Deliverable No.: 1.2

FINAL REPORT

Project number:	686894
Project acronym:	INSCAPE
Project title:	*In situ manufactured carbon-thermoplastic curved stiffened panel*
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Participants:

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AFPisc	Automated Fiber Placement with in situ consolidation
D	Deliverable
WP	Work Package

1. Preface

Main target of Project INSCAPE is the technology demonstration by the manufacture of a curved stiffened panel by the selected and further developed AFPisc process.

This final report is a composition of two major parts: the first reflects the Part B (Periodic Technical Report), the second summarizes the published projects outcomes as presented at SAMPE conference 2018 in Southampton.

Additional reports are available, but limited to project consortium access. The overview of available reports and deliverables is given above in the list of Referencing Documents.

2. Periodic (final) Technical Report – Part B

2.1. Project Objectives

The objectives defined within the DoA at project start are listed and compared to the achievements at project closure.

- Objective as defined
  - Objective as achieved

Technical objectives:

- Development of a new in situ joining process based on the direct lay-up onto a pre-consolidated laminate to manufacture aerospace structures:
  - The developed process and equipment improvements including machine control strategies were demonstrated within WP5 by technology demonstrator structure manufacturing. Preceding research and development activities are joint within Milestone 5.

- Reduction of investment costs per manufactured part by 30%. Skin to stiffener joint and skin manufacturing will be done in the same lay-up tool with the same machine. The proposed approach promises to produce high performance aerospace structures very efficiently even for low part production numbers. Due to its additive manufacturing approach, the TP-APF process is a very flexible process. A TP-AFP machine can manufacture a multitude of different parts without costly hardware adaption. No autoclave will be needed for thermoplastic composite part manufacturing.
  - The described technological approach was demonstrated, but is not quantified in terms of cost reduction. No industrialized approach was applied to the supporting processes like stiffener trimming. Manual trimming operation and fit to layup mould was feasible for technology demonstration, but has shown deviations in terms of accuracy and of course productivity, typically achieved by well-established processes like NC machines. Even the technological principles could be demonstrated, the maturity and process robustness is not at the expected level. Local defects and insufficiencies in the material consolidation requires further development activities to boost the material and component quality to the required aerospace expectations. A cost assessment without comparable or similar component properties was therefore not performed; layup rates and material quantities used are given for correlation of the today's process performance.

- Weight reduction by 20% of final integrated structure compared to state of the art joined panels (with mechanical fasteners) due to fully integrated structure design.
  - The elimination of fasteners could be shown. A stress verification of a baseline component design and the new in situ manufactured component was not part of this project, but would be required for quantification. Before doing that, the performed material testing campaign has revealed insufficiencies in material performance which are opposed to the defined weight reduction target. A material optimization program would be required first before comparison of different design approaches. A test campaign, not only on coupon level, could be feasible.

- Previous projects of TUM proved a lay-up rate of more than 3 kg/h, which is equal to state of the art prepreg hand lay-up. However no further processing, e.g. vacuum bagging and curing is necessary for the TP-AFP process. Additionally no assembly process is needed for INSCAPE's approach. Therefore INSCAPE aims for an overall reduction of manufacturing time of 50%.
    - The equipment developed is capable for the nominal layup rate of 3kg/h and higher. Reduction to ½" instead of 2" wide operation as well as high complexity with local reinforcements reduces this potential. Topics belonging material quality and performance as well as need for high design complexity concurs with the target of fast production. The potential of manufacturing time reduction could be demonstrated, but further detailed material & process development is required to exploit the technological approach on an industrial level

- Reduction of quality assurance procedures. No adhesive joints will be needed in the proposed in situ joining process. This reduces the efforts for preparing the bonding partners for assembly. Also the integrated sensors of the fiber placement machine, e.g. thermographic camera and the recorded robot movement speed will be used for quality assurance (QA). It is expected that this approach can significantly reduce the QA efforts for future aerospace part manufacturing.
    - Integrated manufacturing data gathering was used to show and explain quality issues at the demonstrator structure. The reduced effort for bonding could be proved, even the operation on different substrates makes the AFPisc process much more complex as initially expected. Special and new introduced machine manipulation provides the technology for an automated stiffener integration as demonstrated. In terms of aerospace use, further detailed research and qualification efforts are required for exploitation.

Scientific objectives:

- Parameter study on mechanical and physical properties of in situ placed laminates for aerospace part production (laminate in-plane properties)
    - An intensive material testing program was performed within the project. The expected material performance level was not fulfilled and asks for future material optimization for AFPisc processing.

- Parameter study on mechanical and physical properties of in situ joined structures (inter-plane properties of joint)
    - Mechanical properties were determined within test campaign. The transfer of coupon manufacturing and full scale component manufacturing need to be discussed – testing on subcomponent level is recommended for future activities.

- Methods to influence the draping behaviour of custom blanks during thermoforming
    - The required design complexity could be solved with state of the art approaches. Minor tool improvements were identified to reduce in plane fibre waviness for Omega profiles. The new approach for T-profile manufacturing could be proved.

- Feasibility to integrate lightning protection layer into fibre placement process
    - Due to low material maturity of thermoplastic based LSP material and not expected material behaviour at carbon fibre reinforced tape material, a concentration of activities to the base material was required in the project. The required material development for thermoplastic based LSP material need to be addressed in a decidedly development project.

Ecological objectives:

- Reduction of manufacturing scrap by 15% compared to standard thermoset prepreg part production
  - Reduction is based on tape or fibre placement technology, which provides scrap reduction of more than 50% to prepreg semi-finished products. Minimum cutting length of the process extends the scrap rate, which still remains far below the target of 15% for the skin lamination. Stiffener production, especially Ω-profile forming, requires extended material for processing. Scrap rate was not optimized for these secondary manufacturing steps. The sensitivity analysis of the performed LCA covers theses aspects.

- Out of autoclave manufacturing of high performance composite structures
  - As demonstrated with need for further material performance improvements.

- No need for vacuum bagging and other consumables
  - Tremendous reduction of processing aids were demonstrated.

- Reduction of number of tools required to manufacture a stiffened panel assembly
  - The skin layup mould was used as for assembly, no additional positioning and assembly tools were required.

- Enabling new high performance recyclable thermoplastic polymers with excellent FST properties for future aerospace part production
  - PEEK polymers provide required FST properties and could provide recyclability. Due to missing market accessible recycling possibilities, the LCA don’t count this potential.

- The in situ joining process enables a one material design approach for future aerospace parts. This reduces the part complexity significantly and enables a faster market entry for new materials. Also repairing and recycling of assembly structures can be done more easily.
  - The one material approach was demonstrated within the project. Repair of high temperature polymers need further development activities, since the laser assisted processing is only accessible for in shop repairs. At thin laminates (1 to 3 plies) the low material stiffness complicates the control of fibre alignment.

2.2. Explanation of the work carried per WP

2.2.1. Work Package 1

Work package number	**1**	Start date or starting event:	**M1**
Work package title	Project management		

Objectives

Coordination of the consortium activities, project documentation, dissemination and communication activities.

Summary regarding work progress and objectives

All coordination activities were carried out on EDP services and the WP / Task specific partners. Prior milestones, web conferences coordinated by the TM were carried out.

For data exchange the cloud storage service of the Leibniz-Rechenzentrum is in use (syncandshare.lrz.de).

Deliverables were reviewed in detail by the topic manager, commented and discussed on technical base. After revision and approval the deliverables are uploaded to SyGMa-PPGMS by TUM.

A final presence meeting was held at Airbus Getafe (Spain) on 26th June with presentations focused on WP5 demonstrator manufacturing and processing related topics as well as WP7 material characterization. The results gained were correlated to the machine capabilities and concepts developed in WP3.

Dissemination activities:

- Presentation of the first manufacturing trial, named demonstrator D#0, and project highlights at JEC World exhibition at Paris in March 2018 and both presentations, held several times per day.
- Conference contribution at SAMPE Europe 2018, September 11th-13th, Southampton, UK.
- Second press release by FACC.
- Due to not finally discussed unexpected results within material testing campaign, a presentation and discussion of these results had to be postponed so far.

2.2.2. Work Package 2

Work package number	**2**	Start date or starting event:	**M1**
Work package title	Demonstrator design		

Objectives

The WP address the design of the demonstrator. This includes a consideration of general requirements, a definition of the geometry in accordance with the Topic Manager, a dimensioning of the reinforcement structures as well as a definition of requirements for the lightning protection integration.

Summary regarding work progress and objectives

All major and relevant tasks were closed within the 1st project period. The missing definition and final agreement on material test campaign was implemented to D2.1 General Requirements.

Task 2.1: General Requirements:

The corresponding deliverable 2.1 in DRAFT version was finalized with implementation of the section “Testing”.

Task 2.2 – 2.4:

Closed within 1st period.

2.2.3. Work Package 3

Work package number	**3**	Start date or starting event:	**M1**
Work package title	Manufacturing & equipment concept design		

Objectives

Definition of an overall manufacturing concept. This includes a placement concept under consideration of the enhancement of the lay-up head machine.

