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Towards toolless manufacturing of aerospace CFRP components via thermoplastic AFP

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Abstract
Modern commercial aviation needs to decarbonize at high rates to support climate action. One aspect is the consistent use of lightweight materials such as carbon fiber reinforced plastics (CFRP), that requires novel manufacturing processes. This paper expands on the development of dual-robot thermoplastic Automated Fiber Placement, that enables toolless production of CFRP structures. A hardware and software setup are developed to conduct material tests and evaluate the achievable part quality using the process. It is shown that the process is feasible to manufacture quality on par with conventional, in-situ AFP.

1. Introduction

Commercial aviation has to reduce its carbon dioxide emissions drastically in the next decades to comply with international legal requirements and self-commitments, given by the airlines to reduce climate change. In order to reach these goals, aviation industry has to improve propulsion, substitute fossil fuels and reduce structural weight. A viable approach is the comprehensive use of CFRP in modern aircrafts. However, these concepts have still not been applied to single aisle aircrafts, which account for a significant proportion of new aircrafts (approx. 80%) [1].

Enhanced manufacturing processes for CFRP components and optimized materials are necessary to meet the required high production rates. A reduced consolidation time, out of autoclave capabilities as well as increased component size are all highly desired for this reason. Additionally, high investment costs should be avoided and new processes require a high flexibility towards rapid design changes in order to be ready for the next generation of aircrafts. Due to increasing material and energy costs high efficiency and recyclability are beneficial. Manufacturing techniques that improve all these key success factors have to be identified, developed and implemented for narrow body aircraft production.

Direct consolidation of thermoplastic CFRP via Automated Fiber Placement (AFP) is a highly automated, additive process without size restrictions. The use of a laser heating system ensures local heating and thus a comparatively efficient process. Further, the use of thermoplastic matrices offers better recyclability compared to established thermoset polymers. Drawbacks of this technology are issues regarding mechanical performance with knock downs in strength compared to hot pressed laminates and the need for complex formative molds that constrain design changes. A concept to optimize the process was introduced by Kochoski et al. where the tooling is substituted by a second robot - a dual robot AFP process. Feasibility for the production of complex laminates was shown [2].
This paper extends the current knowledge by optimization of the dual-robot process for CF/LMPAEK. First a functioning setup for dual-robot AFP is designed and tested. This also includes developing an offline programming solution for the process. Since the quality that this process may produce is still unclear, inter laminar short beam strength (ILSS) and 90° tensile pull tests, are conducted to evaluate the achievable material quality compared to a

standard in-situ AFP process. The paper concludes with recommendations on how the process can be enhanced in the future.

2. Experimental Setup

Hardware Design

For the experiments an existing thermoplastic AFP system was modified. The AFP system facilitates a high precision articulated robot (KUKA KR120) mounted on a rail. The AFP layup machine is supplied by AFPT GmbH and places 3 x 1/2” tapes per track, using an infrared laser with a wavelength of 1090 nm as heat source with up to 6000 Watts output power. The machine is equipped with a closed-loop control that utilizes an infrared camera. The temperature measurement via thermal imaging is dependent on the emissivity of the material and the angle between the camera and the laminate. Calibration to an accurate temperature is laborious and error-prone. It was decided to set the emissivity to 1 for all material systems to ensure relative, constant temperatures for one material system at a time. Therefore, the temperature values have to be converted to estimate the actual processing temperature (delta approximately 150°C).

An additional robot was added to the system (KUKA KR300) for the dual robot manufacturing process. It is mounted on the floor in a 90° angle with respect to the layup machine. Mounted on the second robot is a counter tool with a lean design with regards to its size in order to improve reachability during the process. Its main components are a motor-driven aluminium compaction roller and an integrated air cooling. A drive belt between compaction roller and motor is used to nest the motor behind the roller. A visualisation of the setup can be found in Figure 1, the layup machine is depicted on the right side of the image, the counter part on the left side.

