AUTOMATED MANUFACTURING OF LARGE FIBRE-METAL-LAMINATE PARTS

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Abstract

Fibre-Metal-Laminates (FML, e.g. GLARE®) have been used for aircraft fuselage parts for more than 20 years as they offer several opportunities regarding mechanical properties like weight, impact tolerance and crack propagation [1]. A typical GLARE type consists of several layers of aluminium with layers of glass prepreg in between. Fibre orientation, number of layers and stacking influences mechanical properties and can vary for different fuselage designs. In order to reduce costs, allow higher production rates and improve quality the Center for Lightweight Production Technology develops an automated lay-up process for the handling and application of aluminium foils and glass prepreg including integrated quality assurance measures. Based on a state-of-the-art 3/2 lay-up a FML fuselage demonstrator is built in order to validate the selected automation concepts. Where feasible the automated process is compared to the manual production to determine the benefit of the development. Proof of concept can be deducted for aluminium lay-up via collaborating robots and application of glass prepreg with a rolling end-effector up to a scale of 10 meters. Several advanced requirements for material suppliers and logistics have been identified and could be exploited for further improvements towards full automation.

1. Introduction

Modern aircraft fuselages are subject to many requirements like mechanical properties or impact tolerance. Furthermore, reducing weight is a strong motivator in engineering projects. Apart from monolithic aluminium and carbon fibre reinforced plastics (CFRP) Fibre-Metal-Laminates (FML) can be an alternative. One example is GLARE which is used in the A380 fuselage. GLARE is a compound material of aluminium (thickness of one foil 0.2 mm - 0.5 mm) and glass prepreg in alternating sequence. It offers excellent performance in weight, impact tolerance and fracture propagation. In addition costs for wrought material and maintenance are relatively low compared to CFRP fuselages [1]. Contrary to monolithic aluminium the manufacturing of FML parts is mostly done manually leading to high costs, low rates, reduced reproducibility and insufficient in-line quality assurance measures. An inspection of the final part does not allow any adjustments in case of defects during production process which could lead to rejects. In order to provide the opportunity to use FML parts in a wider range of aircraft types higher production rates have to be achieved as well as lower costs and an improved quality. The Center for Lightweight Production Technology (ZLP) in Augsburg, Germany, develops an automated lay-up process for the handling and application of aluminium foils and glass prepreg. Integrated quality management methods are applied to increase process confidence and minimize the risk of defects. The automated process is to be quantified and compared to the manual production in terms of stability, error rate and duration.

2. State of the art

Fibre-Metal-Laminates belong to the composite materials and consist of alternating layers of aluminium foils and pre-impregnated glass fibre fabric. Thickness of the aluminium foils, fibre orientation and stacking order of the structure can vary widely and have a great influence on the mechanical properties of the final part. Adhesive film with the same resin as used on glass prepreg is applied to prevent bridging effects. The lay-up is done manually based on a laser projection on the mould as well as application of auxiliary materials and vacuum bagging. Curing is done in an autoclave and can involve several cycles depending on additional reinforcing measures. Apart from visual inspection by the workers there is no in-line quality assurance management prior to the final ultrasound scan of the cured part. On a non-industrialized scale there are already several efforts to automatize the lay-up sequence. For example Premium Aerotec AG (PAG) has developed an areal end-effector to handle and apply aluminium and glass sheets up to a length of 6 m [2]. The end-effector is able to deform from plane to single-curved configuration and possesses a foam surface to adjust to various degrees of mould curvatures. For both aluminium and glass prepreg the material has to be pre-cut and provided at a defined two-dimensional grip position. General feasibility of the lay-up process has been demonstrated.

