Closing the Quality Gap of thermoplastic AFP: Insights from the Production of the Multifunctional Fuselage Demonstrators Upper Shell

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Abstract:
The CleanSky II Multifunctional Fuselage Demonstrator (MFFD) is the world's largest known aviation structure made from thermoplastic composites. The German Aerospace Center (DLR) Institute of Structures and Design with its Center for Lightweight Production Technology (ZLP) in Augsburg manufactured the 8-meter-long upper shell of the Multifunctional Fuselage Demonstrator. Together with the partners Premium AEROTEC (PAG), Aernnova (ANN) and AIRBUS, the consortium delivered the full-scale upper shell demonstrator. The lay-up of the skin for the 8m demonstrator was done by means of thermoplastic Automated Fiber Placement (AFP) in order to demonstrate a lean and fast production for the fuselage. Several challenges occurred during production resulting in a suboptimal quality of the placed skin. This paper gives an insight into the root causes of the encountered problems during the AFP process and presents approaches to improve the thermoplastic AFP process to overcome the quality gap observed in the skin.

Keywords: Thermoplastic Composites, CF/LM-PAEK, Automated Fiber Placement, in-situ Consolidation

Introduction

Thermoplastic Automated Fiber Placement (AFP) is considered to be a lean production process for large thermoplastic structures. Although the process has been in development with different thermoplastic materials and heat sources for more than four decades, the quality gap between components manufactured strictly in-situ and the respective hot press or autoclave benchmarks has prevented widespread use of the process. Considering the opportunities for an advanced production of large structures without the need for an autoclave, the thermoplastic AFP process was chosen for the skin manufacturing of the MFFD. The production of the skin was validated on a slightly smaller scale in 2022 and subsequently scaled-up to the full 8 m long, 4 m diameter half shell that is now part of the finished MFFD [1]. Several major issues regarding the material and scaled production were reported in [2] causing the overall quality to be subpar compared to the intermediate demonstrator and the lab scale specimen used for process maturing. Reported issues and their respective impact on the process and the overall laminate quality are listed in Tab. 1.

This shows that there were significant quality detriments due to production issues that may explain the overall improvable quality observed in the laminate and shown in Fig. 1(left). However, the direct comparison to in-situ AFP manufactured plates from Suprem LM-PAEK (Fig. 1, right) shows that the in-situ AFP can delivers good laminates with little defects under ideal conditions.

In general, the problems observed during the manufacturing of the MFFDs upper shell are either originating from material issues or process related circumstances not present in a lab-scale test. In order to close the quality gap two approaches are conceivable: first a detailed analysis into the wrought materials and their impact on the process. Second,

Tab. 1: *Manufacturing Issues during skin placement of the MFFDs Upper Shell*

Issue	*Root Cause*	*Impact on quality*
Fiber/matrix distribution	Dry surface of tapes	Poor interlaminar consolidation
Variation in tape quality	Material production process allowance to high	Significant drop in mechanical performance
Strong spring-in	Complex ply design with local reinforcements	Insufficient Consolidation Force
Vacuum Breach	Vacuum distribution underneath large area insufficient	Skin did not stay in place during production
Overheating of equipment	Length of placed tracks	Disintegration of compaction roller

cost effective secondary process steps, in order to increase the reproducibility of the mechanical performance, such as annealing. Afterwards, scaling issues as seen in the MFFD lay-up can be addressed accordingly.

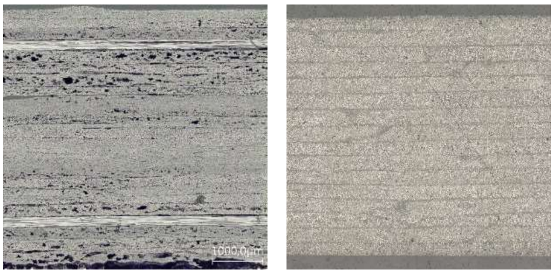

Fig. 1: *Comparison of microsections taken from the MFFD window cutout (left) and the lab specimen placed in-situ with Suprem 55% LM-PAEK (right)*

This work therefore focusses on mechanical results of thermoplastic AFP flat test specimen manufactured with the most suitable tapes for the in-situ process and show the impact of subsequent treatment. The comparison to benchmark specimen reveals a way forward towards the goal of a flexible and lean manufacturing of a fuselage with in-situ thermoplastic AFP.