In the beginning of each placed track, 100 mm of the material is deposited on a frame to fix the tape endings. The actual part is built in the inner space of the frame. In order to enable readily adjustment of the frame, a modular concept using base plates with the dimensions of 300 x 250 x 15 mm was designed. The plates are tapered to improve and smooth the transition between frame and tape when the AFP and counter tool roller merge in the beginning of the part.
A sealing between the plates is added to be able to use a vacuum, to fix auxiliary materials on the frame and thereby improve first ply adhesion. In this case it is achieved by means of a polyimide foil and glass breather, which is favourable due to the reusability of the assembly. This setup has also been used for the standard in-situ AFP process. Due to its modularity, the frame size can be adjusted easily adding new base plates. The frame was designed as rectangle enveloping the workspace, so that tracks can be placed with support for the tape endings from any direction in the plane of the frame. This provides the opportunity to utilized the frame for the investigation of additional, lateral supporting tapes for more complex parts.

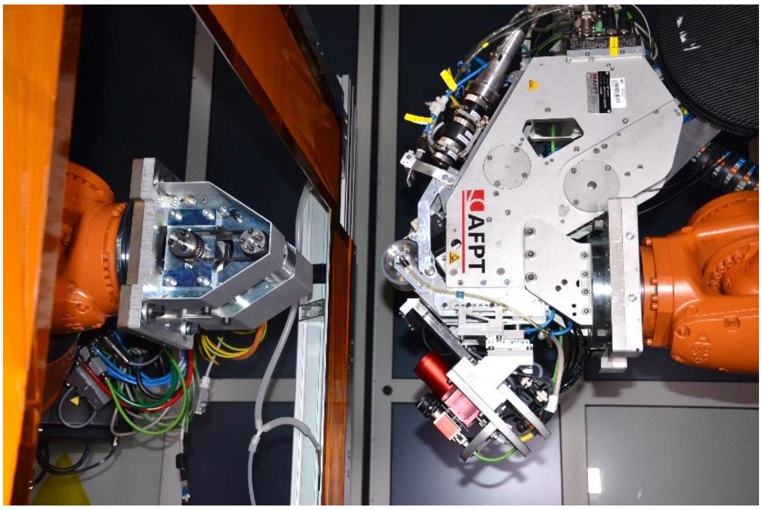

Figure 1: Dual Robot thermoplastic AFP setup

Dual Robot Programming

Due to the high number of individual trajectories that are required for the manufacturing of a part, offline programming for the industrial robots is a strict requirement even for single robot AFP applications. With two robots moving simultaneously for a toolless production, offline programming becomes even more important. Furthermore, a thorough simulation is very useful to identify possible collisions between either the robot or the supporting frame.

The program generation for the dual robot AFP process is performed in multiple steps. The first step is the creation of a “virtual” mold in CAD which is used as base for all following steps. The initial robot programs are generated using the commercial software “VERICUT Composites Programming” (VCP), supplied by CGTECH, fitted with a custom post-processor that generates KUKA KRL files. Using VCP, the design of the part can be specified, i.e. the number of plies, the fiber orientation of each ply and the algorithms used to calculate the respective paths on complex surfaces. Each ply consists of several tracks of tape that are placed adjacent to each other. VCP calculates appropriate trajectories for the robot and the tape laying head using the CAD surface of the mold. Up to this step, the same procedure is used for traditional mono-robot AFP applications.
The resulting programs are only suitable for the robot carrying the AFP head. No programs can be generated automatically for the counter-endeffector using VCP. Therefore, we have developed a custom solution for automatic path generation also for the secondary robot.

The software is integrated as plugin into the offline-programming tool “RoboDK”. The KRL source files that have been created using VCP are parsed and the trajectories imported into RoboDK. Using the CAD models of the frame and the virtual mold surface, trajectories for the counter-endeffector are calculated that take the thickness of the part and the form of the jig into account. Using RoboDK, the motion of both robots can be simulated simultaneously and possible collisions are identified. Using a process-tailored post-processor, KUKA KRL programs are generated for both robots. Synchronization points for the RoboTeam (Motion Sync) are inserted at vital points into the programs to ensure a synchronous motion of both robots during tape placement.

Specimen preparation

Utilizing the developments described above, material tests are performed to assess laminate quality of parts manufactured with in-situ dual-robot AFP. The results are then compared to tests performed with conventional thermoplastic AFP laminates. Therefore, unidirectional test panels are produced with 12 layers in total which results in a total specimen thickness of approximately 2.1 mm. Since initial thermocouple measurements showed that less power is needed for the dual-robot process the control temperature is varied to identify the optimal process settings.