3. Automated process

3.1. Project objective

The Center for Lightweight Production Technology aims to automatize the manufacturing of FML aircraft fuselage parts up to 10 m with integrated quality assurance along the process chain. Based on design principles and general requirements of existing FML parts a new lay-up sequence (plybook) has been created with the following major features:

- 3/2 stacking sequence (3 layers aluminium, 2 layers of 0°/90° directional glass prepreg, Figure 1)
- size approximately 6x2 m
- single and double curved areas
- T-Splice (splice: area of overlap between two aluminium cut-pieces) at the point of transition between cylindrical and spherical area

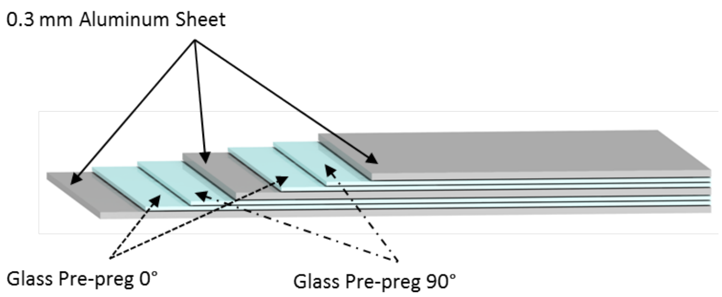

Figure 1. Schematic of a 3/2 FML lay-up

Especially the spherical geometry poses different challenges for the lay-up process. As aluminium does not allow draping it is not possible to place the plane cut-pieces at their final position as required by the three-dimensional design and will inevitably create bridging effects or convolutions. In addition the glass prepreg is highly resistant to steering due to material properties [3]. Together with tight requirements regarding fibre angle tolerances and cut-piece positioning the boundary conditions call for a precise and stable process with high accuracy and reproducibility.

The aluminium foil is available in a limited width and the cut-pieces have to be compounded to cover the whole area of the fuselage part. This is done with a defined overlap (splice) with adhesive tape between the foils. Each splice leads to an increase in weight and its use is to be limited to a minimum. In cylindrical areas of the part the maximum width of the available foils (approx. 1500 mm) is applied in longitudinal direction. In spherical areas the width of the cur-pieces is limited by the local curvature radius. The smaller the radius the larger is the difference between the plane aluminium sheets and the target geometry. This results in undesired tensions in the cured part even if the autoclave cycle presses the foils into their final double-curved form. To determine the optimal width for the cut-pieces extensive tests has been conducted [4].

3.2. Automated lay-up of aluminium foils

The handling and lay-up of large aluminium foils is done by two collaborating robots (Figure 2). The end-effectors are modular and can be set to a plane or a curved configuration in order to pattern the mould geometry both in circumferential and longitudinal direction. The active grippers are vacuum based and are able to safely hold and transfer aluminium sheets up to a length of 8 meters.

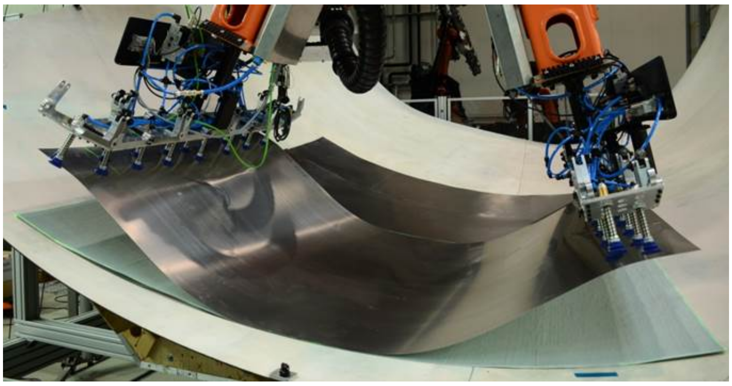

Figure 2. Lay-up of two-dimensional aluminium foils with collaborating robots

The robots are mounted upside-down and allow superior accessibility. The cut-pieces are supplied on a table with known reference to the robot facility coordinate system. The generation of robot code for gripping, transfer and lay-up sequence is done with an off line programming tool and does not involve teaching. Depending on the length of the foils the robots engage a tilted position to allow the cut-piece a catenary-like form in order to avoid damage. The cut-piece is placed at its final position with the central area touching the mould first (Figure 2). This ensures precise positioning without influencing of the layers below or creating air entrapments.

3.3. Automated application of glass prepreg

For the application of the glass prepreg several different approaches have been proposed. A pick-and-place process with an areal end-effector has been tested by PAG [2]. The German Aerospace Center in Stade, Germany, is currently working on a lay-up via automated tape-laying (ATL) [3].