Summary regarding work progress and objectives

The activities within WP3 were divided into two sections:

- Head machine design for future processing equipment
- Machine modification for the existing TUM head for demonstrator manufacturing

The second part was kept open for the 2nd period, to address potential modification needs during demonstrator manufacturing. Learnings during technology demonstration were implemented to the Deliverable D3.5 Machine Enhancements. Not all prepared modifications were finally installed to the existing TUM head due to risk mitigation. New aspects were detected by operating the machine on the challenging demonstrator design.

Task 3.1: Overall manufacturing concept development:

The concepts developed and reported by deliverables were discussed with the topic manager, revised and finalized (D3.1 and D3.2).

The documentation of D3.3 Tooling Requirements was finalized and provided to topic manager.

After the first manufacturing trial of the demonstrator structure in WP5 and manufacturing data analysis the need for more advanced machine control was identified. Significant difference in laser power demand especially for first ply placement a newly developed machine control was implemented. The control mechanisms were developed in a parallel national funded project and were firstly applied to a more complex geometry within the INSCAPE project. Controls of the machine are no more solely based on the automatic control and instead are preset in dependency of location. The documentation of this major step, initially not planned for the project, but required to provide the integrated stiffener assembly approach, is included to WP5 and Deliverable D5.1, since the main activities were carried out there.

Task 3.2: Placement concept development:

The activities for D3.5 were reviewed after demonstrator manufacturing in WP5 and closed in the 2nd period.

Task 3.3: Integration concept for lightning protection skin:

The intended fall back solution with paintable LSP layer provided by LORD CHEMICALS couldn’t be applied, since no response of the material supplier were received.
The coatability was tested by a partial paint of the D#0 structure. As expected the positive build strategy provides a higher level of surface waviness compared to negative build strategy. The global

deformation of the panel prevents an accurate surface preparation and evaluation on a coordinate measurement machine. The deformation is of higher magnitude and cannot be compensated by paintable fillers. Conversely, local waviness could be corrected. For the final demonstrator no paint was applied to keep the surface accessible for evaluations.

2.2.4. Work Package 4

Work package number	**4**	Start date or starting event:	**M9**
Work package title	Tool Design & Manufacturing		

Objectives

WP results in the design and manufacturing of tools for the thermoforming process of the stiffener structures as well as for the AFP in situ joining process of the skin laminate.

Summary regarding work progress and objectives

Due to delays in WP2, WP4 was influenced by the project delay. Due to start of activities on preliminary base, no additional delay was generated. All task could be closed, except reporting, which is in review status.

Achievements:
Tool design and delivery for all demonstrator related components in M15 (planned M9)

Task 4.1: First layer adhesion:

Developments were done and described within the 1st project period. The selected concept was pursued in the 2nd phase. The application on the demonstrator layup mould have shown a major unexpected impact. The solid aluminium tool provides a stronger heat dissipation compared to the testing setups used before; the heat transfer between stacked metal sheets seems to be isolating and therefore reducing the required laser power. Additional trials were performed on flat solid aluminium substrates to optimize power settings for demonstrator manufacturing. To avoid insufficient heat power, the change from a 2” wide operation on D#0 to a four times slower ½” wide operation on D#1 was agreed.

Task 4.2: AFP skin tool design & manufacturing:

Since the design and hardware related activities were closed in the 1st period, only documentation work had to be carried out in this 2nd phase.

Deliverable D4.2 was finalized, reviewed and approved.

Task 4.3: Thermoformed stiffeners tool design & manufacturing:

Deliverable D4.3 was finalized, reviewed and approved.

2.2.5. Work Package 5

Work package number	**5**	Start date or starting event:	**M13**
Work package title	Demonstrator Manufacturing		

Objectives

WP contains the manufacturing of the demonstrator

Summary regarding work progress and objectives

Most of project activities of the 2nd period were related to WP5. Activities of the WP1 to 4 as well as activities in WP7 are combined and tested in 3D operation by means of the demonstrator manufacturing. The technology transfer from flat pre-trials over sub component trials to the demonstrator geometry couldn't cover all technological hurdles. A full scale pre-trial, named demonstrator D#0, revealed additional topics to be addressed. Especially the first ply, as a result the second ply as well, requires individualized control settings apart from closed loop control to address the discontinuous operation. An integration of newly available position based machine programming capabilities improved the result of the demonstrator component. Nevertheless the achieved laminate quality is still not at the expected aerospace standard and requires further development activities to improve material quality and process robustness and maturity. All material, process and manufacturing related topics were documented within deliverable D5.1. The nature of D5.2 is defined as demonstrator hardware; to complete the project documentation, the wish of the topic manager was addressed with a short report presenting the hardware and relevant document links.
Subsequently performed inspections on the demonstrator structure was documented in D5.3.

The WP5 and manufacturing activities were of relevance for WP6, life cycle assessment. All manufacturing was recorded in terms of energy, material and time consumption to fill the balance model.

Task 5.1: Stiffener manufacturing:

Stiffeners could be manufactured as prepared in the previous WPs. The L-shaped preforms were manufactured in a specific fibre placement based winding operation at AFPT. The Preforms were delivered to TUM for further processing and T-stringer consolidation. The required component complexity could be demonstrated. In total 4 stringers were manufactured. The first was used for process optimization and tool improvements, two others were installed to the demonstrators D#0 and D#1.

The Omega stiffeners were press formed from AFPisc placed blankets. All manufacturing steps were performed at TUM. 4 trials were prepared and formed. Friction during forming step required to adapt (increase) the press force above the nominal desired level. Otherwise no tool closure is achieved with deviation in wall thickness and at least insufficient material consolidation. 2 samples were used for demonstrator trials. One sample has shown sever deformation which couldn't explained from technical perspective. Running trials on a higher part count would help to create knowledge in terms of series manufacturing and deviations.

All trimming activities had to be carried out manually to prevent additional tool cost.

Task 5.2: Programming:

The stiffener placement programs used specific programming solutions, already developed in advance. The major step was the offline programing of the demonstrator skin using the environment of CGTech's Vericut code. The TUM machine cell had to be implemented by AFPT. AFPT's postprocessor required detailed development activities to assure the precision of placement. This optimization was carried out in collaborative work at TUM at the machine. Learning the interdependency between offline code and machine reaction was the main target before starting the demonstrator machine code generation. The machine controller KRC2 is limited in file size as well as coordinate count and could react with processing interruptions, positioning inaccuracies, as well as violation of tool centre point speed. Balancing incremental length of machine code with travel accuracy was successfully completed. The constant lamination speed could be proved by recorded manufacturing data.
Since the first time this offline programming tool was used, interfaces to the upstream design process in Catia V5, had to be solved. Even the demonstrator is completely defined by FACC in the Catia composite design environment, the data import for CAM programming is reduced to surfaces and boundaries. Ply definition and track optimization became part of CAM programming. Before manufacturing, intensive code testing had to be performed at TUM to avoid collision, but also to correct code errors. This standard procedure for robot controlled machines is time consuming and requires a multitude of time compared to the later real manufacturing time.
In addition coordinate based machine setting became of relevance after D#0 trial. To prevent overheating of the bonding zones (stiffeners integration), a pre-set is required to stay within the processing window in terms of temperature. This feature is not yet implemented in an offline programing solution and requires the definition of a table defining the machine setting on the relevant coordinates. The feasible compromise between process optimization and manageable programming effort included more than 850 coordinates and interactions and was incorporated by TUM before D#1 manufacturing.

Task 5.3: Demonstrator manufacturing:

All stiffeners had to be fitted by manual grinding to the layup mould prior skin lamination. The initial trial D#0 with higher productivity due to all 2" wide operation had to be optimized as described above, since otherwise no acceptable stiffener integration could be achieved. The D#1 manufacturing was therefore modified for the first two plies to ½" operation. Evaluations in WP7 required a reduction of lamination speed. Laminate properties and consolidation abilities are limiting today the operation speed, which could be higher from a machine speed perspective.

Task 5.4: Online process monitoring

All processing data were recorded by the AFPT machine and are accessible for evaluation. Within the documentation D 5.1 plots are generated with the TUM developed "Heatmap Tool" for visualisation. The change to ½" operation challenged this type of evaluation, since file size was increased from former hundreds of MB to 2.4 GB. Data handling became a new topic, but could be solved.
Other processing like press forming and consolidation were recorded by machine integrated sensors and additional thermocouples. Plots were generated and included to documentation.

Task 5.5: Repair concept

Concepts were investigated on flat base. Different overlapping lengths and manufacturing directions were considered. The most promising results were used for coupon preparation and were tested within the material test campaign in WP7. From manufacturing approach two methods were distinguished:

- In shop repair – using the AFPT equipment
- In service repair – material consolidation by heat transfer from a single sided heat plate and vacuum bagging

Results are part of the reporting of WP7.

