AUTOMATED FIBER PLACEMENT BASED MANUFACTURING OF CARBON FIBER REINFORCED SANDWICH HELICOPTER SIDESHELLS

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ABSTRACT

Robot based Automated Fiber Placement is one of the most promising manufacturing technologies for the highly automated production of complex parts that involve carbon fiber reinforced plastics. A possible new application in the aerospace field are shell parts that contain sandwich areas. Their complex geometry poses specific challenges.

Different approaches for path planning were evaluated based on criteria such as angular deviation, fiber steering and surface cover ratio. We developed a trajectory generation method, which allows flexible, local adjustments. Machine parameters were optimized experimentally in order to minimize characteristic layup imperfections on ramps. The derived machine configuration was used for the manufacturing of one feasibility part, alongside the developed process chain was validated.

The results provide the manufacturing engineering solution and the experimental proof of concept for AFP-based production of sideshells for the RACER highspeed helicopter demonstrator. The proposed reference curve generation methodology might also be beneficial for other complex part geometries.

1. INTRODUCTION

Sandwich structures offer high stiffness at low weight, which is why they are broadly used in civil and military aircraft [1]. Examples of applications in the Airbus aircrafts are external structures like aerodynamic fairings, covers and doors [2]. Because of their high performance-to-weight ratio and the need for very high function densities, helicopter airframe structures are among the most complex in commercial aerospace applications [3]. As the production rates are usually low, the corresponding production technologies, such as the honeycomb-prepreg manufacturing route, are often still based on manual process steps [3]. However, first attempts were made to substitute parts of the process by automated production techniques [4–6], in order to reduce manufacturing lead time, save production costs and improve the environmental footprint by material scrap and reject rate reductions. Further, by using innovative manufacturing techniques, new design and stress approaches can be realized.

A technology that received attention in this context is Automated Fiber Placement (AFP). Typically, AFP uses a deposition head mounted on a conventional 6-axis robot to layup continuous fiber reinforced material in the form of several tows simultaneously onto a mold. Hereby, the degrees-of-freedom of a robot-based AFP system enable a net-shape layup of complex 3D-parts. However, layup width is a discrete function of the actual tow width. Therefore, a full coverage of surface requires parallel trajectories, which are non-geodesic on a double-curved surface [7]. Such layup operations require the movements of the head to involve a z-rotation component, and are often referred to as fiber steering [8]. Simplified, this corresponds to an in-plane bending of the tow, and therefore causes tensile and compressive stress in material [9]. This stress state can result in effects such as tow misalignment, tow buckling or tow pull up [8]. Corresponding experimental studies often focus on the achievable layup quality with respect to the radius and the material-specific processing parameters [10–12].

For those reasons, manufacturing engineering is an important topic towards the application of AFP to actual parts. Defects that result from the perpendicular cutting of the material during the layup process and their effect on part performance were extensively studied in literature [13–15]. As these geometry dependent defects need to be balanced with the angular deviation and tolerable fiber steering, manufacturing aspects already have to be considered in the design process [6]. For manufacturing engineering operations, usually CAD-based modelling and simulation tools are used, as proposed by Shirinzadeh et al. [16]. Rousseau et al. [7] recently reviewed different approaches for Automated Fiber Placement path planning, covering geometrical aspects of reference curve generation and coverage strategies. Lichtinger et al. [17] addressed the layup behavior on sandwich ramps for two different trajectory curves from simulative and experimental side for a single, plane core.

The AFP path planning on large, double curved surfaces with sandwich core areas was not considered in literature yet. However, solutions are required to close the gap towards the application of the process for the production of real parts, such as helicopter sideshells. The goal of the project addressed by this study is the AFP-based manufacturing of two airworthy sideshells for RACER Integrated Demonstrator Platform (IDP) [18, 19]. Fig. 1 shows the location of the focused parts in a digital mock-up of the helicopter. During proof of concept phase, aspects of manufacturing engineering, layup process development and process chain definition were addressed by case studies, which are described in this paper.

