UPSCALING OF IN-SITU AUTOMATED FIBER PLACEMENT WITH LM-PAEK – FROM PANEL TO FUSELAGE

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Abstract: *The application of thermoplastic CFRPs in large aerospace components enables a modern and differential approach to Aircraft manufacturing. Most importantly the opportunity of dust-free joining of components by means of thermoplastic welding technologies allow subassemblies to be pre-equipped with system and cabin elements that are then subsequently joined. The Institute for Structures and Design of the German Aerospace Center (DLR) has been working on in-situ Automated Fiber Placement (AFP) with different thermoplastic matrix materials with the goal to develop a suitable single stage manufacturing process for thermoplastic CFRPs. Different aspects of the scale-up were investigated including the overall ply design, manufacturability of complex areas of a fuselage, first ply adhesion, and the overall laminate quality with regard to weldability. The manufacturing of a test shell with 4 m diameter is presented in this work. It identified key areas of the process that require further refinement in order to assure manufacturability and weldability of AFP-produced parts. Using the results, a holistic approach to the manufacturing process is proposed for the direct manufacturing of large-scale components made with the in-situ AFP Process.*

Keywords: In-Situ AFP, Thermoplastic AFP, Full-Scale Demonstrator, Lightning Strike Protection, Aircraft Fuselage

1. Introduction

In recent years the development of thermoplastic in-situ AFP (T-AFP) process as a slim single stage production method for carbon fiber reinforced plastics (CFRPs) has been a focus of the Center for Lightweight Production Technology (ZLP) in Augsburg. Such a process is seen as an enabler towards the utilization of thermoplastic CFRPs in Aeronautics. Especially the omission of size limitations caused by ovens or autoclaves as well as the possibility of pre-equipping and dust-free joining of the differential designs make in-situ AFP a very promising process if mechanical performance and the scaling of the process can be demonstrated. The mechanical performance has been shown in the past on coupon level [1,2].

Upscaling of the process to manufacture a full-scale fuselage skin results in specific challenges: the composite design for TAFP has to be established, first ply adhesion and lightning strike protection integration has to be managed and a suitable machine layup for large component production has to be established. This paper provides a comprehensive overview on how these problems can be solved, shows specific experiments and results that have been conducted to solve these issues and indicates areas where additional work has to be investigated to upscale T-AFP.

2. Demonstrator Design

The design of AFP components is largely influenced by the existing and applied principles from the production of thermoset prepreg AFP components. Parts are designed to the nominal width and height of the prepreg tapes. Overlapping material and resin pockets that form in areas of wide gaps or missing tows are considered defects that weaken the AFP laminate [3]. One tool used to meet geometric requirements are defined gaps that are tolerated within certain limits dependent on the given component and material. Due to the downstream autoclave process necessary when using thermoset prepregs small gaps are filled with resin, resulting in a smooth laminate. Since this is not viable for an in-situ AFP process due to its transience, process specific design principles need to be defined. Viable design strategies must manage the gaps. On a process side this can only be achieved if either the process or the material is adjusted to a predetermined width. From a design perspective the two most effective measures are the inclusion of planned gaps or the adjustment of the ply geometry.

2.1 Design to Manufacture for in-situ T-AFP

The most important difference between the thermoset prepreg AFP and the thermoplastic in-situ AFP with regards to the design is the width of a single placed tape. With the in-situ process it is not feasible to calculate laminates based on the nominal width of the prepreg material. The material will be flattened due to resin flow and fiber movement and thus widened by the process itself. This behavior is highly dependent on the process parameters as well as the quality of the prepreg material. Apart from the material and process, the specific hardware and its attributes can limit the freedom of design. The design principles for in-situ AFP are as follows:

A consolidated tow width must be determined for a given set of process parameters and materials. The strategy for the lay-up is a zero gap/overlap strategy. Any deviation from a gap- and overlap-free lay-up will cause a noticeably grooved laminate as depicted in Figure 1. The grooves are visible through multiple layers and are not smoothed by consecutive layers.

