drawbacks for a comprehensive use of thermoplastic tape placement are still rather low production speeds when needing a satisfactory consolidation quality [17]. Key-enabler towards a wide spread industrial applicability are higher lay-up speeds of tape with the main aim to increase the efficiency of the process.

Based on the classical reptation theory [18], the concept of bonding between tapes or tapes and substrate involves the stages of intimate contact, molecular diffusion and consolidation. The intermolecular diffusion (reptation, autohesion or healing) will only occur where the intimate contact is achieved. As the diffusion rates increases with increasing temperature the bonding strength of two placed tapes also increases with an increased thermal energy input applied by heating source [19]. Thus an increase of process speed would lower the welding time and would require a higher energy input by the laser irradiation to achieve a comparable bonding strength. However, the material dependent reptation and system limitation, like available laser power, currently limit the achievable placement speeds for the production of parts with high bonding strengths.

The outlined reptation theory and the stated limitations in the achievable bonding strength by direct tape placement, point to the conclusion, that once the placement process is used as a primary process for selective reinforcement with a subsequent forming operation a high bond strength is not necessary. The additional heat treatment of the component, including the joining area between tape and substrate combined with the forming pressure can lead to a post-consolidation and a high bonding strength.

In light of this context the high speed processing of carbon fiber reinforcements tapes sourced from CELANESE type CELSTRAN PA6-CF60 sliced to a width of 12 mm has been investigated. Two tapes were placed onto each other with various process speeds ($v_{process}$ = 500 mm/s, 650 mm/s, 750 mm/s and 850 mm/s) with the aim to evaluate the increase of speed in terms of system limitation of the system described above. The mold temperature was kept constantly at a value of T_m = 120 °C. The incoming tapes were compacted together using a compaction force either of F = 0 N or 50N. Set values for process temperature ranged from T_p = 220 – 280 °C.

The produced specimens were tested using a wedge peel test in the ZWICK/ROELL testing machine like shown in Figure 5. During this test the specimens were pulled over a steel blade with the constant velocity of v_{peel} = 15 mm/min. The steel blade slides between the bonded tapes and splits the bond by initiating a crack and propagating this crack.

The measured force, captured during pulling the tape over the blade, characterizes the bonding between the tapes. For evaluation of the bonding strength and thereby the process parameters only the average force in the range of crack growth, starting at a predetermined measurement length of 50 mm was evaluated.

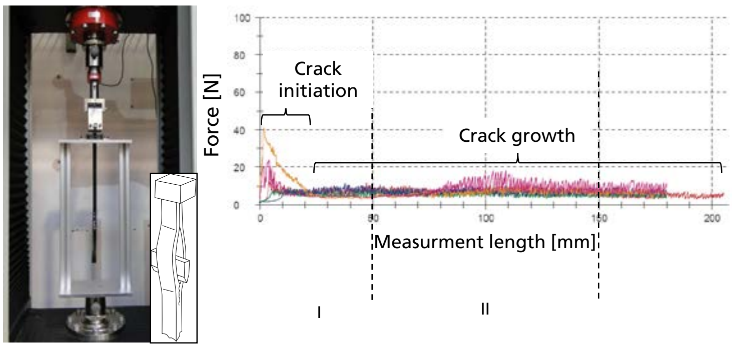

Figure 5: Wedge peel test set up.

4 RESULTS & DISCUSSION

3.1 Interlaminar shear strength

All tested GMT specimens providing selective unidirectional tape reinforcements are characterized by a sufficient bonding strength between substrate and tape respectively between the tape layers. Failure that appears during testing using the short beam test is mainly a material failure inside the GMT substrate by shearing of the polymer or sole failure of the sample under tensile load. Simple interlaminar shearing off of the tape layers only can be observed at one specimen. Hybrid failure which indicates a combination of interlaminar shearing of the tape layers and failure under tensile load can be observed at additional samples with attached tapes.

The interpretation of the failure behavior of the specimens under load, as Figure 6 highlights, indicates that the bonding between substrate and tape using the outlined parameter is sufficient for a selective reinforcement. Failure occurs mainly in the substrate or in the entire specimens under tensile load. Thus the overall strength of the specimen is lower compared to the interface bonding strengths generated by laser-assisted tape placement. Hybrid failures are distributed unsorted within the tested specimens using different ply pattern and do not allow reliable conclusions about the interactions of failure mode and ply pattern. A quantification of the increase of apparent interlaminar shear strength (ILSS) by selective reinforcement is not carried out in this work as the mode of failure in GMT and in selectively reinforced GMT is in the majority of cases different.