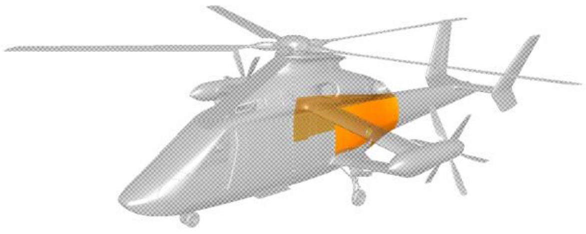


Figure 1. Digital mock-up of RACER IDP; focused sideshell parts are highlighted

2. CASE STUDIES

In order to investigate the applicability of the AFP process for the manufacturing of sideshell parts with complex geometry and sandwich areas, two case studies were performed.

2.1 Technical challenges

Three main technical problems were identified and addressed in this study:

1. Manufacturing Engineering: Fiber architecture of unidirectional tows on complex surfaces with ramps

Complexly shaped surfaces with ramp areas cannot be covered perfectly in AFP layup technology when boundary conditions such as limited angular deviation must be complied with [7]. One reason behind this is the limitation that the material can only be cut perpendicularly to the feeding direction in the layup process. Therefore, angular adjustments result in triangularly shaped defects, which might affect the final part properties such as the mechanical performance [13–15]. To avoid multiple zones of triangular defects, fiber steering capabilities of the machine must be used to generate an adjusted fiber architecture.

2. Layup process: AFP layup in discrete sandwich areas

The layup quality that is achievable in AFP process depends on various factors such as material, processing parameters, mold surface properties and geometry. Sandwich ramps can be considered a technical challenge, as layup in these areas requires extensive machine movements to avoid collisions of the layup head with the tool. At the same time, fiber architecture often is non-geodesic. Adjusted machine configuration and processing parameters can help to ensure appropriate layup quality in these areas.

3. Process chain: Wet-skin transfer concept

For helicopter skin parts, the outer mold line (OML) needs to be in contact with the curing tool during autoclave curing. Therefore, hand layup is often conducted on female molds. However, because of local areas of small curvature, such molds are not accessible by AFP layup heads. Therefore, AFP layup needs to be conducted on a male layup tool. Compared to a female mold production scenario, ramp layup is conducted on a rigid mold instead of the fragile core material, which allows layup with full compaction force. After layup, a transfer of the wet preform to the curing tool is required.

2.2 Part definition

Two different parts are considered in this study. Fig. 2 depicts both. The first one is a demonstrator part that is to be manufactured for RACER helicopter. It contains eight honeycomb cores with a ramp angle of 20° and a height of 15 mm. The second one is a generic shell part with discrete honeycomb cores, that have a ramp angle of 25° and a height of 15 mm. Both parts contain double curved surfaces.

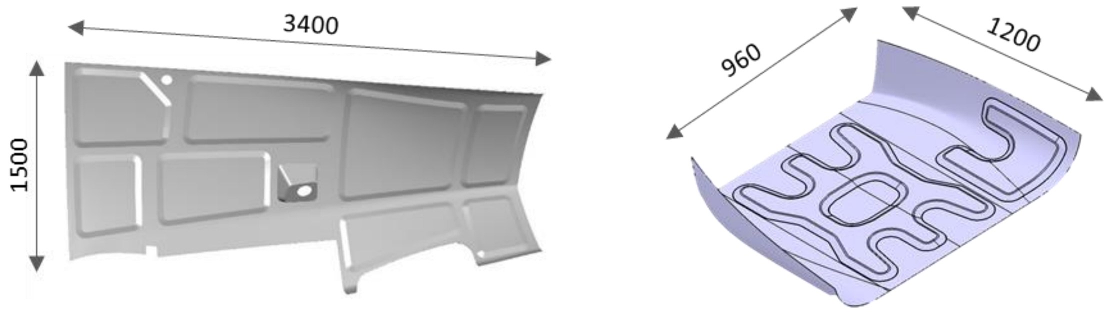


Figure 2. Parts considered: sideshell (left), generic shell part with discrete cores (right)

Manufacturing engineering development was conducted based on the sideshell geometry, as scale and other geometry effects were expected. Due to economic and availability reasons, experimental studies on layup process and process chains were examined with the generic shell structure. A representative, 4 tow wide tape that contains different ramp aspects was chosen for parameter optimization. For analysis, this tape was divided into seven regions of interest (ROI), as depicted in Fig. 3.
Characteristic defects were defined, according to [20] and [21]. Based on the appearance and extent of these defects, the layup quality in each ROI was evaluated by visual inspection.