Figure 1 : Grooved laminate due to insufficient gap sizes placed with in-situ T-AFP

The design is constrained in size to multiples of the consolidated tape width (CTW) perpendicular to the lay-up direction. Conclusively, it is not possible to design the transition between patches in ramps with consistent step sizes. This is not a problem for the performance of the laminate but is a significant difference to traditional AFP design. In order to maximize the design freedom despite this constraint it is desirable to have a standard CTW which is as small as possible. Consequently, the capability to drop tows and place single tapes is beneficial in order to realize intricate laminate designs for T-AFP. The design and the hardware are therefore codependent. This is also the case for the minimum length of track that can be placed. The minimum cut length

(MCL) determines the minimal size of single plies and the amount of excess material in the corners. It is therefore a crucial measurement for the design. Both CTW and MCL need to be defined for a certain set of process parameters, materials and the given hardware before the design can be tailored to the process.

2.2 Definition of Process limits for the Design

The MCL is machine specific. There will always be a free length between the nip-point and the point where the tape is cut. For the MTLH this length is approximately 125 mm. The MCL that can be placed with the MTLH at acceptable quality is 150 mm.
The CTW was experimentally determined for the TC1225 LM-PAEK at 125 mm/s lay-up speed and 500 °C control temperature. Three tapes in parallel were placed in two layers. The width was measured at 41.2 mm. Then multiple tracks with distances of 41.1 mmm, 41.2 mm, 41.3 mm and 41.4 mm were placed alongside each other and gaps and overlaps were measured. The results showed that 41.3 mm is the ideal CTW for the given operating point resulting in a smooth butt joint between tracks. The CTW was confirmed by the placement of full laminates with high lay-up quality.

2.3 Final Design

The final design of the test shell is shown in Figure 2. The overall height is 2270 mm, the width measures 3950 mm and the radius of the half shell is 1930 mm. The layer structure consists of 98 plies in total with fiber direction angles auf 0°, 45°, 90° and 135°. Besides the full-covering and partly covering layers covering the manufacturing edge of part (MEOP) there are three distinct reinforcement features: On the left side there is the octagonal antenna patch consisting of eight individual layers of all fiber angles, which will be placed with a gap/overlap strategy of dispersed gaps. On the right side there is a rectangular reinforcement consisting only of 0° and 90° layers. Finally, there is the octagonal center reinforcement with 34 individual layers which resembles the reinforcement of a door corner.

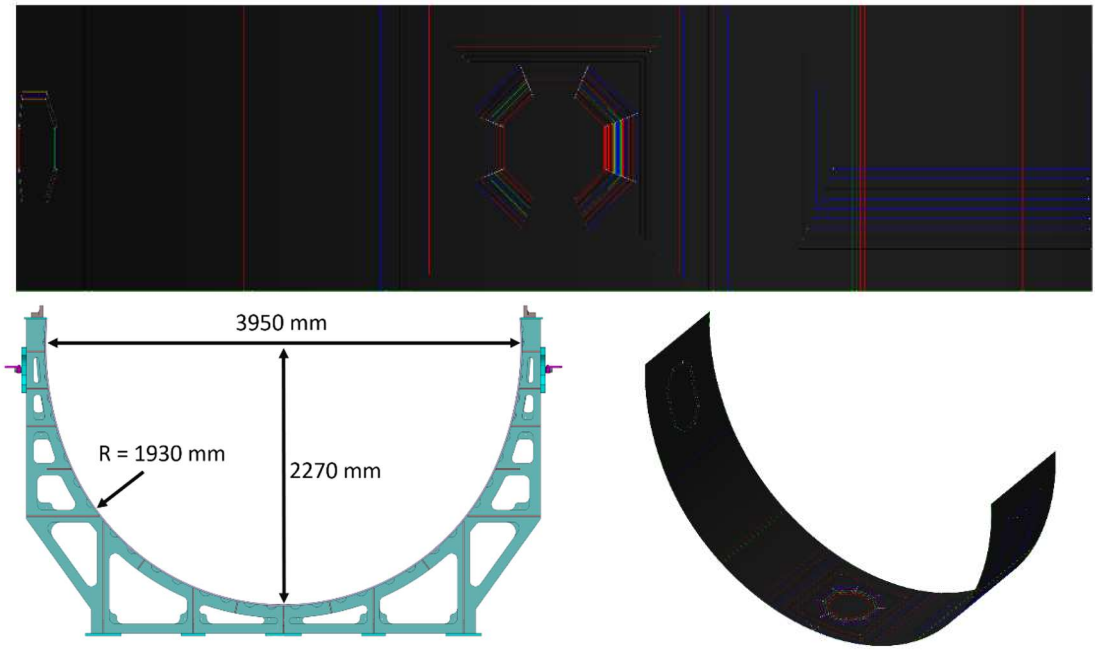

Figure 2 : Final design of the test shell – Measurements (bottom left) and two CAD views

