PRESENTATION OF A TESTED AUTOMATION CONCEPT FOR ROBOT-BASED LAYUP OF A LARGE SCALE GENERAL FML-COMPONENT.

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Abstract

Automation efforts have been taking place in the area of FML component production for some time. Increasing cost pressure and high demands in terms of quality and quantity per time unit call for improvements in material, component structure and process chain management.

In 2019, the Center for Lightweight Production Technology South in Augsburg, in cooperation with Fokker, developed and evaluated a prototypical process for automated aluminum and glass fiber layup for a large generic FML component.

The component dimensions of approximately 5000mm x 9000mm and the complex constructive extensions of the plant technology posed particular challenges.

This paper describes the initial situation and existing challenges, systems engineering used for the layup process as well as its extensions. Furthermore, the challenges regarding offline path planning are discussed and the interaction between material and plant design.

Keywords
FML, GLARE, Fiber Metal Laminate, cooperating robots, Automated layup, Aluminum layup; Fiber layup, automation, robot portal system;

1. INTRODUCTION AND MOTIVATION

A global increase in mobility has led to higher demands for aircrafts [1]. Numerous airlines compete for customers and are looking for ways to optimize prizing. Aircraft manufacturers and their suppliers are under constant pressure to lower their costs and reducing weight while also increasing production rates.

Together with ever growing quality standards these requirements necessitate automation in production of aircraft parts. Fiber Metal Laminates (FML) offer a wide range of advantages (e.g. high fatigue resistance, high strength, good impact and crack propagation behavior, high damage tolerance and inherent fire resistance) but are currently manufactured with a very low level of automation.

While the mechanical properties of FML are very attractive for large scale application, it is necessary to reduce the manufacturing cost and enable (very) high rate manufacturing. In the past decade efforts have been made by industry and research facilities towards automation of FML manufacturing. This paper provides an overview of the development of an integrated process chain for automated layup of typical, large, single-curved aircraft panels including offline programing. It will concentrate on development of an integrated process chain as well as a solution for handling of large aluminum sheets and reinforcing elements like interlaminar doublers.

2. STARTING SITUATION AND CHALLENGES

2.1. Objectives and conditions

Based on previous work of the DLR in FML automation projects [2] and together with project partner Fokker a large, single-curved panel with various design features (e.g. reinforcing elements) was to be manufactured in an highly automated process. This process was to be documented and evaluated to enable further steps to full automation and identify potential risks on a road to higher technology readiness levels.

FML mainly consists of alternating layers of thin aluminum sheets (0.3 mm) and glass fiber prepreg with additional strips of adhesive at the splice areas (Figure 1).

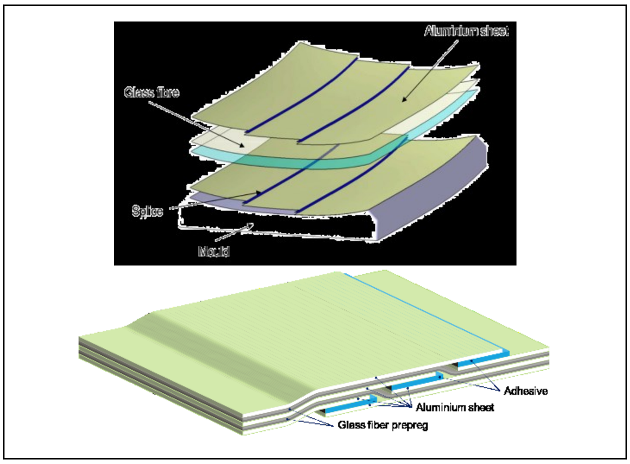

Figure 1: Splicing concept in FML

For a simple FML panel it is relatively easy to automate the placement of the aluminum layers, the glass fiber prepreg layers and the adhesive strips. Several medium size (up to 6 m by 2 m) demonstrator panels have been manufactured in the past using automated processes.

However, a typical FML aircraft panel contains design features that need to be considered during the development of automated processes. Also, increasing the size of the FML panels using the splicing concept reduces the number of panels required and consequently reduces weight (fewer overlapping joints) and cost (less handling, less drilling and riveting).