2.3 AFP Machine and manufacturing engineering software

The layup experiments were conducted on a state-of-the-art industrial robot based 8-tow C1 AFP machine by Coriolis Composites (Lorient, France). Manufacturing engineering operations are conducted in CATFiber 1.8.5.2, a Plug-In for CATIA V5 by Coriolis Composites.

2.4 Material

Pre-impregnated unidirectional composite slit-tape with 8552 epoxy matrix and AS7 continuous carbon fibers (CF) was supplied by Hexcel Composites (Stamford, United States) in the form of ¼”-tows for the purpose of this study (8552/AS7/145gsm/34%). The material had a fiber areal weight of 145 gsm and a nominal resin content of 34% by weight.

2.5 Criteria in manufacturing engineering study

During manufacturing engineering development, different curve types and coverage strategies were investigated for the application on the sideshell geometry. To characterize the suitability of the proposed curves for part realization, three criteria were defined:

- Angular deviation: analysis of the local fiber misalignment; the angular deviation is calculated relative to the translated global axis system; goal is to minimize the angular deviation.
- Fiber steering: analysis of the local steering radius; the layup quality depends on this curvature; 600 mm was defined as material- and case-specific threshold based on preliminary layup trials.
- Cover ratio: fraction of the surface covered by fiber; this addresses the impact of triangular shaped and longitudinal gaps; goal is to maximize the cover ratio.

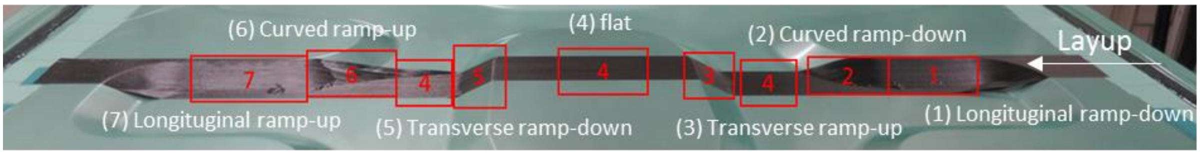
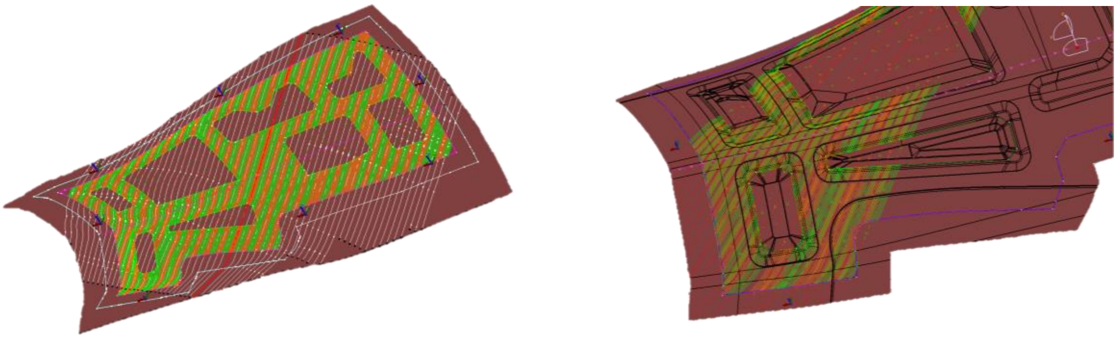
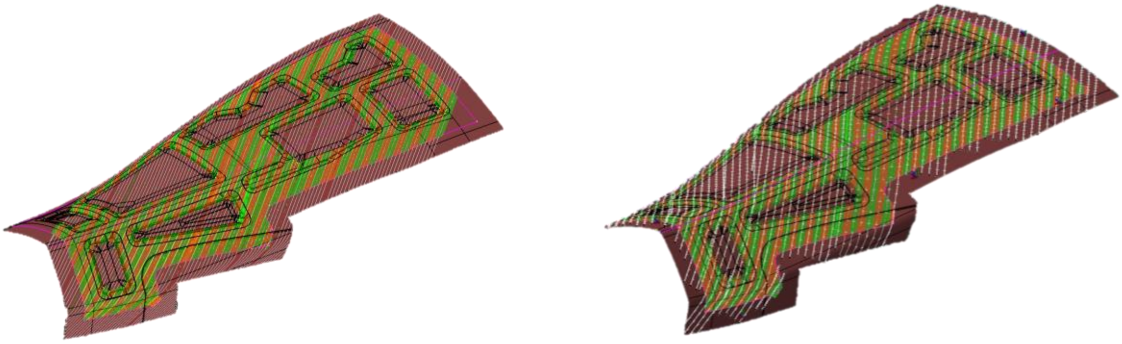