Both octagonal reinforcements are designed with a 1:20 ramp angle. The rectangular reinforcement on the right is designed with a shallow ramp of 1:200 inclination. All features are designed like a real aircraft fuselage with the goal of a subsequent welding of support structures like stringers and frames. Except for the antenna patch all plies are done in an interleaved design, which is in accordance with typical CFRP fuselage designs. The antenna patch is placed on top of the last fully covering layer. This has been done to investigate a potential differential approach in which the reinforcement patches can be placed after the much larger covering layers – which are also more time consuming in production – are placed. The design consists of 9986.2 m of tape placed in 98 individual plies. The estimated weight is 38 kg.

3. First Ply Adhesion

A first ply adhesion is necessary for the process since there is no direct adhesion between a metal mold and the thermoplastic tapes. Therefore, an additional layer is necessary that is temporarily fixed to the mold and that allows a bonding of the placed tapes in order to transmit forces between the mold and the laminate. The bind between the adhesion layer and the tape can be a temporary or permanent.

3.1 Materials

A typical material used as a first layer between the mold and thermoplastic lay-up is polyimide. On the one hand polyimide has a sufficient temperature range of up to 400°C. On the other hand, polyimide forms a temporary bond with the LM-PAEK material which can be separated by mechanical force. Scaling has also been demonstrated before [4]. The polyimide film used in this study is 200HN Kapton from Dupont with a thickness of 50 µm. Another material used by the ZLP in the past is a pristine resin layer for first layer adhesion. The concept was proven for male tooling geometries such as pressure vessels. The pristine resin foil should be the same material as the placed tape. In this case VICTREX 150 LM-PAEK with a thickness of 60 µm. A major drawback however is the additional weight of the added layer, since it does not contribute significantly to the overall mechanical performance [5].
Thus, an adhesion layer that is also functional is desirable. In CFRP fuselages such as the Airbus A350 a lightning strike protection (LSP) layer is vital and is currently placed manually by trained workers [6]. An LSP layer consists of a copper mesh embedded in a matrix foil. Therefore, using LSP as a first adhesion layer dismisses the need for an additional process step altogether. Two different LSP versions were available to the DLR – a version with pristine resin and a blackened version.

3.2 Fixation Methods

The fixation of the laminate needs to transmit forces to the mold, thus ensuring the accurate position of the laminate throughout the entire manufacturing process. Easy demolding of the finished part is also a requirement for the fixation method that needs to be addressed. A vacuum strategy is generally suited for this purpose, but considering the size of the mold and the scale up the application is work intensive and prone to leakage. Thus, an alternative method of fixation using double sided adhesive tape certified for CFRP production is considered. This method has shown decent results on male tooling geometries in the past [5].

3.3 Experiments and Results

A first ply adhesion layer was set up on a planar lay-up surface with different combinations of material and fixation methods. Afterwards at least five tracks of 800 mm length were placed next to each other for four layers – totaling to at least 20 tracks per lay-up. The results were compared after the first and the last layer. Double-sided adhesive tape works well for male tooling geometries but proofed unsuitable for planar or female molds. Wrinkles occurred at the end of the track or at splices of the adhesion layer. This was observed for all materials and can be seen in Figure 3. The wrinkles show that material has been displaced by the process forces and the first layer needs to be fixed over its entire surface.

Figure 3: Wrinkles at the end of tracks caused by displacement of material

A vacuum setup is the most feasible approach and was tested for all materials. A breather layer that distributes the vacuum evenly is necessary for all investigated materials. This will cause the laminate to have a textured surface on the outside.