A large (5 meter by 9 meter, single curved with a radius of approximately 2 meter) generic panel has been designed that contains typical design features found in FML. The design features include interlaminar waffle plate doublers, interlaminar doublers, crackstopper bands and splices.

An example of a panel with a waffle plate interlaminar doubler is shown in Figure 2. A waffle plate increases the thickness of the panel only at the locations of the stringers and the frames. The waffle plate interlaminar doubler concepts allows for reduced skin thickness between the stringers and the frames while maintaining the minimum required thickness for riveting and for repair at the stringer and frame locations.

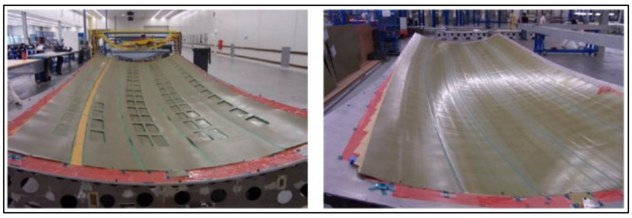

Figure 2: Interlaminar waffle plate doubler. Left: during lay-up. Right: After lay-up and curing

A typical interlaminar doubler build-up is shown in Figure 3. An interlaminar doubler basically increases the skin thickness in areas of high loading, such as but not limited to areas around cut-outs and at longitudinal and circumferential joints. Interlaminar doublers can vary in size.

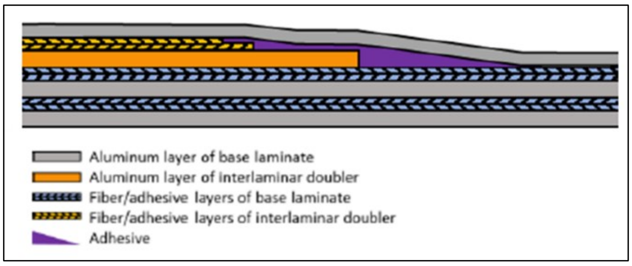

Figure 3: Interlaminar doubler build-up

Several relatively small interlaminar doublers are included in the generic panel design. An automated process should be able to handle the different design features desirably without specific end-effectors for each design feature.

Also, an aircraft design might contain panels of different size and complexity. A full scale industrialized automated lay-up cell will require significant capital expenditure. It is therefore attractive to develop processes that are suitable for different panel sizes and complexity and to minimize the time it takes to lay-up a panel in the automated lay-up cell.

The DLR has vast experience in development of pick-and-place processes, as well as end-effectors for a range of materials and tasks. In previous projects [2] several approaches to automated manufacturing of FML have been evaluated. The site at Augsburg operates a large and flexible robot facility with the possibility to adapt to various use cases. The DLR provided said facility, end-effectors for handling of aluminum and glass fiber prepreg, path planning and offline programming of all robots, and specialist for the panel build-up.

Fokker provided the detailed design of the generic panel, including the plybook that describes each individual part of the panel. Furthermore, Fokker provided all materials cut to size and the tooling. As the DLR does not have an autoclave large enough for the panel, the panel was transported to Fokker after lay-up and cured in the large autoclave at the Fokker facilities in Papendrecht, the Netherlands. Before and during the test Fokker FML specialists supported the DLR.

2.2. Challenges

In addition to analyzing the manual work steps, the main focus was on conception of automatable process steps and their implementation.

Plant layout, component properties and design features had to be taken into consideration, as well as the handling of various different cut-pieces as defined in the plybook. Amongst others, relatively thin sheets of aluminum with large dimensions (and in some cases cut-outs) had to be handled damage-free and within tolerances. Although the weight of the sheets is comparably small, a single robot would require a huge gripping system to support the sheets and prevent wrinkling. Such a big system has several disadvantages, e.g. the weight of the gripper and the inflexibility to adjust to different geometries. Therefore, it was decided to use three independent robots with smaller, more flexible gripping systems for the handling of the aluminum sheets. When several robots are used it is vital that all robots move exactly simultaneously and on the same trajectory.