Task 5.6: Trimming and finishing

As described above no state of the art NC routing was applied, since neither programming nor additional clamping tools were planned for the project. For demonstration reasons the manual cutting, trimming and fitting to layup mould was selected. The larger straight cuts were done on a diamond saw with less excess material and succeeding trimming with hand-operated tools. Deviations in terms of gaps must be counted to this approach and may not be relevant in a fully industrialized scenario.

As an additional task, to follow the requirements of TAE-T-NT150124 section “3.6.3 dimensional control and tolerances”, the demonstrator structure was inspected at FACC. Measurements on a coordinate measurement machine (CMM) as well as trials on NDI equipment, ultra-sonic inspection and thermography, were performed.

The dimensional inspection as reported in D5.3 don’t address the above mentioned requirements. Strong deformation due to residual stress implicates violation of the required dimensional tolerances. Nevertheless the performed evaluation don’t address them. Therefore the D5.3 is considered as failed.

2.2.6. Work Package 6

Work package number	**6**	Start date or starting event:	**M19**
Work package title	Life Cycle Assessment		

Objectives

The material and manufacturing steps is examined regarding their environmental impact. The analysis is executed by FACC as they have profound experience in Life Cycle Assessments in the field of composite manufacturing.

Summary regarding work progress and objectives

Due to the dependency of WP6 from WP5 with its manufacturing data, this work package was one major task of the 2nd period. To work at the latest state of technology, FACC subcontracted the MAI Carbon Cluster Management GmbH, who already generated a proved data base for composite processing in previous research activities. For AFPisc operation measurements were performed at during pre-trials to define placement rate dependent consumption values. The model calculation were than compared and corrected by the real operation data. The other major manufacturing steps at the press could be modelled with already available data and were calibrated with the total values determined during manufacturing.
The LCA was performed and evaluated for a baseline “thermoset process chain” (TS) in comparison to the applied “thermoplastic process chain” (TP). According to the guidelines series ISO 14040 and 14044 provided by the International Organization for Standardization (ISO), an LCA consist of the following main phases which were performed:

- Goal and Scope definition
- Inventory analysis of extractions and emissions
- Impact assessment
- Interpretation of the results

A reduction potential of 47 to 59% compared to the TS process chain is possible. The sensitivity analysis shows that there are also potentials for the TS process chain, but in best case the TP chain provides still a significant improvement in terms of its ecological impact.

The full result is documented in deliverable D6.1.

Task 6.1: LCA of in situ manufacturing:

Determination of missing process related data by pre-trials and in line with WP5 manufacturing activities.

Task 6.2: LCA benchmark:

Comparison of two scenarios – thermoset baseline vs. applied thermoplastic approach. Evaluation according to standards ISO 14040 and 14044.

2.2.7.Work Package 7

Work package number	**7**	Start date or starting event:	**M1**
Work package title	Testing		

Objectives

The WP covers all material testing related activities in INSCAPE as well as the data analysis and interpretation.

Summary regarding work progress and objectives

The test program was based on the general project requirements (Task 2.1) and as described in the test matrix of deliverable D2.1. The results for the pre-test campaign served as input for the demonstrator design and dimensioning (WP2).

For the entire experimental test campaign, the test panels were manufactured by TUM. The main focus of the test campaign was to assess the effect of the process in the mechanical properties of the chosen material. For this purpose, test coupons were prepared and tested at room temperature and at high temperature after exposure in hot/wet conditions. Furthermore, a brief assessment was conducted on the effect that the variation of the material deposition speed had on the mechanical properties. Amongst standard material characteristics, the interlaminar fracture toughness will be of special interest to characterize the quality of the in situ joint of stiffeners and AFP skin.

The experimental test campaign included not only layups according to the applicable standards but also a chosen layup, of a possible structural panel configuration applied in the aerospace industry, and configurations with repaired coupons.

In the present work package, Thermogravimetric Analysis (TGA) and Differential scanning calorimetry (DSC) were included. The TGA was used to determine the amount of matrix/fibre in the composite needed for the determination of the material crystallinity using the DSC test(s) for the different material deposition speeds and the effect of the exposition in hot/wet environment.

The results are further analysed with the goal to present design allowable for future applications of the INSCAPE process.

Task 7.1: Test program definition:

This task was mostly affected by delayed project start, since all topics on the demonstrator were prioritized. The expectation of the TM was a larger test program in terms of total number of specimens and standards, including wet conditioned testing, compared to the proposed amount. Therefore, discussions on available test equipment and applicable standards between INEGI and Airbus D&S were needed to agree the Test Program (M15, planned M2) which is reported in this period in D2.1.

Task 7.2: Coupon manufacturing:

Within the 1st period coupon manufacturing for a first batch of more than 50% of the test panels were carried out at TUM on the agreed base of single tow 1” operation. Additional panels were manufactured in the 2nd period already using the final machine setup and new laser optic. Trimmed test panels were send to INEGI for further processing. All test specimen preparation like coupon

cutting, bonding of tabs and instrumentation was done at INEGI.
Due to unexpected test results additional panels were provided to prove the gained values.

Task 7.3: Coupon testing:

All testing activities are documented and reported in Deliverables D7.2 and D7.3. Due to the delayed start of the task these Deliverables also suffered a significant delay. The table below summarizes the experimental mechanical test campaign conducted at INEGI.

Panel	Description
LEVEL I	
#1	ASTM D3039 UD tensile and modulus 0º (f11tu, E11t) UT0
#2	ASTM D3039 UD tensile strength and modulus 90º (f22tu, E22t) UT90
#4	ASTM D3518 In-plane shear strength and modulus (f12su, G12s) IPSS
#6	ASTM D6641UD compressive strength and modulus 0º (f11cu, E11c) UC0
#6	ISO 14130 Interlaminar shear strength (f13)ILSS
#8	ASTM D6641UD compressive strength and modulus 90º (f22cu, E22c) UC90
#10	ASTM D5528 Interlaminar fracture toughness energy - mode I (Gic) GIC
#11	ASTM D5766 Open hole tensile strength (OHT) and modulus OHT
#12	ASTM D6742 Filled hole tensile strength (FHT) FHT
#13	ASTM D6484 Open hole compressive strength (OHC) and modulus OHC
#14	ASTM D6742 Filled hole compressive strength (FHC) and modulus FHC
#15	ASTM D6484 modified Plain compressive strength and modulus PC
#17	ASTM D7136 + ASTM D7137 Compresssion after impact (CAI) CAI
#19	ASTM D5961 Bearing strength BR
#21	ASTM D3039 modified Plain tensile strength and modulus PT
#28	ASTM D3039UD tensile strength and modulus 90º (f22tu, E22t) UT90 - speed 3m/min
#29	ASTM D3039UD tensile strength and modulus 90º (f22tu, E22t) UT90 - speed 9m/min
LEVEL II	
#22	ASTM D5528 Interlaminar fracture toughness energy - mode I (Gic) GIC_str
#23	ASTM D7905 Interlaminar fracture toughness energy - mode II (Giic) GIIC_str
#27	ASTM D5868 Single lap shearSLS_str
#24	ASTM 3039 Repaired laminate by AFP - in shop - 10mm overlap/layer
#25a	ASTM 3039 Repaired laminate by vaccum bagging - in service - 10mm overlap/layer
#25b	ASTM 3039 Repaired laminate by vaccum bagging - in service - 5mm overlap/layer
LEVEL III	
#1	ASTM D3039UD tensile and modulus 0º (f11tu, E11t) UT0
#3 (#3a)	ASTM D3039UD tensile strength and modulus 90º (f22tu, E22t) UT90
#5	ASTM D3518 In-plane shear strength and modulus (f12su, G12s) IPSS
#7	ASTM D6641UD compressive strength and modulus 0º (f11cu, E11c) UC0
#9	ASTM D6641UD compressive strength and modulus 90º (f22cu, E22c) UC90
#16	ASTM D6484 modifiedPlain compressive strength and modulus PC
#18	ASTM D7136 + ASTM D7137 Compresssion after impact (CAI) CAI
#20	ASTM D5961Bearing strength BR
#26	ASTM D7905 Interlaminar fracture toughness energy - mode II (Giic) GIIC_str

Furthermore, TGA and DSC tests were performed at INEGI in samples at room temperature and samples subjected to hot/wet conditioning extracted from panels manufactured by fibre deposition and in-situ curing at different speeds.

To support the discussion on test results TUM performed mechanical tests for comparison and prove of results. Micro sections were prepared for visual laminate quality inspection and wet chemical analysis for fibre volume fraction and porosity content determination were performed.

Task 7.4: Design allowable substantiation

Design allowable were determined using the data generated in the experimental test campaigns and reported in D7.2 and D7.3. The method applied to generate the design allowable were done following the methodologies presented in the composite materials handbook MIL-HDBK-17-1F.

Task 7.5: TRL3+ demonstration

The TRL3+ demonstration was a requirement by the TM incorporated during the project implementation phase to ensure the project reach. This was accepted by the consortium, since AFPT and TUM finished several projects at higher levels. The demonstration should base on literature work based on preliminary works carried out and be documented within Deliverable 7.1. Since not all available data are free for further exploitation, detailed selection and approval steps has to be done by TUM. Not all requested aspects could be answered or at least material performance was below expectation. Therefore discussions were started questioning the project ongoing and delaying the project proceedings.