State of the Art

Contrary to thermoset AFP which is used for example in the manufacturing of the Airbus A350 or Boeing B787 fuselages [3], thermoplastic AFP has not been widely used in the aerospace industry in the past. Potential advantages of thermoplastic AFP for aircraft manufacturing include a cost-effective single step manufacturing with subsequent opportunities for assembly such as thermoplastic welding. The resulting dust-free assembly offers unique equipment strategies like pre-installation of electrical components that further enhance overall productivity [1].

Generally, there are two approaches to in-situ consolidation that use either a heated or a cold tooling. On a cold tooling the cool down of the laminate is immediate resulting in little crystalline structures within the matrix thus generating components with less favorable mechanical properties. A heated tooling slows the cool down and depending on the tooling temperature even promotes crystallization in the placed laminate if the tooling temperature above glass transition is chosen.

For CF/LM-PAEK a previous study found ILSS (Interlaminar Shear Strength) values of 67 % of the benchmark for specimen placed on an unheated tooling at placement speeds of 125 mm/s [4]. In comparison, [5] reported a maximum ILSS value of 49.9 MPa at crack initiation for samples placed on a 250 °C tooling with an otherwise comparable setup. This is 74 % of the strength of a pressed reference laminate of the same material. The crystallinity of laminates placed on a heated tool reach 23.7 % compared to 26.7 % crystallinity of the pressed reference [5]. In [6] good consolidation quality of 63 MPa in a short beam shear test (SBS) with porosity below 0.5 % is reported. The results were achieved at speeds of 50 mm/s on a heated tooling with a temperature of 100 °C. This equals to roughly 70 % of the reference strength.

Experimental Setup

The machine setup for the AFP process in this work is comparable to the setup used in the MFFDs skin manufacturing with a Multi Tow Lay-up Head (MTLH) provided by AFPT GmbH. A 6 kW Diode Laser from Laserline is utilized as heat source with a rectangular optic focus of 43 × 43 mm². The layup machine is mounted on a KUKA Quantec KR120 HA articulated robot. Three ½" tapes are placed in parallel resulting in a nominal width of 38.1 mm.

The process parameters for the thermoplastic AFP are the same that have been optimized within the MFFD project. Due to the use of the identical resin and overall comparable materials the manufacturing with the existing process parameters still show the best results. Process speed is set to 125 mm/s, compaction pressure is 6 bar and set point temperature is set to 500 °C which is equivalent to 364 °C nip point temperature [4]. Overall three different tapes are considered: The initial MFFD material from Toray and two different Suprem materials at 55% and 60% fiber volume fraction (FVF). The Toray material is TC1225 with a fiber areal weight of 194 g/m² combining a T700 fiber with Victrex LM-PAEK matrix. Both Suprem tapes use the same Victrex matrix system as the Toray material. Instead of the T700 fibers AS7 fibers are used. Further, the Toray tape is slit into its final width ½" whereas the Suprem tape is directly produced in its final width. All produced sheet laminates have a unidirectional (UD) ply design and were tested mechanically with a five-point bending (5PB) test according to DIN ISO 19927:2018 to determine the ILSS values. This was done after a regular SBS according to DIN EN 2563 proofed to cause irregular plastic failure limiting the accuracy and universal validity of the test method. This was also stated in [5] which found that compared to the regular method of ILSS characterization with a three-point bending test, the results for thermoplastic test specimen is more reliable due to interlaminar crack initiation that can be observed using digital image correlation (DIC). In addition, micro sections for all specimen were prepared and analyzed for porosities and other defects. The optical analysis of the microsections is done on three 10 mm wide microsections per sheet using the software ImageJ.