Figure 3. ROI definition for layup parameter optimization



(1) Parallels

(2) Geodesic lines



(3) CATFiber line pattern

(4) Knowledge-based spline template

Figure 4. Tape generation results (orange/green) based on different line types taken as guide curves

3. RESULTS AND DISCUSSION

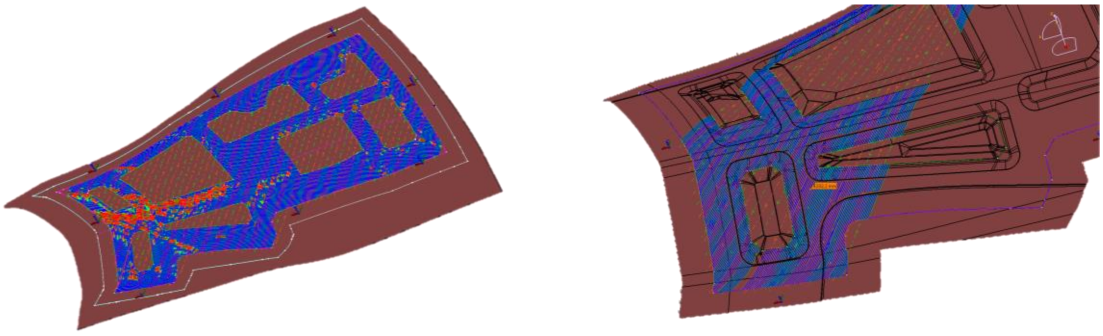
3.1 Manufacturing Engineering

Three curve types were investigated during the preliminary assessment:

1. Parallels to initial curve based on the global axis system of the part. This corresponds to the offset curves approach, which is the most common path planning strategy in the AFP field according to [7].
2. Geodesic lines in desired fiber angle and standard course wide shift (50.8 mm) on the neutral fiber. Geodesics are curves of zero geodesic curvature [22]. As an alternative, frequently used definition, a geodesic path is often described as the shortest path on a surface [7].
3. CATFiber Curve Network line pattern based on the neutral fiber.

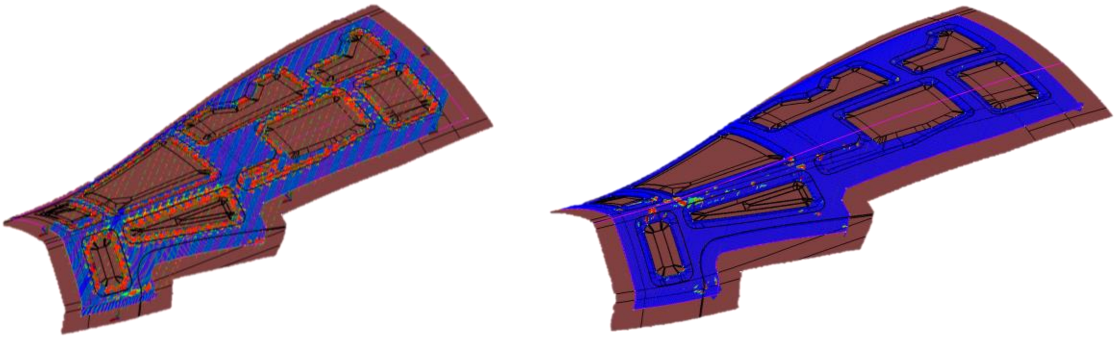
Tape generation results based on these curves are presented in Fig. 4 (index 1-3) for a 135° ply with cutouts in the sandwich areas.