Within the 2nd period additional test were performed. Results were included to D7.2 which was extended for additional testing. At project end the D7.1 was revised to correlate topics of discussion with outcomes of the project.

2.3. Impact

The impact in terms of environmentally friendly production could be proved by the LCA performed in WP6 based on previous gathered data and the new process route developed for the demonstrator structure. Considering the main impact indicators an improvement of more than 50% could be achieved for in situ AFP. Vario-thermal processing of thermoplastics as applied for the T-stringers should be avoided, since this energy intensive manufacturing way worsens the environmental balance.

The benefit during operation couldn’t be confirmed, since the mechanical properties determined in WP7 are below the expected level of performance. Work on the route cause and enhancement of material performance need to be content of subsequent works, to transfer the initial benefit also to aircraft operations.

The indirect impacts on cost effective assembly operations for composite structures was demonstrated. Since no (sub-)component testing was included to the project an assessment of mechanical performance need to be intensified before exploitation of this new design and manufacturing feature. Material performance as well as manufacturing speed is still on an early stage and low maturity. Solutions for further improvements were presented.

In terms of competitiveness the approach of highly automated and controlled production could be demonstrated.

The impact for project partners are unchanged.

2.4. Exploitation and dissemination of result

Industrial exploitation as planned for project partners. Technology exploitation for topic manager is limited due to mentioned material performance below expected level. Process challenges could be shown, a better technology understanding could be provided by the consortium.

Dissemination:

JEC World 2018 exhibition was used by TUM to present the project and demonstrator structure to the public.

Postponed SAMPE Europe event in November 2017 will be replaced by SAMPE Europe event in September 2018 since results of WP5 as relevant project outcome had to be available.

2.5. Update of the data management plan

The project was extended to end of May 2018 according to Amendment. All physical activities were closed in this time. Data evaluation was extended till the project final meeting at 26th of June in Getafe (Spain). Reviewing all deliverables, revision and closing exceeded that date.

3. Publishable Summary

3.1. Abstract

Thermoplastic Fibre Placement with in situ consolidation (AFPisc) is the focused process of this contribution. Compared to established composites processing routes, TP AFPisc concentrates on an additive “one box” approach and can fulfil requirements of ecologic friendly, energy efficient and high automated and digitalized future production. A short wrap up of the last six years of research activities on the AFP-isc process at Technische Universität München (TUM) is presented and ends in a technology transfer to a 3D demonstration carried out in Clean Sky II project INSCAPE. Promoted by Airbus DS SAU as part of Airframe ITD, the main objective of this project was the enhancement of the automated thermoplastic fibre placement process with in situ consolidation (TP AFPisc) focused in high performance polymers such as PEEK or PEKK. Latest development of the project consortium was demonstrated on a curved stiffened panel with direct integrated stiffeners, as a continuation and complementary activity carried out by ADS SAU in the frame of CS as member of Eco-Design ITD.

An overview of the processing equipment and settings as well as manufacturing strategy will be presented. The interaction of tape and laminate quality will be discussed. These results show the current state of a future composite manufacturing process for carbon fibre reinforced aerospace structures and gives an outlook to further required developments for economic exploitation.

3.2. Introduction

3.2.1. AFPisc - a niche process in terms of majority of composite production technologies

Material and process developments are often driven by the need of specific applications and industries. The latest aircraft design e.g. Boeing 787 and Airbus 350 with increased demand on composites created new processes and automation equipment to fit size, product quality and rate of these products. A similar surge with focus on short cycle wet press moulding and resin transfer moulding was caused by the automotive industry. A different technology development with lower automation level was chosen for the wind energy sector, where a compromise between component size, production rate and cost had to be found. All of these material, process and equipment developments are not targeting in replacing available technologies and instead of that specific solutions were introduced to their best use and application.

Compared to the market volume of these three sectors, thermoplastic composites play a niche role, even more and more activities are published [1, 2] and the interest grows. Typical motivation for the use of thermoplastic based composites are short cycle times, weldability, formability, often good impact resistance, commonality to other plastics already in use and potentially improved recyclability. Material performance and product cost are in direct competition with thermoset composites as well as other lightweight materials and constructions. Benefits of facilitated material logistics and improved hazardous substance management are counted against different process equipment operating at higher temperature levels with potential higher energy cost.

In opposite to the majority of composite processing methods, organized in processing chains like material preparation, cutting, placement and forming, curing or consolidation, AFPisc concentrates these steps in one higher complex operation. In direct comparison AFPisc is more akin to additive manufacturing processes instead of AFP known from thermoset processing.

3.2.2. AFPisc – origin and developments at TUM

The technology used at TUM is based on the technology of the AFPT GmbH, Dörth Germany, which is originated on the research work of P. Kölzer [3]. Compared to other Tape or Fibre Placement processes, the use of a laser beam as energy input acting in a close loop control is the major step to improve the temperature control for in situ consolidation.

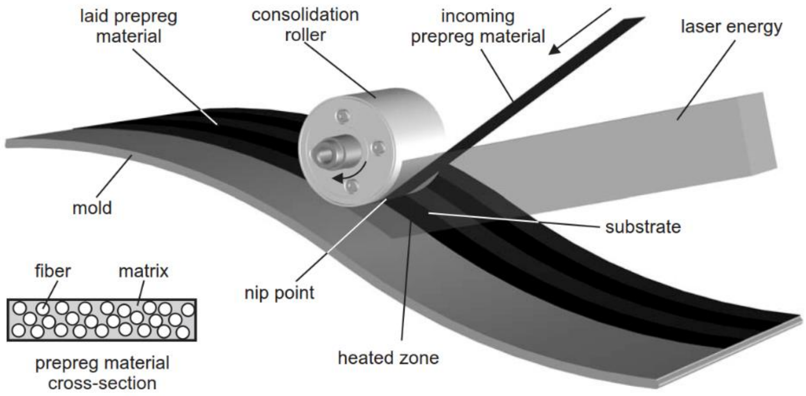


Figure 1. Principle of the process as described by P. Kölzer [2].

The interaction of the laser beam and tape material was in detailed investigated and modelled by Ch. Stokes-Griffin [4]. A 2D Matlab simulation was generated and validated by TUM to understand the thermal conditions during processing. In parallel the initially designed AFPT winding head was successively improved starting in 2012 to a full placement head with start on the fly operation and varying tape setup (1x ½”, 1 or 2x 1” up to 4x ½” or 2”).
Figure 2 gives an overview of the funded research projects on the AFPisc technology at TUM.

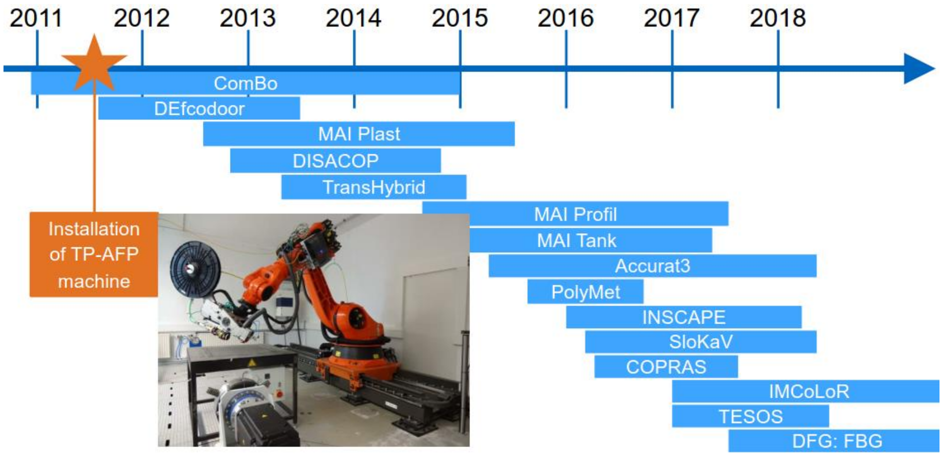


Figure 2. AFPisc technology development at TUM, based on public funded projects.

The manufacturing of a PPS based pressure vessel for rocket booster applications already required placement operation at the flange reinforcement. The dimension of more than 1.2 m in diameter and 3.5 m in length kept the process on a constant level with smooth control operation, see Figure 3.