Table 1 : Performance of different adhesion layer materials

Material	Pro	Contra
Dupont 200HN Kapton	▪ Good lay-up quality ▪ Temporary bond	▪ No temperature control in first ply
VICTREX 150 LM-PAEK	▪ Good lay-up quality ▪ Comparably cheap	▪ No temperature control in first ply ▪ Prone to rupture at edged during process ▪ Additional weight without further advantage
LM-PAEK/LSP	▪ Good lay-up quality ▪ Additional functional layer enhances overall process ▪ Temperature control of first ply if blackened	▪ No temperature control in first ply ▪ Stiff and hard to handle for vacuum setup ▪ Limited size impedes scale up ▪ Material still in development

The trials showed that all materials are suited for the process. An overview of pros and contras for each material is given in *Table 1*. Due to the most logical benefits for the overall production of large fuselage panels the blackened LSP was chosen for the demonstrator.

3.4 Scaled LSP First Ply

The first step of production is the application of the adhesive layer. One major difference is the necessity for splicing two sheets of the LSP foil in order to cover the entire part with one vacuum system. The splice is done with Kapton adhesive tape which faces the mold. The vacuum connectors towards the pump are located on both sides of the mold at the top edges of the MEOP as well as at the bottom of the mold. In order to secure leakage from the vacuum the LSP was double sealed towards the mold – one seal with double sided adhesive encircling the MEOP and in addition a Kapton adhesive band on all edges. The stacking of the entire vacuum setup is displayed in Figure 4. Using this setup, the vacuum was successfully kept under 50 mBar over the entire production time. However, an optimized distribution of connectors for the vacuum pump is necessary for larger parts.

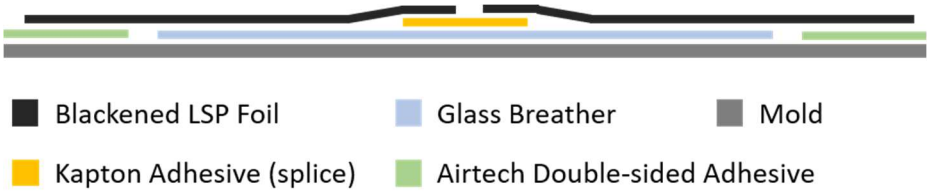

Figure 4 : Stacking of the vacuum fixed adhesive layer

4. Full Scale T-AFP Manufacturing

The design presented in 2.3 was placed on the LSP adhesive layers with the T-AFP process. Used machinery and the results of the manufacturing process are discussed in the following.

4.1 Machine Setup

The manufacturing of the test shell was done with a Multi Tow Lay-up Head (MTLH) by AFPT mounted on a KUKA Quantec KR120 R2700 extra HA industrial articulated robot. The robot is mounted on an additional linear drive. The MTLH places three ½" tapes in parallel. Its heat source is a 6.6 kW pulsed diode IR laser emitting a wavelength of 1090 nm. The lay-up speed of the process is 125 mm/s. The Tooling used for the layup is made from invar steel. The MTLH and the entire setup is depicted in Figure 5.

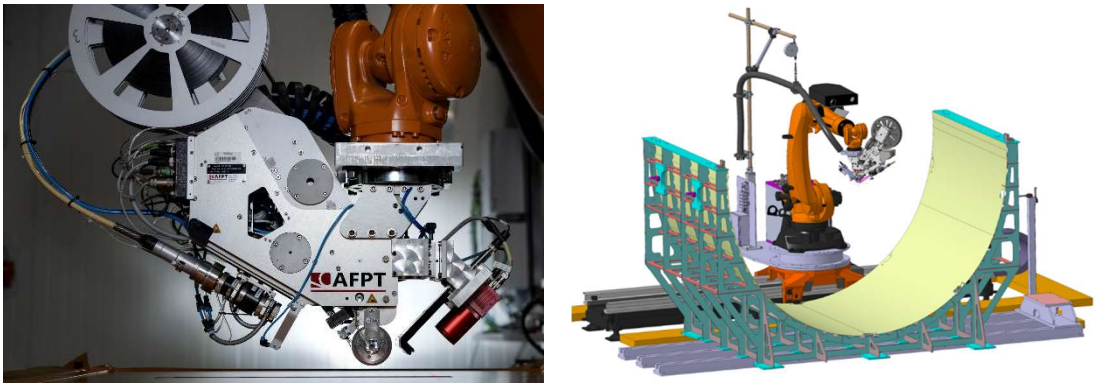

Figure 5 : Machine setup - MTLH AFP endeffector (left) & CAD layout of the robotic cell (right)

The offline Programming of the robot is done using the software 'Vericut Composite Programming' (VCP) from CGTech.