Fig. 5 and Fig. 6 show the corresponding results of the fiber steering and the angular deviation analysis, respectively. The simple parallels approach (1) leads to high angular deviations in double curved areas. Furthermore, a high amount of fiber steering could be found in double curved areas that are in certain distance from the initial curve. The all geodesic approach (2) did not show any steering by the definition of the curves. However, angular deviations were high, which correlates with the results of Lichtinger et al. [17]. Also, this approach would result in a very low cover ratio, as triangularly shaped defects occur between all courses. The curve pattern created with CATFiber (3) showed good global results. However, curves tended to deflect when going over ramps, which results in high steering and local angular deviation in these areas. As fiber misalignments in ramp areas were found to be crucial [23], this cannot be tolerated.



(1) Parallels

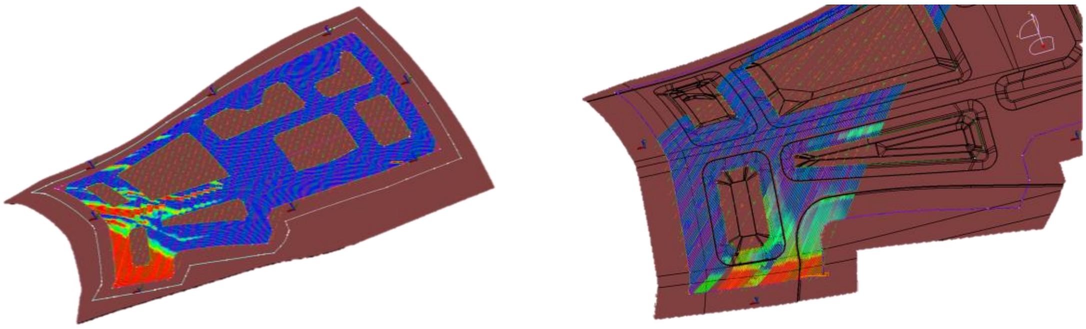
(2) Geodesic lines



(3) CATFiber line pattern

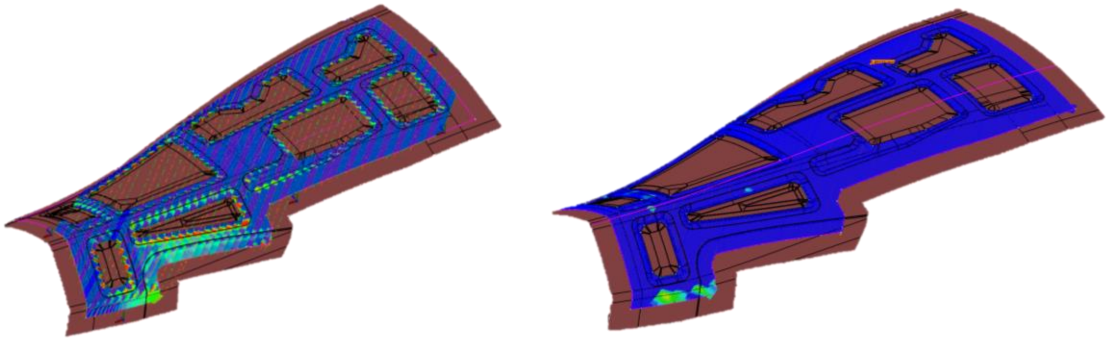
(4) Knowledge-based spline template

Figure 5. Color-coded result of Steering analysis for tapes based on different line types; radius > 800 mm depicted in blue, radius < 600 mm depicted in red



(1) Parallels

(2) Geodesic lines



(3) CATFiber line pattern

(4) Knowledge-based spline template

Figure 6. Color-coded result of Angular analysis for tapes based on different line types; deviations < 5° depicted in blue, deviations > 10° depicted in red