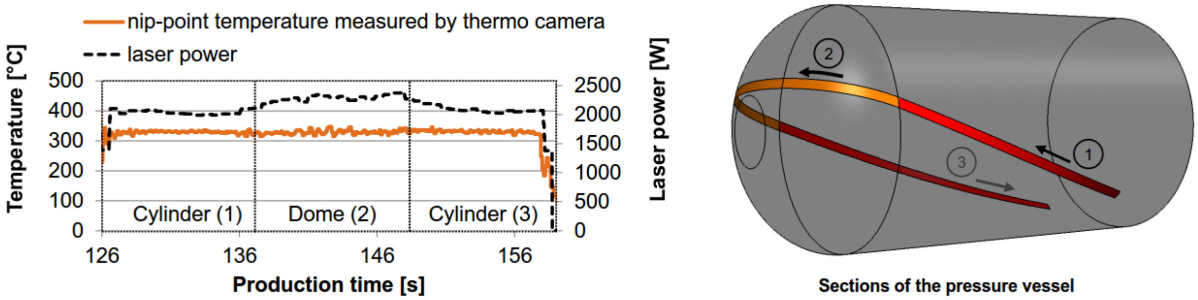


Figure 3. Initial AFPisc project ComBo with semi winding operation and low variation to laser power control in accordance to steady changing conditions e.g. dome section [5].

The CleanSky project DEfcodoor already considered hot forming of AFPisc placed blankets to omega shaped profiles, which were closed by an in situ consolidated skin in a second placement step. The joints were characterized and published by V. Radlmaier [6]. The profile size twice as long as the laser spot length already showed the challenge for an automatic power control. The temperature controller is optimized for a point or line at the nip point, but changes in power or distribution between incoming tape and substrate are affecting the entire laser spot and is applied to different conditions e.g. base substrate and joint. Therefore constant power strategies were chosen in TransHybrid and PolyMet projects were metal – carbon composite hybrid joints were generated (Figure 4). In both cases the processing window and settings are optimized for the joint section only; due to higher heat conduction or lower laser power absorption of the tool sections no overheating issue occurs. The direct integrated joints were mechanically tested and proved their integrity. Up to projects Accurat3 and INSCAPE all components were close to cylindrical shapes. On large curvatures and during winding operation AFPisc provides a constant situation for the laser beam and heating of substrate and incoming tape; converse edges and radii smaller than the laser spot height leads to deviations in temperature control out of the acceptable processing window.

Without manipulation of the automatic controller edges and smaller convex radii can’t be placed by AFPisc. A predictive controller approach and a coordinate based setting of the laser angle and power extends the AFPisc application to 3D operation and was developed in the national funded ZIM project Accurat3, compare Figure 5.

Figure 4. Joints manufactured by AFPisc, left helicopter drive shaft of project TransHybrid, right AL-profile stiffened barrel manufactured in project PolyMet

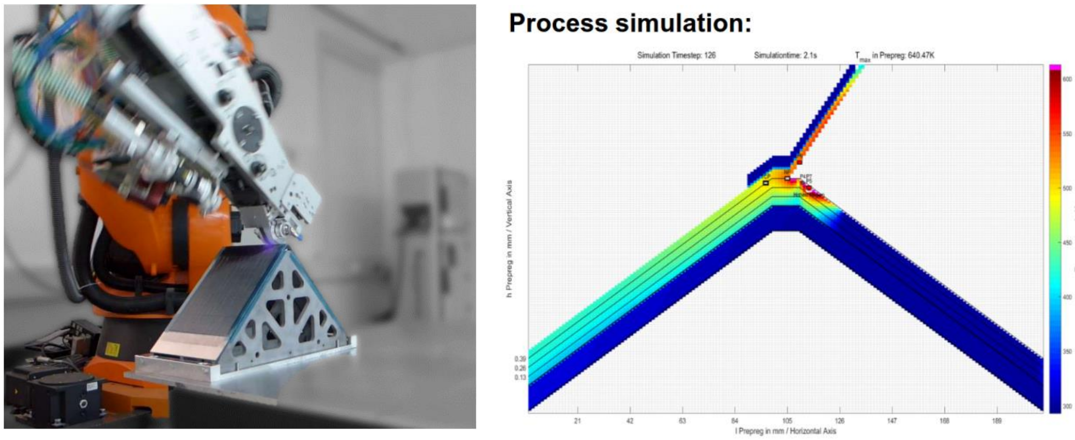
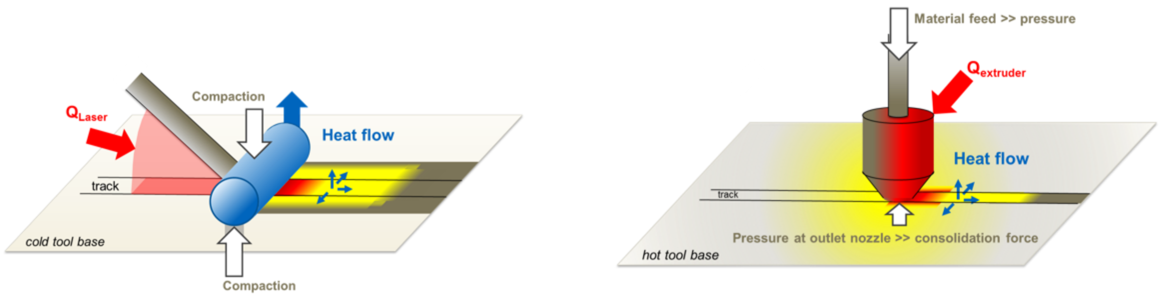


Figure 5. AFPisc applied on smaller edges and radii close to the spot size with need of predictive laser power control or coordinate based settings. Results of project Accurat3.

The technological approach chosen in the INSCAPE project, is therefore the results of several research activities and the next step to apply AFPisc on a free 3D shape. The manufacturing setup and technology demonstration on a curved stiffened panel is part of the succeeding chapter.

3.2.3.AFPisc - in between worlds of thermoplastic or additive manufacturing

Apart from the understanding that composite materials are layer based and build up from fibres, tapes or flattens to shell or volume parts, APFisc represents a technology close to representatives of additive manufacturing like Fused Filament Fabrication (FFF or FDM™), one of the dominating plastic processes besides Selective Laser Sintering (SLS). New material is deposited along a path and fused to a build base or already build structure by use of temperature and consolidation pressure. The heat input is generated by a laser beam at AFPisc with the possibility to have the substrate as well as the incoming material above melting temperature, whereas FFF heats up only the incoming material within the hot end or extruder by heat transfer or laser [7]. A heated build platform / build chamber and the radiation and convection of the hot end heat the substrate and helps to improve interlaminar adhesion and reduce deformation due to residual stress. Consolidation forces are generated differently; AFPisc uses a compaction roller (often fluid cooled), FFF relies on the extrusion pressure which creates in the expansion zone the consolidation force in relation to the distance between nozzle and substrate; combined versions are already shown e.g. in [8]. Common is the local heat input and cool down by heat transfer which is in contrast to the standard in composite manufacturing, where curing or consolidation is done by a major process step at least on part level; cyclical heat treatment of the material is characteristic for additive processing.



AFPisc

Track size: 120-200 µm x 12-50 mm
Temperature setting: 480-500°C for PEEK
Typ. manufacturing speed: 2.000 – 6.000 mm/min

FFF

Track size: 75-150 µm x 440-600 µm
Temperature setting: 480°C for PEEK
Typ. manufacturing speed: 2.000 – 4.000 mm/min

Figure 6. Process comparison between AFPisc and FFF with similarity on processing principals and parameters, but different at heat input.

Even the machine size of the comparison in Figure 6 varies in physical dimension (processing head by AFPT and APIUM print head) the thickness of material deposition is similar as well as processing temperature and speed. In terms of material processing and optimization of polymer chemistry, AFPisc is related to FFF; in terms of component design, machine technology and programming it is a representative of the fibre placement technology.

As a cross-border process between additive and composite manufacturing, AFPisc provides different potentials:

The economic benefit does not arrive from higher deposition rate and high material throughput, but provides a much faster realization time from part design to a component as already known from other “3D printing” approaches. Therefore it is not expected, that AFPisc will compete with meanwhile established processing routes as described above and instead will provide composite products to markets where individual part design and fast response time are success factors. AFPisc high speed winding is already an exception, which started the direct competition to wet filament winding.

Complex processing routes results in diversified engineering and production planning activities; reduced

complexity with short steps from CAD to CAM addresses the need for future digitalized production. AFPisc can facilitate composite technology to enter these future markets.
Boosting material properties by fibres became a topic of additive manufacturing development activities – AFPisc derived from others composite technologies already presents a potential solution for improved properties.
In that context project INSCAPE developed and evaluated the AFPisc technology.

3.3. Experimentation

Main target of the Clean Sky II project INSCAPE was the AFPisc technology demonstration on a generic curved stiffened panel for a potential aerospace use. High performance polymers like PEEK or PEKK were addressed. The demonstration case, machine equipment, selected material and process setup is presented in this chapter.

3.3.1.Demonstrator component of project INSCAPE

The demonstrator measure approx. 1.4 x 1.2 x .25 m in length x width x height direction. The skin consists of 16 plies, reinforced by a surrounding frame of 32 plies and local central pad up made from 48 plies in total. All areas are realised as a quasi-isotropic laminate. The skin is reinforced in longitudinal direction by an Omega- and T-stringer, in transvers direction by a rectangular profile representing a spar foot. The integration is done by in situ joining, no additional assembly process is applied, compare manufacturing route in Figure 7.