The large number of different sheets make manual robot programming (by teaching) a tedious task. To facilitate the programming, an offline programming (OLP) tool is desired which can automatically create the required robot programs from the plybook.

3. PLANNING AND EXPERIMENTAL PROCEDURE

3.1. Development and planning of process steps

A simplified procedure for implementing the set objectives is shown in Figure 4. To simplify dependencies the steps are shown here as a sequence. The mutual influence of non-adjacent process steps is not shown.

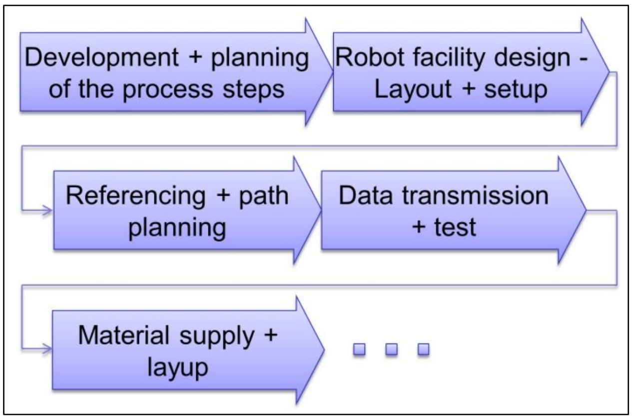

Figure 4: Process steps of the experimental procedure

The component typical design was provided by the project partner Fokker. This design served as a practical basis for the development and implementation of the process steps.

3.2. Robot facility design – Layout and setup

Basis for the plant layout was the Multifunctional Cell (MFZ). This is shown in its first expansion stage in Figure 5. More detailed information on MFZ in this expansion stage can be found in [3].

Figure 5 : First expansion stage level of the MFZ

This cell was later extended with a further articulated arm robot on the central gantry axis. This system configuration is the starting point for the further layout design.

The final plant layout consists of the Multifunctional Cell with three vertical articulated arm robots, pick up tables and a mold with extensions (see Figure 6 and Figure 5).

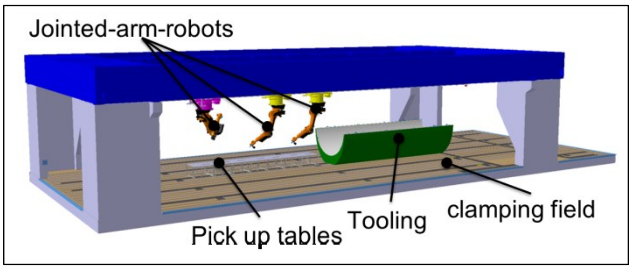

Figure 6 : Simplified layout with test equipment

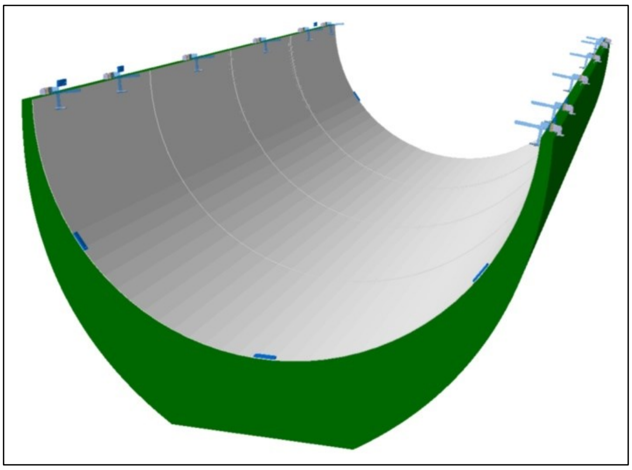

Figure 7 : Mould with extensions

Both the pick-up tables and the mould are arranged under the central axis of the MFZ on a clamping field (Figure 6). Currently three articulated arm robots are available. These robots on the central gantry axis are movable in longitudinal direction.

The mould (see Figure 7) and the tables are located centrally in the working area of the articulated arm robots.

A further advantage is that these KUKA KR270 robots have a low tendency to oscillate and high repeatability compared with the lateral gantry robots. Furthermore, their movements can be synchronized (see also chapter 3.3). They are well suited for handling long components.