These results show that none of the standard curve types provides a suitable general solution for this complex problem. Therefore, a flexible trajectory generation is necessary, which allows local adjustments to overcome geometrical challenges. This was implemented in the form of a knowledge-based template. When applying this template to a suitable base curve, a certain amount of points is built on the curve in a specified spacing. These points define a spline. The shape of the resulting curve can be controlled by adjusting the point locations via design parameters. The adjacent spline can then be either based on the first curve or based on a new base curve. As in both cases, the shape of each curve can be controlled individually, this method can be classified as independent curve method according to [7]. Fig. 7 shows the template applied in a curved ramp section. Points P_{n-1} and P_n were adjusted to compensate unwanted curvature of the base curve.

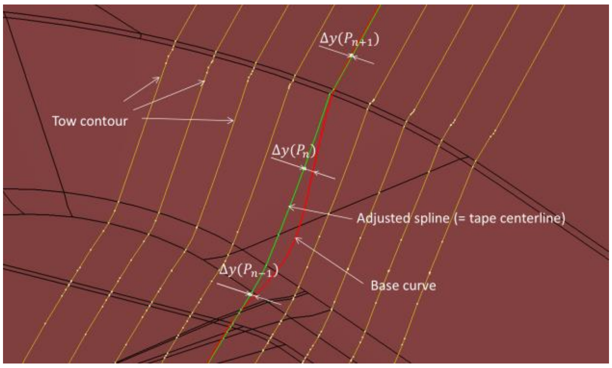


Figure 7. Application of knowledge-based template in curved ramp section

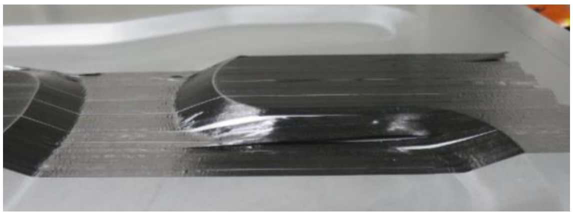
The results achieved with the spline template method (index 4 in Fig. 4-6) are better in terms of fiber steering and angular deviation compared to the other three curve types. By slight adjustment of local points, small longitudinal defects can be designed to address geometrical changes such as ramps in fiber direction instead of large triangular defects in tow drop areas of independent curve approaches [24]. Even with a high amount of core areas, cover ratio as high as 99% could be achieved. Another advantage of the spline based method is that it allows subsequent adjustments, which is useful for curve corrections based on a preliminary experimental validation.

3.2 Experimentation

Three kinds of defects were observed during the process parameter optimization study. These were tow pull-up, wrinkle formation and bridging, as depicted in Fig. 8. All these defects were previously described by Heinecke and Willberg in their review article on AFP manufacturing-induced imperfections [20] as well as by Harik et al. [21]. The following observations were made:

- A compaction roller with a smaller, adjusted width (27 mm) is preferable over a standard 8-tow roller (54 mm), as it particularly reduced the frequency and extent of tow pull-up and bridging
- Increasing the compaction force can reduce bridging (ROI 2, 6) but increases wrinkles on longitudinal ramps (ROI 1, 7)
- Toolpath smoothing increases the layup quality, in particular on longitudinal ramps (ROI 1, 7)
- Increasing the TCP speed does not reduce overall layup quality by default

Tow pull-up



Wrinkles

Bidging

Figure 8. Defects observed for AFP layup on ramps

The derived parameter set was used for the layup of an entire feasibility part. The part has a stacking sequence of [0°/45°/90°/-45°]s, with the honeycomb cores in the plane of symmetry. Fig. 9 shows the four plies of the Inner Mold Line (IML) side facesheets after layup on the left and the layup process of a ply of the OML side facesheets after core integration.