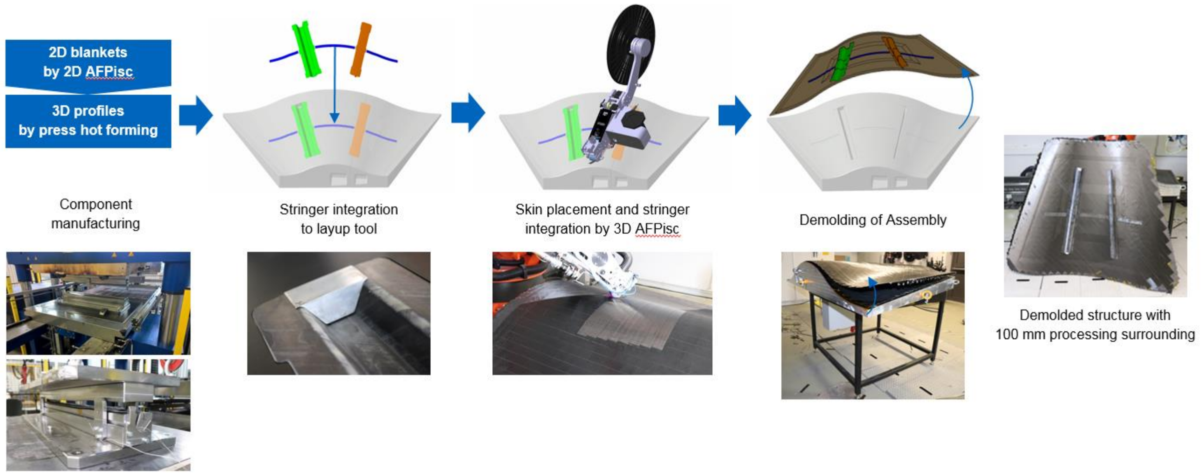


Figure 7. Demonstrator part of project INSCAPE and manufacturing route consisting of a blanket placement, stringer forming and skin placement with direct joining.

Both stringers have a reinforced laminate of 2x 17 plies at the ends and a thinner nominal laminate of 2x 13 plies in the centre section. Due to the local reinforcements and curvature no continuous process is capable for production of this local reinforcements. Preforms were therefore placed by AFPisc and formed in a hot press to final shape; the profile's radii are too small for a direct placement.
The Omega profile is made from a flat blanket with reinforced laminates at the outer areas and a nominal centre area. Standard processing by IR heating up to 390°C and hot forming (180°C tool temperature) is applied to get the final shape.
Since a T-profile can't be generated the same way, an alternative approach was selected. The T consists of two asymmetric L-segments (compare middle of Figure 8), which were extended to a trapezoidal geometry for winding operation of a preform. The segments were slit and trimmed to fit in a consolidation tool. The joint between the L-segments is filled with PEEK-CF granulate as shown in Figure 8 (prior consolidation). A full heating cycle up to 390°C and a press force representing 6 bar pressure to the component surface is applied for consolidation.

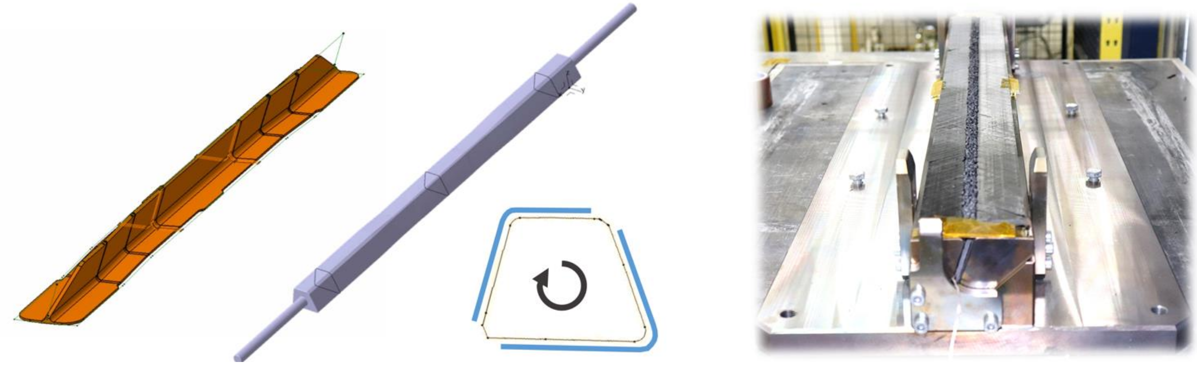


Figure 8. Asymmetric T-stringer profile (left), winding mandrel for preform manufacturing using a trapezoidal geometry containing the two L-segments (middle), installation to forming tool for consolidation (right)

The spar foot is placed on the skin layup mould (LM) and need trimming to fit into the pockets.
After installing the reinforcement elements to the LM, the skin placement can be conducted by AFPisc. The research and development activities were concentrated on:

Material and Processing:

- First ply placement on a concave / convex surface
- Direct joining on the preinstalled elements

Production technology:

- Accessibility for the processing head
- multi tow enhancement
- offline programming / machine code and limitations

3.3.2. AFPisc machine technology

All placement operations were performed on a system based on the 2” wide single tape winding head (STWH) from AFPT installed on a KUKA robotic system (KR180 with KL1600) controlled by KRC-2. The base head was modified by separation and guiding elements to be capable for single tape placement ranging from ½” to 2” and multi tow placement with two times 1” or four times ½” tapes. Cutting is done for all setups at once for all tapes – concepts for individual cutting were done by AFPT but not introduced to the machine used for demonstrator build.

Relevant processing parameters:

Nip point Temperature 485°C

Lamination speed:

Nominal 6 m/min (variations at 3; 4.5 and 9 m/min for test panel manufacturing)

Demonstrator lamination: 3 m/min 1st and 2nd ply, 4.5 m/min others

Laser power: variable due to closed loop control, maximum 4.400 W at 1st ply to approx. medium level of 2.100 W at 4.5 m/min and 2” operation. Optics adapted to tape size.

Head Angle: Nominal 32°, local increase up to 38° to avoid head-tool collision

Laser Angle: Typ. 0 – 1° automatic controlled for nominal lamination, coordinate based steering within 1st ply from -1.2° to 1.5°.

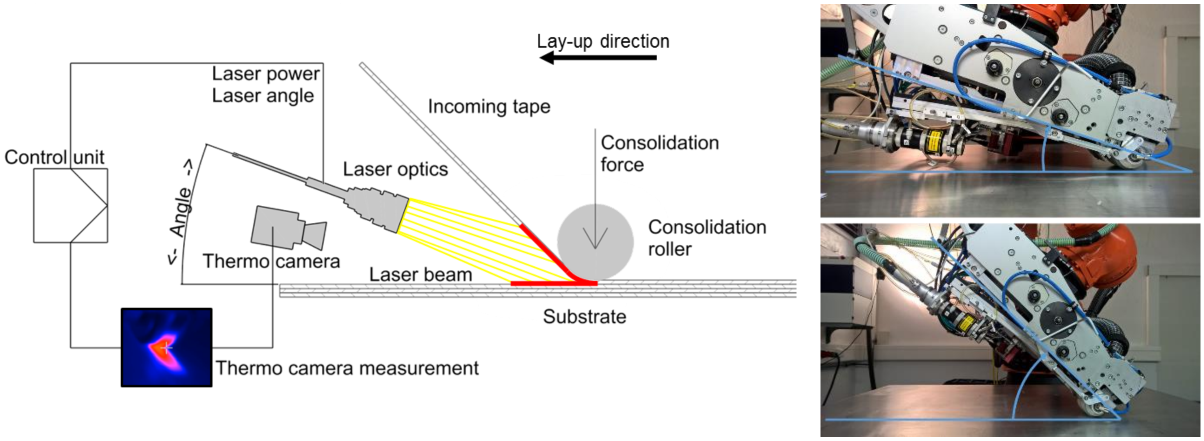


Figure 9. Laser heating system and controls. Left – closed loop control of laser power and power distribution by laser angle; head angle as machine pre-set, right top min. 22°, lower right 45° as maximum.

The head angle is mainly a head design dependency and can be varied in a limited range due to alignment of consolidation roller and its travel orientation, tangential tape feeding to the nip point, accessibility to the tool surface and collision aspects. Since the optical elements (laser optics, IR and VIS camera) are mounted on an adjustable frame linked to the nip point, the variation to the processes is limited to a variation of incidence angle in a range of theoretical +/-10° in practice below +/-5°.

The drive for laser angle adjustment is mounted to the adjustable frame as well and therefore acts independently of the head angle. Working in closed loop control mode the optimization runs for simultaneous heating of incoming tape and substrate. Within the first ply lamination, the manual setting is chosen to bring more energy to the tool surface (neg. angle) and avoid overheating of stringer joints (pos. angle).

3.3.3.Materials used

Two tape materials were considered to be used:

TenCate, Cetex, TC1320 (PEKK polymer, AS4D fibre)

Teijin, TohoTenax, TPUD PEEK-HTS45 (PEEK polymer, HTS45 12k fibre)

Identical in fibre areal weight and matrix content (145g/m², 34wt%) suitability for in situ consolidation was investigated. As constituted below, the TohoTenax tape was used for the test program and demonstrator manufacturing.