4.2 Machine Lay-up

The lay-up worked well at a process speed of 125 mm/s. The maximum deployment rate at this speed is 5 kg/h and is therefore relatively low especially compared to industry standard thermoset AFP where process speeds reach over 1500 mm/s. The transfer of the zero gap/overlap strategy worked well from panel to the large mold. The result of the first ply is shown in *Figure 6* (top left). The result was a smooth surface without noticeable wrinkles.

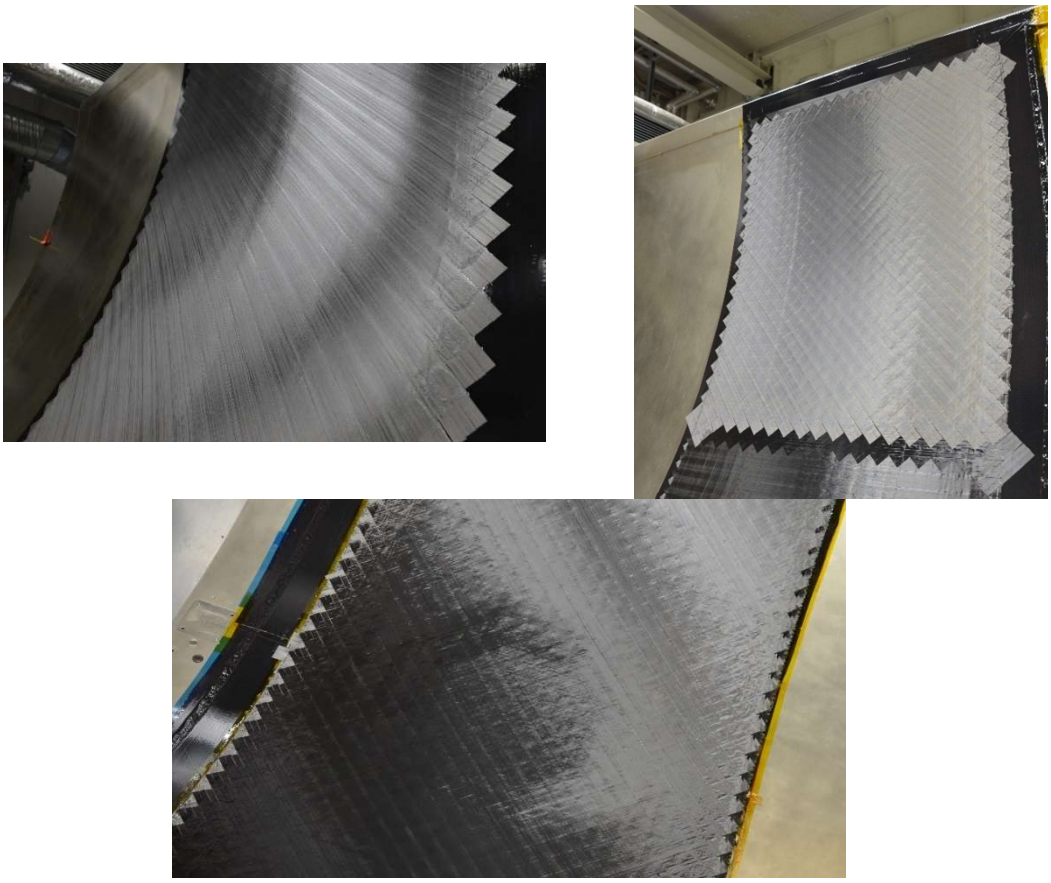

Figure 6 : Examples of laminate quality after plies 1 (top left), 22 (top right) and 98 (bottom)