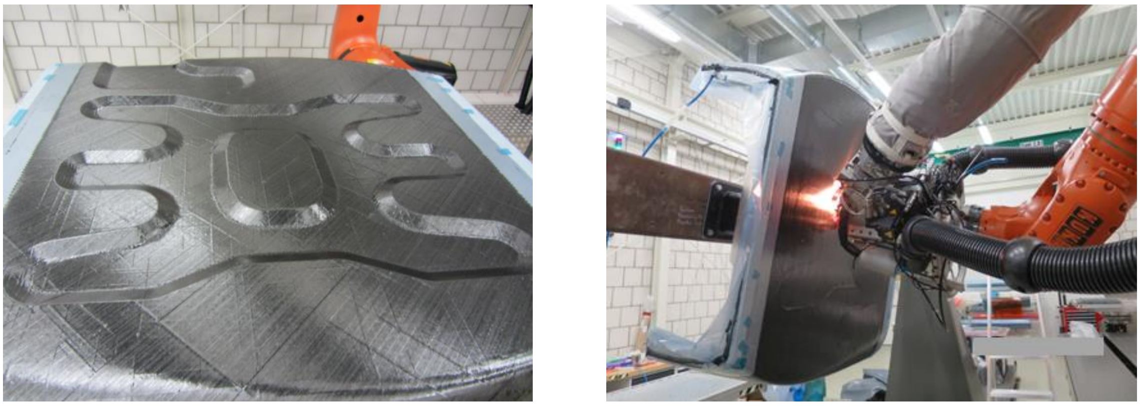


Figure 9. AFP layup of the generic shell part: inner skin (left), outer skin (right)

Fig. 10 depicts process chain developed. In order to avoid any damage to the wet panel, a film based approach was chosen.

First, a stretchable layup film was applied to the layup tool surface using conventional vacuum bag technique. Then, the wet preform was layed up onto this film in the AFP process. Subsequently, the curing and layup tool were aligned. The film was detached from the layup tool and attached to the curing tool. Finally, the layup tool was removed. The proof of concept was achieved by an experimental validation of the process chain by means of manufacturing the generic shell part (Fig. 11).

4. CONCLUSION AND OUTLOOK

The results of the study provide the manufacturing engineering basis as well as the experimental proof of concept for the AFP based manufacturing of complex sideshell parts with sandwich core areas. Two airworthy sideshell sections for the final assembly of the airframe of CleanSky2's high-speed helicopter demonstrator are to be produced with the developed manufacturing process. The premise for this helicopter is to reach the best trade-off between speed, cost-efficiency, sustainability and mission performance. The efficient manufacturing process for sideshell parts developed in this study have been an essential contribution to reach these goals. In order to further reduce manual labor aspects, alternative core materials, such as polymer foams, might be considered, as they could possibly be integrated to the structure without adhesive films. The feasibility of the direct layup on polymer foam cores was demonstrated by the manufacturing of a generic shell part.

The developed knowledge-based template is a useful tool for detailed programming of complex reference curves, which might be well applicable to other part geometry types. However, in the current state, it involves several manual steps, which makes the manufacturing engineering time and cost intensive. The use of CATIA macros might help to automatize parts of the programming process. Because of the complex nature of the curve adjustment problem and the many parameters involved, the implementation of artificial intelligence algorithms might however be necessary in this context to reach a comparable quality.

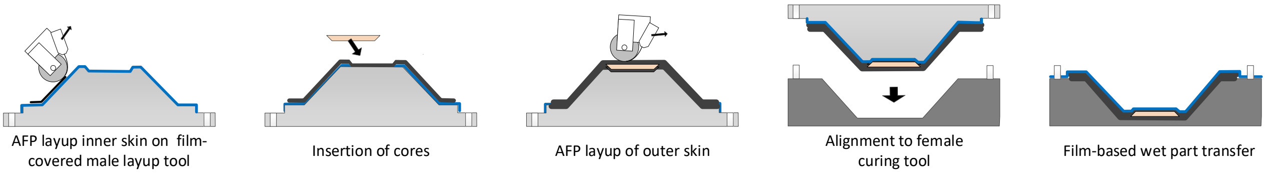


Figure 10. Process chain for AFP based sideshell manufacturing

Figure 11. Generic shell wet panel on curing tool after transfer (left); cured generic shell part (right)

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