3.3.4.Process setup

Tools with none active heating were used (test panel manufacturing as well as demonstrator part). Only heat input by the laser system is increasing the tool temperature during lamination. This setup leads to higher cooling rates and contradicts approaches also used at FFF processing to deal with residual stress. Considering cost effective production especially of larger components and safe industrial environment a non-heated tool approach looks to be mandatory for future application.

3.4. Results

3.4.1.Material selection and laminate properties

Visual tape inspection, manual peeling tests at varying processing parameters (nip point temperature, lamination speed), in plane shear testing and micro sections of single tapes as well as laminates were the basis for material selection.

Concluding Cetex TC1320 (batch from 2017) is a tape of highest homogeneity in terms of fibre distribution and constant thickness. In comparison the Tenax TPUD PEEK-HTS tape is less homogenous, but provides better mechanical properties in terms of in situ consolidation. Over the project time, a change in properties, generally detected as reduced interlaminar strength were detected for the Tenax material. Considering the micro sections shown in Figure 10 an assimilation of the tape quality can be stated, resulting in identical improper tape quality for in situ consolidation.

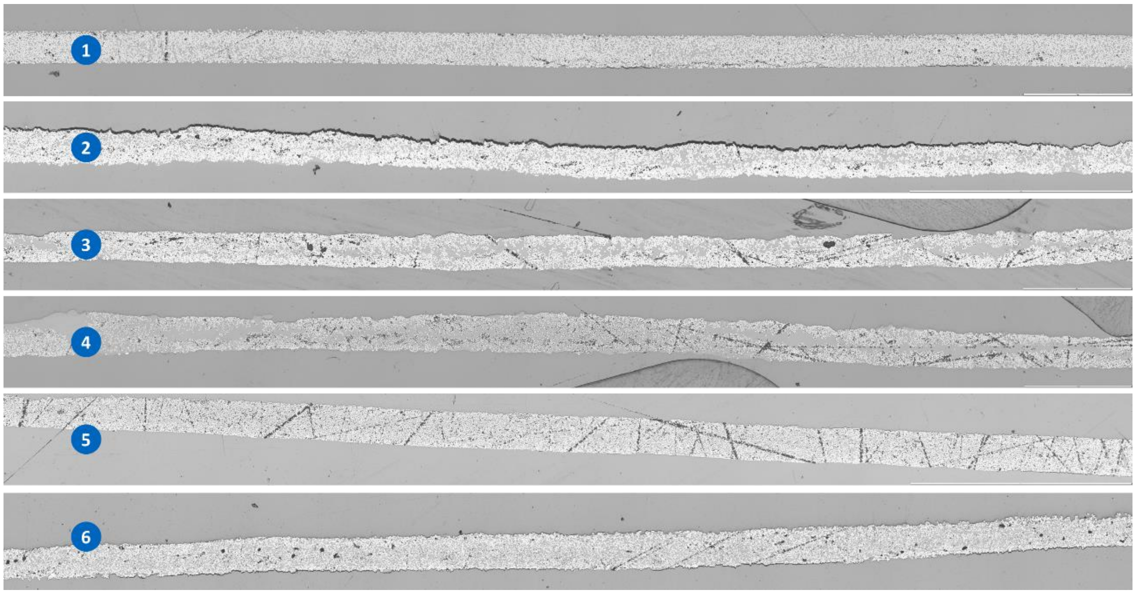


Figure 10. Representative micro sections of different tape batches 1) Cetex 1320 batch 2016, 2) Tenax batch 2010, 3) Tenax batch 2013, 4) Tenax batch 2015, 5) Tenax batch 2017, 6) Tenax batch 2018; shadow at tape boundary and straight lines are shortcoming of specimen preparation and are no material quality indicator

The higher quality tapes typically provides almost no polymer film on the tape surface as illustrated in Figure 11 upper left. In opposite, at less homogeneous tapes matrix rich surfaces can be found, compare lower left picture. Due to poor flow behaviour of PEKK and PEEK material this criteria was identified as key criteria for in situ consolidation suitability. Even low porosity contents (below 1%) of the high quality tapes results in 6-7% at laminate level since gaps are created in the tape interfaces, Figure 10 right. Post consolidated specimens nevertheless could be reduced to porosity levels below 0.5% [9]. Variation in lamination speed (2m/min – 9 m/min) and increase of nip point temperature up to 520°C couldn’t improve this effect. In comparison to tapes based on PA or PPS polymers an improved flow property, good surface wetting and creation of an intimate contact can be stated.

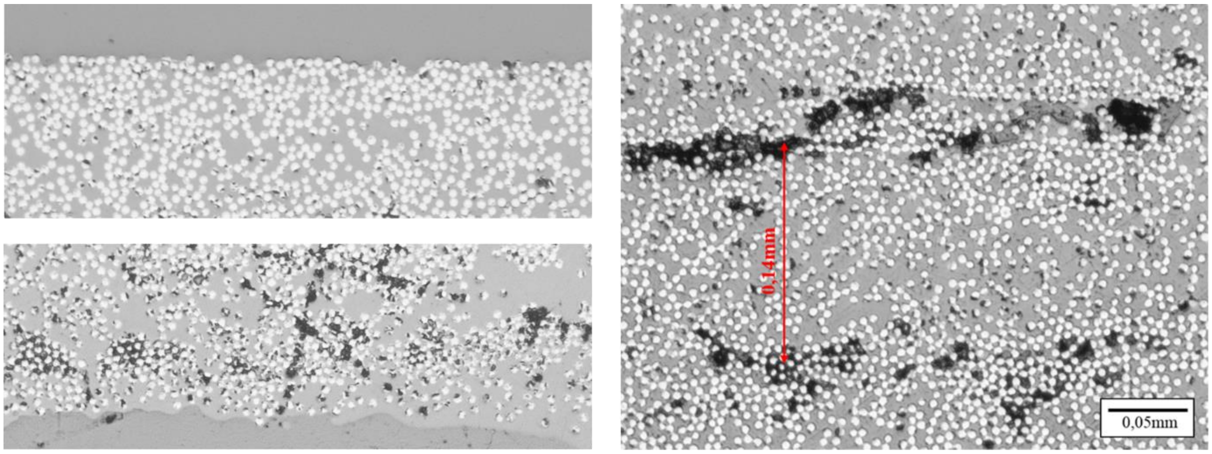


Figure 11. Upper left, no resin film at surface of high quality tapes. Lower left, resin film on tape surface, relevant for AFPisc suitability. Right, significant porosity agglomeration at tape interfaces due to poor melt flow properties of PEKK and PEEK.

The intensive mechanical test campaign with more than 30 test series including impact and aging can't be discussed herein. As conclusion the results can be summarized: AFPisc laminates can't compete with traditional manufactured composites in terms of mechanical performance, at least valid for the chosen setup. Depending on load type 60-80% of reference values were determined. The current available tape material and processing setup leads to lower crystallinity and higher porosity level. Post crystallization at elevated temperature potentially compensate aging effects, typical knock down factors between ambient and aged testing couldn't be detected.

AFPisc optimized tapes (matrix rich interfaces, low porosity) as well as an elevated temperature level for the processing setup are considered as drivers for improved material performance in future for in situ consolidated laminates.

3.4.2.AFPisc lamination

Tape – process interaction

Apart from material performance criteria, the selected tape materials have shown a good suitability for AFPisc lamination in terms of process stability and robustness.
The stiffness of the tapes and surface quality assures a reliable feeding of the material. Longitudinal cracks in the tapes are critical in ½" operation since the lateral positioning is affected with potential loss of control in terms of placement accuracy; operation at 1" or higher provides a higher robustness to this defect.
A very low matrix transfer to the consolidation roller and no sticking to the roller assures a high productive time of the system; no tape winders to the roller occurred during test panel and demonstrator manufacturing. Roller sleeve changes were caused only by temperature wear of the silicon material but not due to polymer build up.
Tape slipping at start-on-the-fly operation is on low level and can comply with a tolerance band of below +/-2 mm, but cannot compete with cutting tolerance at track ends at +/-1mm.
In total only 5 defects / interruptions belonging to tape properties and quality were recorded during demonstrator lamination.

Programming

Machine programming was one of the major tasks to assure the manufacturing demonstration. Test panel manufacturing is based on Kuka Language code and limited to flat rectangular shapes; also acceptable for blanket manufacturing as long as material scrap optimization is not in focus. Winding on polygons could be performed on an AFPT developed code. A new approach was required for the 3D lamination of the curved panel. Precise surfaces and boundaries were exported from Dassault Systemes' Catia V5 for each layer. Path planning was performed by CGTech's Vericut software. The head specific commands are integrated by an AFPT developed post processor. The first data interface is of high reliability and avoids inadequacies of surfaces generated automatically within Vericut (potentially divergent surface normal vector due to meshing). The interaction between Vericut, optimization of postprocessor and KUKA control reaction required several iteration loops and is mostly critical in terms of data minimizing to deal with the no more state of the art KRC-2 capabilities. Apart from short tracks close to the minimum layup length, acceptable solutions could be generated. In x-y direction a path accuracy at low tenth of mm can be achieved; the z-accuracy in a band of 5 mm is good enough since the roller with 22 mm travel could compensate much more deviation. This reduced requirement on path accuracy simplifies the code generation.