Finally, in order to address issues regarding inner thermal stresses as well as varying tape quality, a second stage annealing process is investigated on the overall best specimen with regards to mechanical strength, porosity and manufacturability. This cycle is run at four temperatures above T_g (148°C) between 160 and 220 °C in equal increments. The annealing cycle needs to be simple for a potential industrial application. Thus, it is performed in a convection oven using a vacuum bag as the only auxiliary material. This way the annealing cycle is relatively cost effective with a low threshold of preparation. The heating cycle is defined as follows: Heat-up at 5 K/min to the target temperature, holding time of 5 minutes at target temperature and finally a controlled cooling at a rate of 3 K/min to room temperature. This cycle was found to be beneficial for reducing inner stresses and flatten out warped sheets at pretrial. All specimens are analyzed for crystallinity using DSC on a NETZSCH DSC 204 F1 Phoenix.

Results and Discussion

A comprehensive overview of the results is given in Tab. 2. Bracketed values represent the given standard deviation. The knockdown is calculated in comparison to the Toray datasheet for ILSS (SBS) value of 96.5 MPa [7]. Specimen numbered 1 - 3 are placed in-situ with no secondary step. Specimen 4 - 7 are annealed at 160 °C, 180 °C, 200 °C and 220 °C.

Tab. 2: *Overview Test Results*

#	*Material*	*ILSS [MPa]*	*Knock-down [%]*	*Crystallinity [%]*	*Porosity [%]*
	Toray TC1225	96.5	-	24.0	0
1	Suprem 55%	77.4 (±2.3)	19.8	7.0 (±1.4)	1.5 (±0.1)
2	Suprem 60%	81.0 (±0.4)	16.1	5.4 (±1.6)	1.4 (±0.3)
3	Toray 60%	75.2 (±1.2)	22.1	3.8 (±2.7)	1.3 (±0.3)
4	Suprem 55%	89.0 (±1.6)	7.8	7.2 (±1.6)	0.9 (±0.1)
5	Suprem 55%	93.3 (±1.4)	3.3	20.5 (±0.9)	1.3 (±0.1)
6	Suprem 55%	92.0 (±1.1)	4.6	18.7 (±1.3)	1.0 (±0.1)
7	Suprem 55%	91.7 (±0.2)	5.0	20.0 (±1.5)	1.1 (±0.1)

The values for all in-situ specimen are within the expected values and reach between 77 % and 84 % of the ILSS compared to the Toray TC1225 datasheet. This is still a significant knockdown in line with results in literature. It is noteworthy that the Suprem material reached slightly higher values compared to the Toray material even with a lower FVF of 55 %. In comparison the Toray material showed a FVF of 61 % in the optical analysis of the microsections (see Fig. 2).

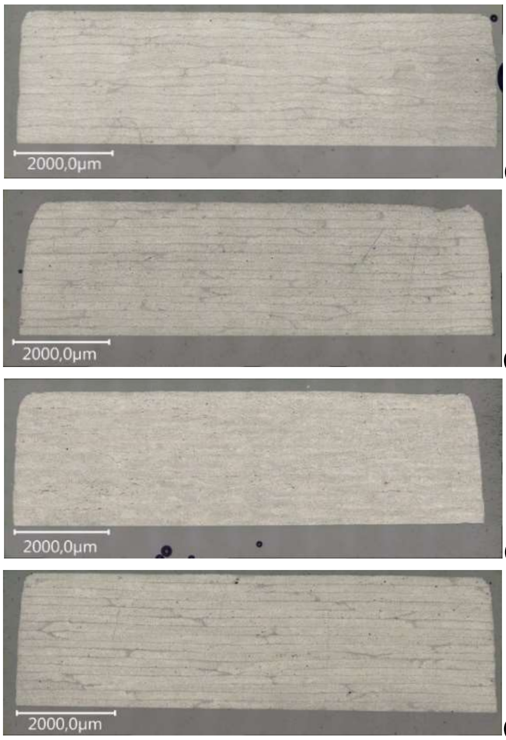

Fig. 2: *Microsections from different samples Benchmark (a), Suprem 55 % in-situ (b), Toray 60 % in-situ (c) and Suprem 55 % annealed at 200 °C (d)*