At the ZLP the glass prepreg is applied via a continuous rolling process with on-the-fly cutting. The maximum width of the material is 460 mm and allows for high placement rates despite relatively slow traverse speed of the end-effector (Figure 3). The end-effector is equipped with an adjustable array of draw rolls to emulate the mould geometry and several ultrasonic knives. Both edges can be cut according to plybook design and to avoid material overlap.

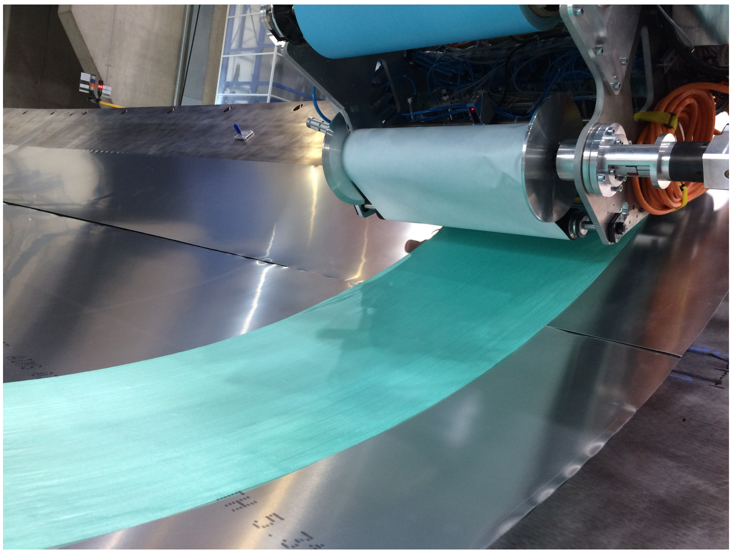

Figure 3. Application of glass prepreg

The material used for testing originates in manual manufacturing and has several deficiencies regarding automated application. For example the position of the glass prepreg on the roll is undefined and can vary several centimetres from roll to roll. The edge of the material needs to be actively measured with live course correction of the end-effector or a certain width has to be cut away on both sides to ensure precise and reproducible placement. Also the carrier paper proves to be unsuited for automated handling with a lot of potential for improvement regarding stiffness and tack.

4. Quality assurance

As depicted in section 2 (State of the art) the in-line quality assurance of the manual process consists of visual inspection during the lay-up. After curing the part is checked via water coupled ultrasound in an automated process.
For the automated lay-up the quality assurance concept was reconsidered. As the different process steps are under development the concept cannot be finalized yet. Nevertheless, a FMEA (failure mode and effects analysis) was conducted to identify the process steps where in-line quality assurance is most reasonable. The assessment criteria include severity of the failure effect, probability of occurrence and expectation of detection with given methods.
The tack of prepreg and adhesive and the path accuracy can be highlighted as the foundation for the quality assurance concept. The concept can be divided into in-line and final inspection methods [5]. Particularly the in-line inspection should ensure an intervention and a readjustment of deviations in the running process to minimize expensive repairs and rejects [6].

For this reason edge detection with a laser light-section sensor (LLS) has been selected for application during the lay-up process. The measurement system facilitates the comparison of the actual contour of the cut-piece in the mould with the target contour from the CAD-model.

In principle, the LLS can be used for all three materials: adhesive, prepreg and aluminium. Due to the thickness of the materials the contour points of aluminium and prepreg are more likely to be recognized. The LLS is mounted on a robot with off-line path programming in order to measure the contour of the foils (Figure 4).

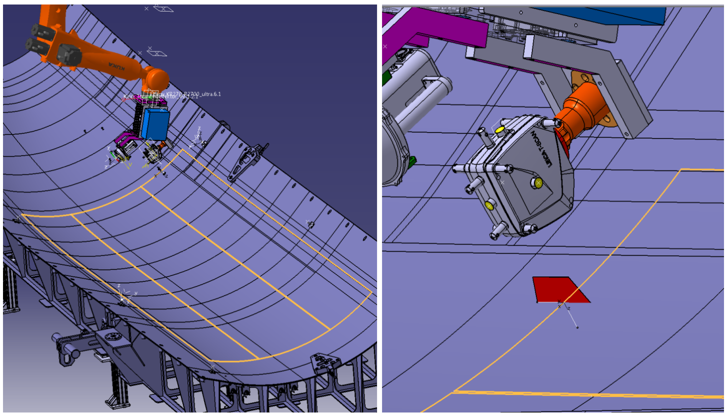

Figure 4. CAD model of the mould and the contours of an aluminium layer. The laser light-section sensor is mounted to a robot (left). The laser light-section sensor is moved along the contour (right)