The AFPT processing head controller provides the feature of coordinate based action viz. parameters can be adjusted apart from closed loop control based on predefined location. This feature is of high relevance where discontinuities require step responses. For first ply lamination this feature was introduced in simplified manner to overcome the strong varying energy demand between placement on tool surface and bonding at stiffener areas. No automated programming is currently available for this feature and was therefore introduced by combination of mapping and teaching.

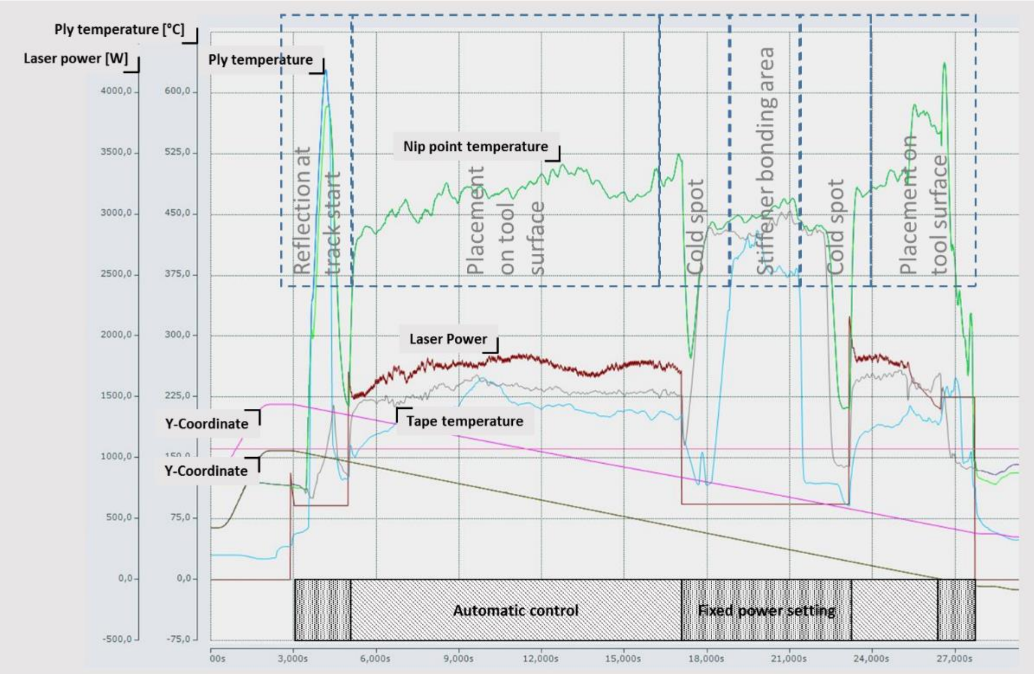


Figure 12. Processing parameters (temperatures, laser power) plot along a single track showing the effect of local manipulation of automatic power control and laser angle (hidden).

Joining the tape and substrate at the right temperature at sufficient pressure and cooling under the consolidation roller are the target controls of the processing equipment. A single track running over a stiffener is exemplary shown in Figure 12. The laser power applied on the tool surface is approximately three times higher compared to the power required for stiffener joining. The closed loop control cannot react that fast. To prevent overheating in the joining area, predetermined settings of laser angle and power limit are applied for the bonding zone. Cold spot areas (no stick to the tool surface) are acceptable in front and after rather than overheating (degradation of material). With additional set points the cold spots can be avoided and was tested on flat test panels. A full transfer to 3D parts requires an integration to the offline programming.

Productivity

The lamination of all 48 skin plies with in total 9.6 kg of tape material placed, took a manufacturing time of 13.35 h, meaning an average layup performance of 0.72 kg/h. This value includes all interruptions in case of defects or machine errors as well as spool changes and machine travel times between tracks and from/to parking position; listing in ascending order of dominance. The nominal maximum layup rates are:

- 0.5 kg/h at 3 m/min layup speed and ½ ” wide operation (1st, 2nd ply)
- 1.5 kg/h at 4.5 m/min layup speed and 1” wide operation (all 45° plies)
- 3 kg/h at 4.5 m/min layup speed and 2” wide operation (all other plies)

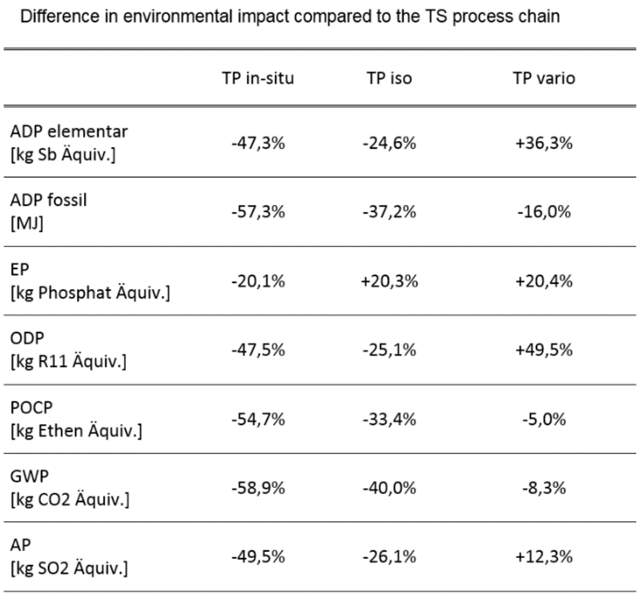
The following table shows the achieved lamination rate in comparison to the theoretical maximum.

	1st & 2nd ply	*+/- 45° framed & pad plies*	*0/90° framed & pad plies*	*Full plies*
Theoretical max	0.5 kg/h	1.5 kg/h	3 kg/h	3 kg/h
Real rate	0.31 kg/h	0.35 kg/h	0.7 – 1.5 kg/h	1.95 kg/h

Table 1. Nominal layup rates in comparison to the measured manufacturing rates including all non-productive activities like travelling, spool change and actions due to errors/defects.

3.4.3.Life Cycle Assessment

The process route described in Figure 7 was compared to a standard thermoset (TS) prepreg hand lamination route with autoclave curing. The thermoplastic (TP) route includes the AFPisc approach as well as the additional isothermal (TP iso) and variothermal (TP vario) forming steps. Considering the part manufacturing in comparison to the TS baseline, a high reduction potential for especially the AFPisc process could be confirmed as shown in the table below. Even the isothermal forming step provides an environmental positive effect. This changes in case of a variothermal processing setup as applied to the T-stringer. The energy efficient, waste optimized processing of thermoplastics is a key for a more environmental friendly composite production, but doing it the wrong way can worse the impact. Best results are gained for the AFPisc process, which has proven its potential as more ecological friendly manufacturing technology.



Difference in environmental impact compared to the TS process chain

	TP in-situ	TP iso	TP vario
ADP elementar [kg Sb Äquiv.]	-47,3%	-24,6%	+36,3%
ADP fossil [MJ]	-57,3%	-37,2%	-16,0%
EP [kg Phosphat Äquiv.]	-20,1%	+20,3%	+20,4%
ODP [kg R11 Äquiv.]	-47,5%	-25,1%	+49,5%
POCP [kg Ethen Äquiv.]	-54,7%	-33,4%	-5,0%
GWP [kg CO2 Äquiv.]	-58,9%	-40,0%	-8,3%
AP [kg SO2 Äquiv.]	-49,5%	-26,1%	+12,3%

Table 2. Main impact indicators evaluated in a LCA for part production. Thermoplastic processing in relation to thermoset, hand layup, Autoclave baseline. *(ADP – resource depletion potential, EP eutrophication potential, ODP ozone depletion potential, POCP photochemical ozone creation potential, GWP global warming potential, AP acidification potential)*

3.5. Conclusions

The developed processing setup and equipment was able to manufacture the requested demonstrator structure. The approach of direct integration of reinforcing elements could be proven. The processing equipment provides a wide range to create the best processing window, but also requires a deep understanding for machine programming and polymer chemistry to achieve the best material properties. Considering the laminate quality it must be stated that even high quality grade tapes with PEEK or PEKK matrix and high fibre content are not appropriate for AFPisc at least for aerospace use. The poor melt flow behaviour of the used polymers result in poor wetting of tape to tape interfaces and therefore insufficient interlaminar strength or at least high macroscopic porosity. To exploit the benefits of AFPisc with positive effect on environmental accounting the way forward requires a step back to optimize the tape grades and used polymers to the process specific needs. The equipment provides the potential for much higher lamination speeds at even higher temperatures, but for doing that the matrix must already be at the right place or the polymer melt flow properties must be superior high.