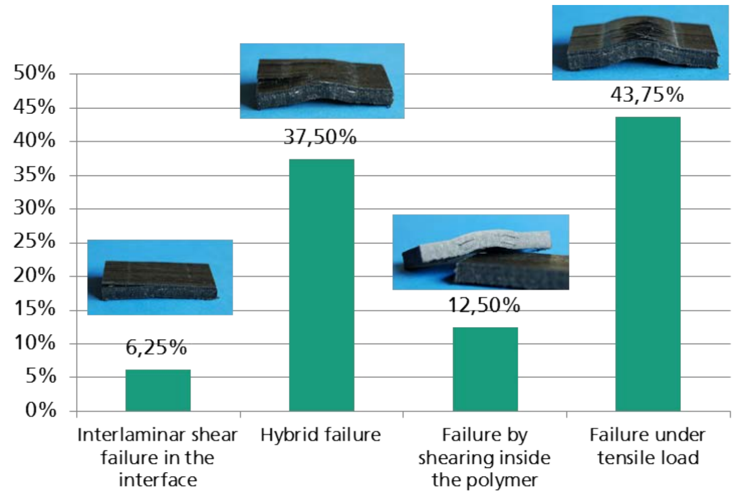

Figure 6: Histogramme of occurring failure modes by ILSS testing of selectively reinforced GMT

3.2 Bending behavior

As displayed in Figure 7 (left) the test results show that the application of unidirectional reinforced tapes on the bottom side (tensile load) of the random fiber-reinforced GMT results in a significant increase of the average flexural modulus. This increase follows a degressive course with the increasing quantity of applied layers. Caused by the completely different anisotropic characteristic between the GMT and the UD tape in combination with the load condition of the 3-point-bending test as well as the differences in the mechanical material values the linear rule of mixture does not describe this increase.

The influence of pattern and the used tape width was analyzed using the statistical hypothesis of t-distribution with a significance level of 5%. Hereby it was proven that all - the size of the used tape widths, the combination of these and finally the configuration of the two tape width inside the several plies - have an significant influence on the flexural modulus. In consideration of the standard deviations those specimen on which wider tapes at least in one of the plies were applied, provide a higher flexural modulus than the specimens with selective reinforcement structures containing only narrow tapes. An essential influence of the order of the layers consisting of wide tapes and layers consisting of narrow tapes, in case both are being used, on the flexural behavior cannot be identified as only specimen with ply pattern 4 and specimen with ply pattern 5 can be compared among one another.

However these influences, like the use of wider or narrow tapes, are minor compared to the influence on the increase of the flexural modulus by the increase of the applied quantity of additional tape layers.

The high stiffness of the brittle carbon fibers inside the selectively applied UD tape in combination with the high fiber volume fraction of these tapes lead to a reduction of the elongation at break compared to the one of GMT in case only a single tape layer is applied, Figure 7 (right). With the increased number of additional tape layers the elongation at break increases. This observed characteristic might be traced back to a deconsolidation at a certain number of applied layers under bending load. Thus the applied tape layers can move against each other resulting in a higher elongation at break. *Holschuh et al* confirm this phenomenon of deconsolidation with an increasing amount of tape layers during 3-point bending test [11].