The entire measurement system includes a lasertracker which is locked onto the LLS via laser beam and records the position. The accuracy of the system amounts to 60 µm and is able to neutralize the inaccuracy of the robot facility.
The data generated by each scan line consists of point clouds with 3D coordinates. The point-to-point distance and the line-to-line distance can be adjusted and have to be fine enough to dissolve the contour. Figure 5 (left) shows a point cloud which includes the 3D contour of an aluminium layer. The point cloud is unstructured and of varying density. To identify the probability of each point lying on the contour one common approach is to observe the neighbourhood of each point.

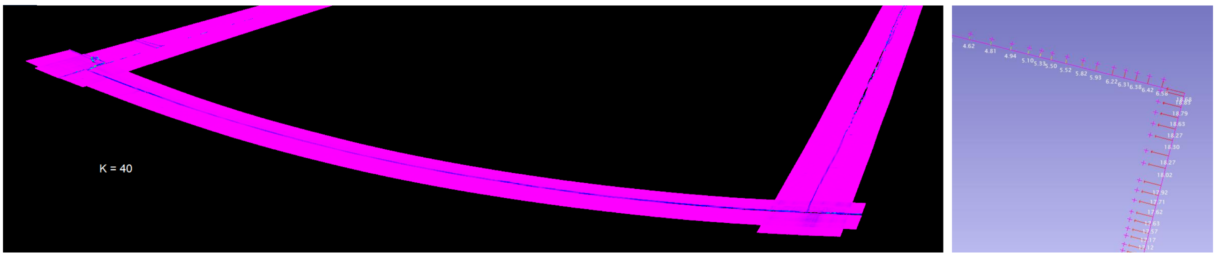

Figure 5. Point cloud with detected contour points in blue (left). Visualisation of the target/actual deviation

[7] presents a method to calculate the surface variation as a measure for the probability of the point lying on an edge. Figure 5 colours each point with the result of the surface variation. Violet represents points with low values and blue points with higher values for surface variation. The blue points include the contour very well in this case.
[8] and [9] describe an approach where a lot more indicators and machine learning algorithms are used to find points on an edge and to generate wire-frame models out of the point clouds. These and one further approach are actually reviewed in detail. One aim has to be particularly emphasized: It is important to depict the 3D shape of the cut-piece for example waves in the aluminium cut-piece. This allows to give a precise information about the cause of the deviation. One possible visualization of a target/actual

deviation is shown in figure 5 (right).
Both approaches will be considered for future evaluation of large amounts of data.

5. Performance assessment

FML manufacturing divides into three major production steps: material preparation, lay-up and autoclave process. While the material preparation with all its sub-steps impedes optimization, the lay-up requires many manual tasks with high potential for automation. The lay-up is done with two or more workers leading to a time and cost consuming process. To demonstrate potential cost and time savings the automated process is compared to a manual lay-up process.
The positioning of the aluminium sheets and the glass prepreg were executed in separate experiments. The tests for the adhesive film application are still ongoing but due to similarities conservative estimations based on the ATL process were used. It should be pointed out that the obtained results only refer to the lay-up process and that the individual results are summed or scaled up to demonstrate the automation potential. Process related challenges that are yet to overcome (e.g. prepreg wrinkle formation in double curved geometries) are not considered.
The relevant parameters for the pick & place process were identified as duration per sheet positioning, robot speed and the number of sheets. For the rolling application of prepreg roll length, the required material length, cutting duration, maintenance for the cutting unit and most importantly the feed rate were considered. In comparison to the manual process it was found that the automated process offers potential time savings up to 23% (Figure 6).