The mechanical values of the annealed specimen show an increase to over 90 % of the reference ILSS value. In addition, an increase in porosity due to expansion of voids was not observed as microsections of all sheets with the exception of the Toray material show little interlaminar porosity. In the analysed microsections in-situ produced specimen have a porosity of 1.3 % – 1.5 %. Annealed specimens are measured to have lower porosity in comparison (0.9 % – 1.3 %). All values are within the expected margin of error for a visual analysis, thus an increase in porosity from the annealing cannot be concluded. Most pores in the Suprem samples were found in intralaminar areas. However, a comparable porosity was already observed in the microsections of pristine tape. In comparison the microsections of Toray tape showed less porosity in the pristine tape but a rather dry surface. This leads to the conclusion that a dry tape surface facilitates interlaminar porosities and decreases mechanical performance. Over all a more matrix rich tape benefits the thermoplastic AFP process. Therefore the 55 % Suprem tape was chosen for the annealing cycle.

Before the annealing cycle the unidirectional laminates are warped. Since the in-situ process results in a low crystallinity, a further warpage caused by secondary crystallization was expected. However, all annealing cycles flatten out the test specimen, while crystal formation is promoted. The specimen annealed at 160 °C do not show a significant increase in crystallinity compared to the in-situ samples. In-situ samples have a crystallinity between 3.8 % and 7 %. While the annealed specimen crystallinity remains at roughly 7 %, specimens annealed at higher temperatures show a crystallinity increase to approximately 20 %. A maximum crystallinity of 24 % - 26 % was observed for LM-PAEK Material in a previous study [4].

Conclusion and Outlook

In-situ consolidation of CF/LM-PAEK by means of AFP is highly desirable from a manufacturing point of view. In literature the highest ILSS values reached for the process and material combination are around 70 % of the reference. In this study the best mechanical ILSS values generated in-situ on a cold tooling reach 84 % of the reference. This was achieved by using tapes with beneficial properties for the AFP process compared to the tapes formerly used for the MFFDs upper shell and rigorous process optimization. The most important tape requirements are a resin rich surface on all sides, an even distribution of fibers as well as little internal defects.

Due to the inherent limitations of AFP with regards to a controlled cool down and holding times, the full mechanical potential is still not reached in a single step production. That is why the authors proposed a secondary thermal treatment in an oven under vacuum. This annealing cycle has proved to increase the laminate properties substantially: Inner stresses are eliminated, crystallinity of the polymer is improved and over all the laminate is homogenized. This results in an increase of the mechanical performance with ILSS values reaching 96% of the reference value and thus to a more viable production process for critical components. So far, the annealing has only been performed on UD flat specimen. Annealing of a more complex ply design and more complex geometries needs to be conducted to further validate the approach. If the additional annealing proofs equally viable for complex parts, the production issues as seen in the upper shell of the MFFD can be overcome. The steps towards a high-quality large-scale production with thermoplastic AFP are as follows: Development of an AFP suitable tape which has beneficial characteristics e.g. limited internal defects as well as a resin rich surface. Optimization of the first ply and vacuum for large molds by omission of the glass breather and introduction of a more complex vacuum system that distributes forces over the entire surface of the skin. Annealing of the whole skin after placement in order to heal inner stresses, homogenize the skin and improve mechanical performance.

The next steps for the further development of the AFP Process will be a more detailed analysis of the annealed laminates and a comparison to other thermal treatments such as the use of a hot tooling. In addition, a complete mechanical characterization of the process using CF/LM-PAEK is targeted.

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