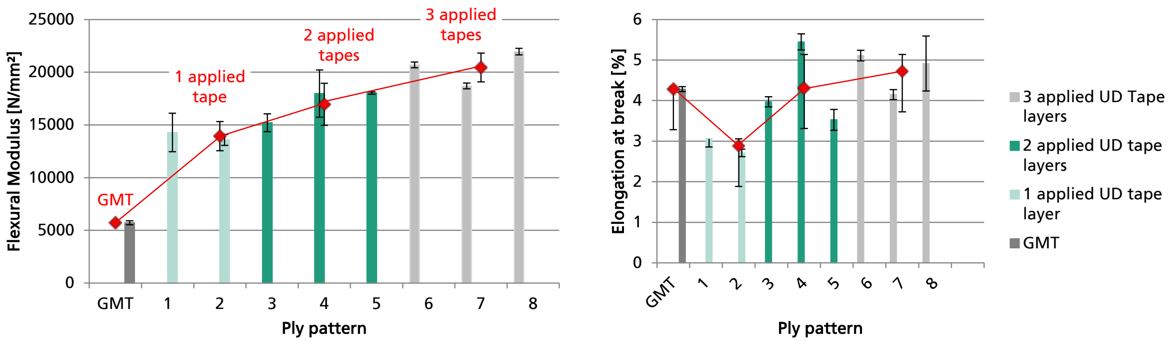

Figure 7: Analyzed results of 3-point-bending test following DIN EN ISO 14125

3.2 Wedge peel test of high speed tape placement specimen

As Figure 8 shows the measured peel resistance tends to decrease with an increase of the placement velocity. The lower values of the specimens produced with a velocity of $v_{process} = 750$ mm/s and $v_{process} = 850$ mm/s can either be induced by an insufficient thermal energy input as the laser power and thereby the irradiation intensity at a fixed rectangular focal spot size is limited or be caused by the insufficient time for autohesion for the polymer PA6. Nevertheless even these low peel resistance and thereby low consolidation quality may offer a sufficient condition for the formation of a good consolidation after subsequent forming operation. For enabling a post-consolidation by heating and press-forming both the surface of the tape and the surface of the substrate need to be molten during tape placement with the aim to achieve a levelling of the roughness asperities. Thus the intimate contact for molecular diffusion can be generated and voids can be prevented. Produced air inclusions in the joint between tape and substrate during tape placement cannot necessarily be corrected during a subsequent forming.

Overall the peel resistance values for process velocities of $v_{process} = 500$ mm/s and $v_{process} = 650$ mm/s are higher compared to the values *Holshuh et al* achieved for selective reinforcement of woven PA6 organic sheets [11]. Thus by the improvement of the closed-loop temperature control the possibilities of high speed in-situ placement with process velocities up to $v_{process} = 650$ mm/s could be established.

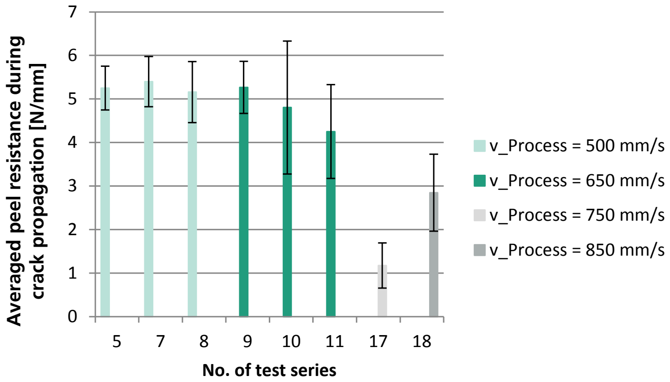

Figure 8: Best practice peel force values during crack propagation standardized to tape width for different process velocities

9 CONCLUSIONS

In the paper the influences of selectively placed unidirectional reinforced tapes onto random fiber-reinforced thermoplastic substrates using in-situ tape placement were examined.

The increase of the flexural properties of the random fiber-reinforced substrate material can be achieved, although a degressive correlation between the quantity of applied layers and the increase of flexural modulus exists. Based on the present investigations the widths of the applied tapes as well as the ply pattern have significant influence on the flexural behavior. An initial assessment of these influences allows drawing the conclusion that the use of wider tapes for selective reinforcement is preferable compared to the use of narrow tapes. Limitations for this statement and interactions between the tape width and the ply pattern still need to be examined more in detail.

It could also be shown that the elongation of break is affected by selective UD reinforcements. A typically decrease of this characteristic by the application of one UD tape layer could be detected caused by the high fiber volume fraction and the brittle characteristic of the carbon fibers. The assumption of *Holschuh et al.* considering deconsolidation effects with an increasing number of applied UD layers [11] under bending load could be also observed within the present study.

The possibilities of the increase of in-situ tape placement speed up to $v_{process} = 650$ mm/s using an improved temperature control architecture could be shown. In combination with improved system technology a fast economic selective reinforcement of existing component process with short cycle times and the reduction of auxiliary process time are given. The ability for general joining of the tape by laser-assisted tape placement using process speeds up to $v_{process} = 850$ mm/s has been proven. In further investigation it needs to be proven whether this joint is sufficient to achieve an adequate consolidation in a subsequent forming process. In this case the laser-assisted tape placement enables an efficient opportunity for tailoring substrate materials for the manufacturing of formed parts with the best composition of costs, performance and weight.

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11 USED MATERIALS

Substrate		QUADRANT PA-GMT / EP589-4
Fibers		randomly oriented glass fibers
Matrix		Poly amide 6 (PA6)
Laminate thickness	mm	4,2
Area weight	kg/m²	5,63
Fiber content	%	30
Density (Laminate)	g/cm³	1,34
Density (Molded)	g/cm³	1,35
Tensile Strength (23°C)	N/mm²	84
Tensile Elongation at Break (23°C)	%	2,10
Tensile Modulus (23°C)	N/mm²	5500
Flexural Strength (23°C)	N/mm²	149
Flexural Modulus (23°C)	N/mm²	4400
Tape		CELSTRAN CFR-TP PA-GMT / EP589-4
Fibers		UD carbon fibers
Matrix		Poly amide 6 (PA6)
Tape thickness	mm	0,25
Area weight	g/m²	363
Fiber content	%	49
Density	g/cm³	1,45
Tensile Strength	N/mm²	2050
Tensile Elongation at Break	%	1,65
Tensile Modulus	N/mm²	102000
Flexural Strength	N/mm²	806
Flexural Modulus	N/mm²	6400

Table 2: Material properties according to manufacturer´s data

REFERENCES

[1] J. Z. Zhang, Study on Carbon Fiber Composite Materials in Sports Equipment. *Applied Mechanics and Materials*, Vol 329, pp. 105-108, Jun. 2013.