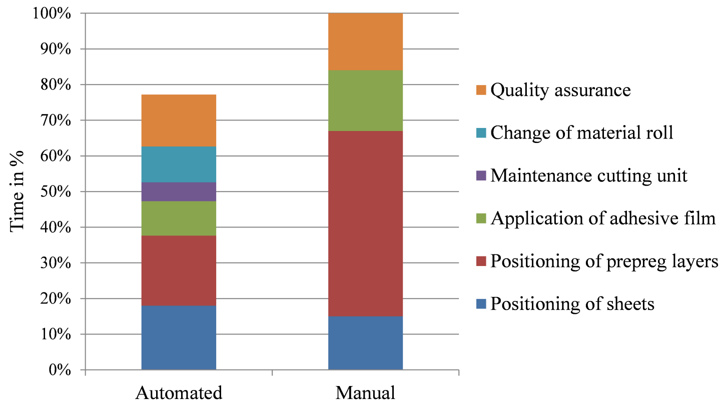

Figure 6. Process time comparison of automated and manual lay-up process

The aluminium sheet positioning shows similar durations in both processes, however the robot transfer speed was not yet optimized. Contrary to that the glass application yielded strongly different results. Since the worker needs to position the prepregs over large areas and additionally tailor the edges, the automated glass application offers high time savings using on-the-fly cutting. For this evaluation the test mode feed rates of 0.1 - 0.15 m/s were used.
Due to extensive use the cutting unit requires maintenance in terms of cleaning or change of the blade. Additional downtime results from the material roll length of 40 meters. In case of the 6x2 m demonstrator three changing operations were necessary. The duration of the quality assurance in terms of position detection showed comparable results for both processes.
Resulting from the calculated process times and the material prices a cost analysis was executed. Figure 7 shows the cost proportion for material cost, facility cost and labour cost. While the material costs remain the same for both, labour cost was reduced from 34% to 8% and facility costs increased by 15%. Overall the automated process yielded cost savings of approximately 11%.

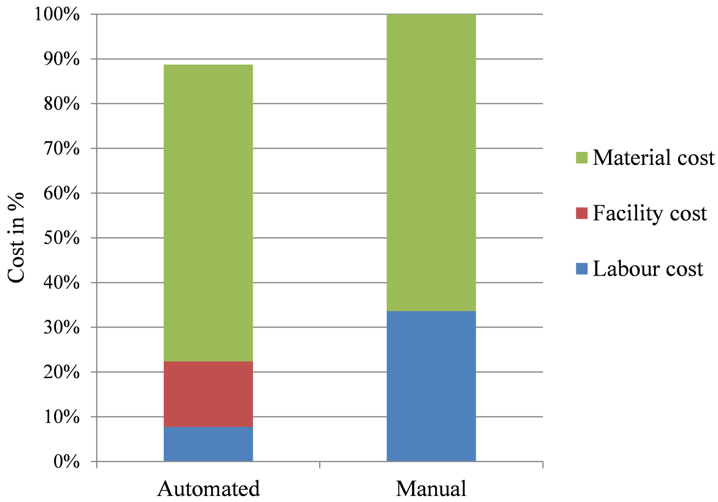

Figure 7. Cost comparison of automated and manual FML lay-up

The present evaluation was conducted partly on documented and estimated values. However the documented values were based on experiments that were not trimmed for performance and therefore still offer optimization potential. The unknown values were discussed with the respective experts of their field and conservatively estimated. Summarized it can be said that automated process reduces the lay-up time by approx. 23% and the costs by approx. 11%. Considering the moderate technological readiness level further savings are possible.

6. Conclusion

Feasibility of automated lay-up of aluminium foil and glass prepreg has been demonstrated. An accuracy of 2 mm – 5 mm can be achieved in positioning (exact value is subject to the local curvature radius) with implemented in-line quality assurance. The use of collaborating robots for large aluminium foils and a rolling application method for glass prepreg offers great flexibility regarding size and geometry of the FML parts.
The prototype end-effectors used for the tasks have been analysed during lay-up process and several potential improvements in performance and process stability have been identified.
Also the materials and design features used in the manual manufacturing of FML parts still offer opportunities for further optimization. Adjustments of certain properties (e.g. carrier paper of glass prepreg or adhesive) could save several work steps and further streamline the process chain.
In general an automated lay-up could offer savings in process time and costs as well as the opportunity to decrease risk of rejects.

Acknowledgments

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