In a total four end-effectors were used. Their function is explained in chapter 3.5.

3.3. Referencing and path planning

Both the tooling and the pickup table are referenced with respect to the root coordinate system of each of the three robots. This is achieved by using a built-in base referencing utility of the KUKA robots. The positions of the mould and the pickup table are been imported into the offline programming environment which allows a realistic simulation of the process.

The workpiece is designed using CATIA Composites Design (CPD), resulting in a plybook containing all relevant information about the individual sheets. In a first step, grip- and drop points are calculated using a custom software tool [4]. First a mesh of corresponding points on the flat sheet (as provided on the pickup table) and the sheet's final position in the mould is calculated. Second, each gripper can be positioned on the flat sheet, resulting in a pair of grip- and drop-points for each gripper. Since the sheet needs to be rolled up during pickup, additional grip-points are calculated for each individual gripper module. No corresponding drop-points are required, because the sheet already has the final form after pickup and therefore can be laid down onto a single (central) point per gripper.

Offline programming is conducted using an extended version of the tool already used in a previous project [2][4]. The long aluminum sheets are too long for handling with only two robots; therefore, an additional third support point in the middle has been added. The gripper in the middle is a simplified variant of the other grippers without the possibility to adjust to different radii and with only two gripping positions (Figure 9). For the sake of simplicity all three grippers are treated identically from a software perspective.

The existing OLP software was extended to support three robots. Since all aluminum sheets have to be placed in the same longitudinal direction and all sheets require handling by three robots, the path generation algorithm is rather straight forward.

The sheets are provided manually on a flat table and are aligned to two sides of the table using mechanical stops on the table. They are picked up from the table, then transferred into the mold and finally placed to the proper location.

The transformation of the flat sheets into the final three dimensional forms happens during pickup. This strategy has been selected for several reasons. First, the curved sheets are more stable and less likely to flatter during transport. Second, the grippers do not need to transform while a sheet is attached, which significantly reduces the complexity of the mechanical construction. In order to achieve the transformation of the sheet during pick up, a simultaneous rolling motion of all three grippers is performed. The middle gripper needs to perform the same motion as if it had the same number of gripping points like the outer grippers, even though it only has two.

The sheets can be transferred into the mold using a synchronized motion of all robots along the external linear axis. Real-time motion synchronization is required so that the grippers do not move with respect to each other during the transport.

Once the sheet has reached the form, the orientation is adjusted such that the sheet is located directly above the final position (above in direction of the normal of the center line of the sheet). Placement is then performed using a synchronous linear motion to the destination.

The motions for the glass fiber layup are created using CAD software. A set of splines constructed along the surface of the mould depicts the path of the end-effector and ensures complete coverage with prepreg without overlaps or gaps. The bases of the splines are transferred to the robot controller via a CSV file.

3.4. Data transmission and test

All paths for the aluminum sheet layup process are created and visualized using the offline programming environment described in section 3.3. For the execution on the robotics cell the programs are converted in to KUKA Robot Language (KRL) source files. A separate source file is generated for each of the three robots. Each program consists of a set of motions either in joint space (PTP) or in Cartesian space (LIN). The required real-time synchronization is achieved using the KUKA RoboTeam package. All motions which need to be synchronized are planned appropriately by the OLP software (i.e. the distance of all three grippers is kept constant) and marked with special tags. The Motion-Sync feature of RoboTeam ensures those motions are executed synchronously, i.e. all parts of the motion including the acceleration and deceleration phases are occurring simultaneously for each robot.

3.5. Material supply and layup

It is useful to consider the lay-up of the aluminum sheets and the glass fiber prepreg separately.

As defined in the plybook the longest aluminum cut-pieces were approximately 9 m long. Based on previous experience and preliminary testing a pick-and-place approach with three cooperating robots was chosen. Two fully functional end-effectors (see Figure 8) plus a more basic work-around (see Figure 9) are available for the layup.

The end-effectors are modular and contain several independent groups of vacuum cups. They can be controlled separately and enable the handling of sheets of different sizes. The end-effector can be adapted to different curvatures and then fixed in shape prior to pick-up.