[2] X. Bai, N. Li, The Application of Carbon Fiber Composite Material for Sports Equipment, *Advanced Materials Research*, Vol 496, pp. 480-483, Mar. 2012

[3] R. Schledjewski, Thermoplastic tape placement – in situ consolidation is reachable. *Plastics Rubber and Composites*, Vol. 38, Issue 9-10, pp. 379-386, Nov. 2009

[4] M.B. Gruber, I.Z. Lockwood, T. L. Dolan et al., Thermoplastic in situ placement requires better impregnated tapes and tows, *SAMPE 2012-Baltimore, MD*, 2012

[5] C. Brecher, A. Kermer-Meyer, D. Werner et al. Customized solutions for laser-assisted tape placement, *JEC Magazine*, No. 76, pp. 70-73, Nov. 2012

[6] C.M. Stokes-Griffing, P. Compston, A combined optical-thermal model for near-infrared

laser heating of thermoplastic composites in an automated tape placement process, *Composites Part A: Applied Science and Manufacturing*, In Press, August 2014
[7] Z. August, G. Ostrander, J. Michasiow, et al., Recent developments in automated fiber placement of thermoplastic composites, *Sampe Technical Conference Proceedings, Wichita, KS*, October 2013,
[8] C. Brecher, A. Kermer-Meyer, H. Janssen et al. Economic production of load-optimized thermoplastic composites, *JEC Magazin*, No. 83, pp. 64-67, Aug/Sep. 2013
[9] W.J.B. Grouve, L.L. Warnet, R. Akkerman, Critical assessment of the mandrel peel test for fiber reinforced thermoplastic laminates. *Engineering Fracture Mechanics*, 101, pp. 96-109, 2013
[10] T. Rettenwander, M. Fischlschweiger, M. Machado et al., Tailored patch placement on a base load carrying laminate: A computational structural optimisation with experimental validation, *Composite Structures* 116, pp. 48-54, 2014
[11] R. Holshuh, P. Mitschang, R. Schledjewski: Controlled influence of component properties using hybrid techniques by combining different lightweight structures, *Proc. 18th International Conference on Composite Materials (ICCM18)*, Jeju, Korea, Paper Th11-2-AF0057, pp. 1-6, August 21-26, 2011
[12] P. Kölzer: Entwicklung eines laserunterstützten Ablegesystems zur lokalen Verstärkung von flächigen Bauteilen mittels Faserverbundkunststoffen. *Tagungsband zu den 10. Karlsruher Arbeitsgesprächen »Produktionsforschung 2010«*. Karlsruhe Germany, Federal Ministry of Education and Research, pp.161-168, Mar. 2010
[13] D.Werner, M. Emonts, Multi-Material-Head, *JEC Magazine*, No.89, pp. 60-63, May 2014
[14] B. Bradley, High-Speed Fiber Placement on Large Complex Structures, *Industry News Thomasnet.com*, May 25, 2011
[15] M. Kurcz, B. Baser, H. Dittmat et al., The Case for Replacing Steel with Glass-Mat Thermoplastic Composites in Spare-Wheel Well Applications, *Proc. of 4th annual SPE automotive composites conference*, Troy, MI, USA, Sept. 14-15, 2004
[16] M. Steyer, Laserunterstütztes Tapelegeverfahren zur Fertigung endlosfaserverstärkter Thermoplastlaminate, *Dissertation RWTH Aachen Apprimus Verlag*, 2013
[17] F. O. Sonmez, M. Akbulut, Process optimization of tape placement for thermoplastic composites , *Composites: Part A*, Vol. 38, pp. 2013–2023, 2007
[18] P. G. de Gennes,Reptation of a Polymer Chain in the Presence of Fixed Obstacles, *Journal of Chemical Physics* 55, pp. 571-579 ,1971
[19] .J.B. Grouve, L. Warnet, R. Akkerman, et al., Weld strength assessment for tape placement, *International Journal for Material Forming*, Vol. 3, Issue 1, pp. 707-710, 2010