The quality of the lay-up and the surface quality was found to be good for the first layer as well as consecutive layers. This was observed for the entire part. Even at the thickest area of the test shell – the octagonal door corner support with 70 layers – the lay-up quality was good on visible inspection Figure 6 (bottom). Thus, the proposed design principle for zero gaps and overlaps is successful for the in-situ T-AFP process. The second design strategy of dispersed gaps was applied to the final reinforcement layer. The resulting surface quality after eight placed layers is rough. Since staying within the designed boundaries of a ply is the main focus of this placement strategy, additional staggering cannot be implemented. The combination of defined gaps and no staggering results in a laminate which is holey for several layers down. Figure 7 shows the final result of the antenna patch. The difference in layup quality is apparent compared to the first lay-up strategy. The rough laminate quality is also impacting the overall process due to overheating in the trenches resulting in an inhomogeneous temperature measurement via thermal imaging. This is not acceptable for the internal power control loop which relies on the observed temperature to adjust the laser power.

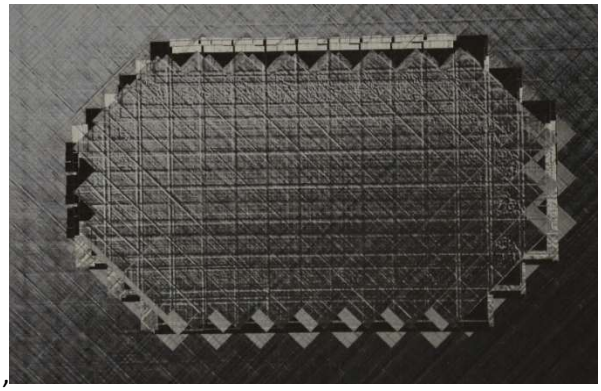

Figure 7 : Antenna patch placed on top of the laminate with dispersed gaps

There were two major problems regarding the scale up. Firstly, the staggering of plies caused issues with the lay-up. Secondly, the durability of the compaction rollers made from silicone is problematic for a smooth flow in production.

The staggering was done in steps of ⅕ of the tape width. Thus, after five consecutive staggering steps placement started from the initial position relative to the edges. This however led to issues with tape placed on a slant with at least one of the tapes not in contact with the laminate. The main defect caused by this was bridging of the tapes in 90° tracks. This can be easily avoided if staggering is done in only one direction over the entire laminate.

Two different silicones have been used in the past as compaction rollers for the T-AFP process. Both silicones were recommended by the machine manufacturer for use with the MTLH. Sylgard 184 from DOW with a shore hardness of 43 A and SF45 a casting silicone with a shore hardness of 45 A. The MTLH has a cooled compaction roller with a silicone cover. Since the silicone is a thermal isolator it heats up from the process significantly and despite the active cooling from its inside. The accumulated heat and the resulting residual temperature are therefore directly linked to the length of placed tracks and the duration respectively. The temperature of the silicone was not constantly monitored, however the thermal camera measured temperatures of up to 230 °C during the production. The longest tracks had a length of 6500 mm. The two silicones started to disintegrate after approximately 180 m (Sylgard 184) and 350 - 450 m (SF45) respectively. After this operating length the silicone covers became increasingly brittle and showed visible cracks. The Sylgard 184 silicone lost material debris if used further, which contaminated the laminate. Further, once the silicone becomes dull and brittle the process leaves a mark on the placed material and the placed surface is noticeably dull. Therefore, a regular change of silicone roller is essential.

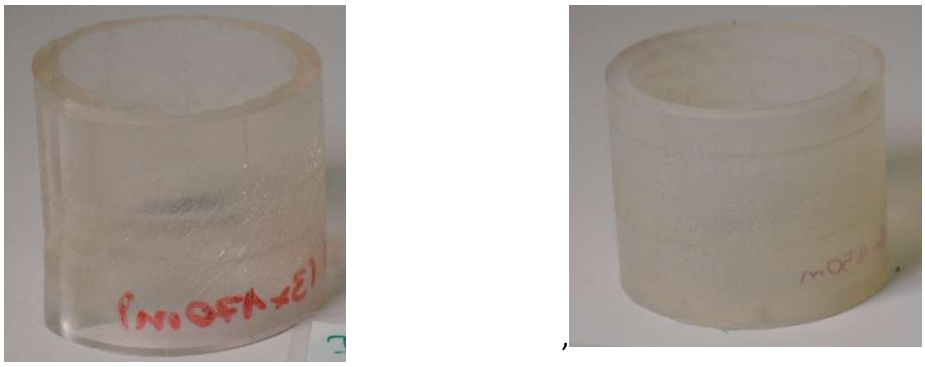

Figure 8: Degraded silicone covers: Sylgard 184 after 170 m (left) & SF45 after 450 m (right)