As the tooling geometry is cylindrical all sheets are provided on a flat table and picked up with a rolling motion. For transport and layup the final curvature is maintained at all times. Together with a constant distance between the end-effectors and a certain tension on the material this stabilizes the sheet and allows a damage-free and fast transport.

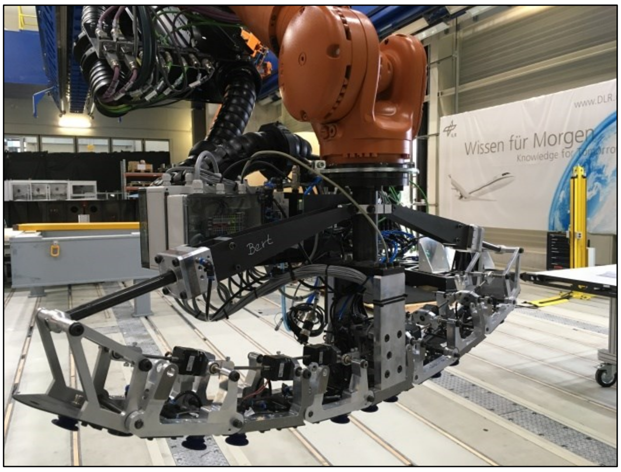

Figure 8 : End-effector for draping and handling of aluminum sheets

Transfer to layup position is conducted with a synchronized movement by all robots. The relative distance between the gripping points is constant thus minimizing the risk of damaging the material during transport. Upon reaching target position the sheets are lowered vertically into the mould. Air entrapments or impairment of already present layers did not occur.

Figure 9 : End-effector (workaround)

Smaller cut-pieces like doublers or other reinforcing elements can be handled with one end-effector; pick-up strategy and placement is similar to large sheets.

Position of the vacuum cups and gripping points can be adjusted to sheet design. A large variety of cut-pieces can be handled with the same end-effector and thus lowering the complexity of industrialized facility. The application of adhesive is also possible prior to layup. The sheets can be provided in advance with adhesive on a flat surface and outside the mould. Offline programming can take into consideration the position of those adhesive strips and avoid contact with the gripping points. A whole process step can be decoupled from the time critical layup inside the mould and further decrease the complexity of the required facility.

Glass fiber prepreg is applied with a rolling end-effector (Figure 10). Curvature of the pressure rollers can be adjusted to different geometries. It is possible to lay material up to a width of 460 mm and in both longitudinal and circumferential direction of the mould. For more details on prepreg layup please refer to [2].

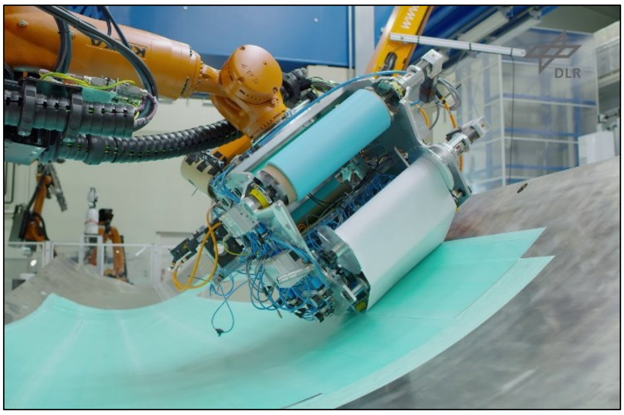

Figure 10 : End-effector for glass fiber layup

4. SUMMARY AND OUTLOOK

Using a multi-robot system with compact, lightweight gripping systems has proven to be a flexible solution for handling thin aluminum sheets with largely varying geometries. While this solution reduces the variety of the required end-effectors it also increases the complexity of motion programming. Using an offline programming environment that is able to automatically generate all motions and allows visualizing the production process helps mitigate this challenge. In the future the application of the developed solutions on an even more complex use case – e.g. double curved target geometry – could provide further insight to the feasibility of the technology in an industrialized environment and increase the degree of automation in aircraft part production.

5. ACKNOWLEDGEMENTS

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