For the three control temperatures two different mechanical characterizations are performed: ILSS according to DIN EN 2563and tensile pull tests perpendicular to the unidirectional fiber according to DIN EN 2597. Both are designed to test the consolidation of a part rather than the fiber characteristics and are therefore beneficial to evaluate the process instead of the material quality.
For the short beam test specimen with the size of 10 x 20 mm are cut of the panels and tested on a universal testing machine supplied by ZwickRoell. Ten specimen per panel were investigated. Using a speed of 1 mm per minute a cylindrical stamp is pushed on to the specimen that rest on two support bearings with the same radius of 3 mm. More information can be found in standard DIN-EN 2563 that the test followed [3].
For the perpendicular tension test specimen with a size of 250 x 25 mm were cut out. In total 15 specimen per panel were tested. They are equipped with caps on both sides for the clamps. This results in a free tested length of 130 mm. The tension tests were conducted on the same machine using a slightly slower speed of 0.5 mm per minute, following the test standard DIN-EN 2597 [4].

3. Results & Discussion

All results can be found in Table 1. For the perpendicular mechanical tests, a decrease in strength is visible with a knock down factor between 37.5 to 44.1 % compared to conventional in-situ AFP. The best values of 22.8 MPa can be found for a control temperature of 500 °C, which corresponds to the optimal process parameters for conventional in-situ AFP for this material and a processing temperature of roughly 365 °C.
For the ILSS values the dual-robot AFP test panels showed higher shear strengths than the benchmark with an increase between 27 - 29 %. The highest values were reached for a process control temperature of 525 °C where 51.4 MPa are measured.

Whereas the results at first contradict each other, an examination of the test specimen explains the lower tensile tests. Due to the missing mold, the unidirectional panels exhibit a macroscopic waviness. The tensile test is susceptible to such deformations due to the tension and compression peaks that build up in these areas. Additionally, a relatively large curvature over the length of the specimen is given, which lowers the mechanical values determined by the test. Thus, the specimens are non-conform to the norm.
The much smaller short beam tests are less influenced by these macroscopic deformations and the results are promising. The specimen is subjected to plastic deformation and do not fail spontaneously. In this case according to DIN-EN 2563 the values are not representative of the absolute mechanical strength but adequate for qualitative comparison of specimen. The higher values might indicate that the material is consolidated well or has a slower cooling gradient that results in higher crystallinity. It can be stated that the process needs to be enhanced further to produce more geometrically accurate panels in order to optimize process parameters. Otherwise, a comparison to the conventional T-AFP will generate flawed results. However, the ILSS results show that the dual robot AFP can potentially produce laminates with mechanical strength comparable to conventional AFP and above due to slower cooling rates and associated higher crystallinity.

Table 1:Results material tests dual-robot AFP

Control Temperature [°C]	**Mechanical Test**	**Dual Robot in-situ T-AFP [MPa]**	**Mean deviation [MPa]**	**Conventional in-situ T-AFP [MPa]**	**Mean deviation [MPa]**
465	tension	17.9	2.3	32.0	4.4
500	tension	22.8	3.0	36.5	3.4
525	tension	20.0	2.7	32.1	7.3
465	ILSS	45.5	-	35.2	-
500	ILSS	49.8	-	40.9	-
525	ILSS	51.4	-	40.6	-

4. Conclusion and Outlook

It was shown the chosen hardware and software setup is sufficient for the production of test panels without a supporting mold. The mechanical test results showed that in general dual-robot AFP could provide material quality on par with the conventional process. For the two conducted test methods, tensile testing showed a significant knock down and dual-robot ILSS values surpassed the benchmark. For the former a comprehensible answer was found for the lower values. However, more work has to be done on the optimization of process parameters such as compaction forces, tape tension and intentional overlap between the tracks.

In addition to these fundamentals, manufacturing of more complex parts should be investigated and improved further. Starting with single curvature and evolving to dual curvature, the combination of overlaps and support structures may support the production of dimensionally accurate parts. One way of improving the geometric accuracy is a revision of the counter tool based on the current findings.
A focus should also be put on the evaluation of accuracy of the robotic setup. Precise measurements are necessary to identify and eliminate smaller lags between the two synchronized robots. Since the layup machine applies a significant force on the counter part robot, this influence should be accounted for. It might be highly beneficial to compensate these geometrical and load induced inaccuracies to obtained precise parts.

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