4.3 Lessons Learned

The successful placement of the entire test shell helped to understand the dynamic of the scale-up of a part manufactured with T-AFP. Specific actions for the overall process can be derived from the result.

First Ply Adhesive Layer
Beginning with the build-up of the adhesive layer there are three major points of improvement. The quality of the LSP foil needs to be increased. Splicing of the foils needs to be refined with a focus on vacuum tightness. Lastly, more vacuum connection points are needed for an even distribution of the vacuum and thus a secure fixation of the laminate within the mold.

Silicone Compaction Roller
The durability of current rollers is not acceptable for a large-scale production. High temperatures caused by long tracks accelerate the decay of the silicone. There are several actions that can mitigate the problem. Another silicone which is more durable and heat resistant can be used for the compaction unit. In addition, the geometry of the silicon can be adapted for a better heat transfer (e.g. thinner silicone layer). Last, the heat flux of the cooling system can be significantly increased to further cool and thus preserve the silicon layer.

Design
A design with dispersed gaps planned over a fixed geometry of a ply is not feasible for in-situ T-AFP. Further, the stacking needs to be planned in a way, that the direction of the staggering is always the same in order to prohibit edges on which the endeffector cannot deploy material without noticeable defects.

5. Conclusion & Outlook

A total of 9986.2 m of LM-PAEK tape in 98 plies were placed to build the half shell demonstrator with in-situ T-AFP. The lay-up was done on a functional LSP layer. The scaling of the LSP adhesive layer for larger parts will require an improved slicing of the individual sheets. The deployment of tape with zero gap and overlap strategy resulted in a smooth surface and laminate of high quality. The design of the laminate needs to be suited to the specific consolidated tape width of the used material. This may limit certain designs in the future. The biggest issues of the process with regards to scale-up are frequent material changes and a high degradation rate of the compaction rollers made from silicone. This will cause down times and ultimately limit productivity. Increased cooling of the compaction roller as well as alternative silicones with better heat resistance will be investigated for improvement. In general, the T-AFP process has proofed to be scalable to large components. With a maximum deployment rate of 5 kg/h at current process speeds the productivity is relatively low. However, due to the slim single stage process, manufacturing times can be viable – especially if additional measures such as deployment of more tape in parallel are taken. Investigation of laminate quality at higher speeds are ongoing. The next step for the test shell is the integration of stiffeners by means of ultrasonic and resistance welding. A larger demonstrator with 8 m length is planned to be built in summer 2022 which will demonstrate the improved process on an even larger fuselage with more complex features such as a fully reinforced door surround and stepped longitudinal edges for the joining of two shells.

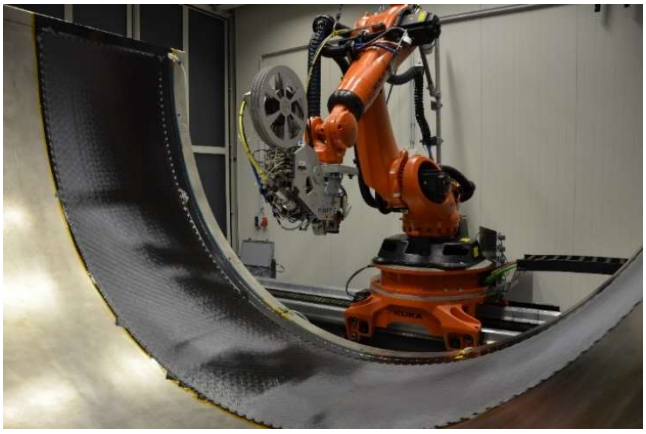

Figure 9 : In-situ AFP-manufactured half-shell in the DLR facility in Augsburg

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Disclaimer

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