PREPREG LAY-UP TECHNOLOGY FOR MANUFACTURING OF LATTICE STRUCTURE FUSELAGE SECTIONS

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Abstract
The main objective of this process technology project is the development of a composite fuselage that reduces weight and improves safety in worst case scenarios. To achieve these objectives a lattice fuselage structure has been developed and automated tape placement has been investigated from the IVW as a method of manufacturing these kind of structures. During the project mostly all challenges (as example: rib crossing design, compaction of the ribs during the Out-of-Autoclave (OoA) curing, mold material for undercuts) were addressed and different samples manufactured.

1. Introduction

1.1. Automated Fiber Placement

The Automated Fiber Placement (AFP) technology was developed in the 1960s for the manufacturing of large aircraft structures [1]. An AFP system increases the lay-up rates and decreases the manufacturing costs. Mostly a robot or gantry system, with a special tape placement head, is used as AFP system. Input materials for the thermoset placement process are mainly unidirectional fibers, which are preimpregnated (prepreg) with the matrix material. For the selected project carbon fiber and epoxy resin were chosen. Depending on the prepreg resin two curing processes can follow the AFP process. Traditionally, the laid up material cures within an autoclave under pressure or without additional pressure in an Out-of-Autoclave method (only vacuum). To reduce manufacturing costs for a fuselage production all parts were cured with an OoA method.

1.2. Lattice structures

Conventional airplane fuselage sections like the Airbus A350 XWB are manufactured with reinforced material in a stinger & frame design. Lattice structures can help to decrease the weight and increase the safety in worst case scenarios (next step in aircraft design [2]). Key points for lattice structures are rib crossing sections which represent a challenge for the chosen placement technology [3]. In Figure 1 an typical design of the fuselage section is shown.

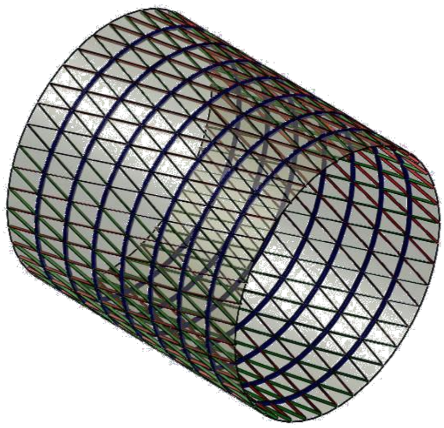

Figure 1. Lattice structure designed by KhAI1

2. Assumptions and determined parameters

2.1. Definition of requirements

As reference aircraft the airplane P180 Avanti from Piaggio Aero Industries is used (see Figure 2). The fuselage of this aircraft has a radius of 0.90 meter. Within this project a metallic section of 2 m in length was replaced by a carbon fiber lattice fuselage section. Different project partners were involved in the design process of this lattice structure.

Figure 2. P180 with exemplary lattice structure design

2.2. Manufacturing process

The project focuses on two different manufacturing processes: wet filament winding (FW) [4] and automated fiber placement (AFP) with prepreg material. The Institut fuer Verbundwerkstoffe GmbH leads the work package "Wafer Section Manufacturing Design" and is responsible for the AFP process. All required samples were manufactured with a special lay-up test rig by hand, or industrial robot system. The automated robot systems and the lay-up test rig were originally designed for thermoplastic tape placement [5] and modified for thermoset prepreg tapes. To reduce the tackiness between prepreg tape and metallic

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feeding guides, all feeding guides were covered with a special coating film. To further reduce the tackiness, mostly all components were cooled with a vortex tube. The out coming cool airflow is used to cool the cutting device, the compaction roller, the feeding guides, and ends inside the tape placement head. The protection film of the prepreg tape is stored in an optional material box.

2.3. Material selection

Epoxy resin and carbon fiber (HTS040 / HTS 5631) were chosen for the selected processes. AFP prepreg material is MTM44-1 from CYTEC (formerly Advanced Composite Group). The reinforced material is a unidirectional carbon fiber tape with an epoxy resin. The material has a T_g of 190 °C (dry) and is designed for OoA (Out of Autoclave) and autoclave processing. The fiber volume content was set to 60 % inside the parts. For the AFP-Process an “Out of Autoclave” curing was defined. Figure 3 shows the curing cycle for the material and Figure 4 represents results of two DSC measurements (Differential Scanning Calorimetry with a heating ramp 2 °C/min and 5 °C/min).

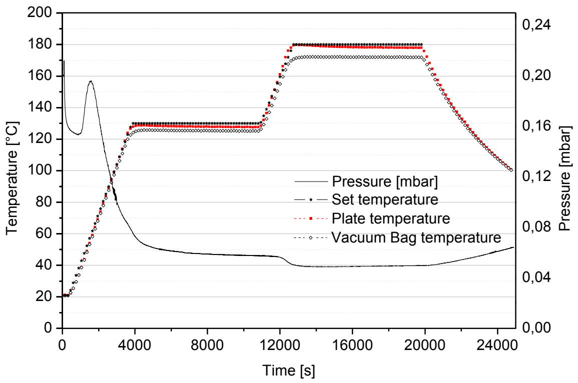


Figure 3. Measured curing cycle (temperature and vacuum pressure)

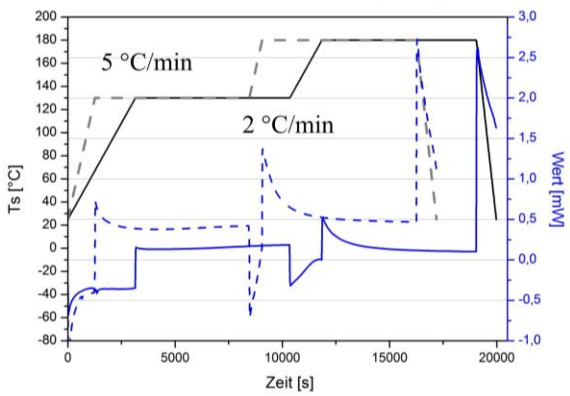


Figure 4. DSC results for two heating ramps

The “Out of Autoclave” curing system requires a heated tool or oven for the thermal energy input. As shown in Figure 3 the exothermic reaction of the material depends on the heating ramp. The exothermic reaction of the tests with 5 °C/min is higher than with 2 °C/min. For the manufacturing of a large demonstrator or a complete fuselage section the temperature distribution needs to be homogeneous. Different temperatures result in different exothermic reactions in one sample and this can result in residual stresses. To achieve the best test results all samples were cured with the complete mold in an oven.

3. Results for the automated fiber placement process

3.1. Rib geometry and manufacturing

In consequence to the required material (slitted prepreg material) it is not feasible to produce a rib with triangular cross section geometry with and AFP-Process. For this reason the rib geometry was redesigned and simulated for the AFP–Process. The new lattice structure had only a draft angle of 1°, which is enough for the demolding of the parts and is manufacturable with the AFP process. The rib height (20 mm) requires 200 prepreg layers. To achieve a high laminate quality the laid up prepreg normally needs to be compressed under vacuum after several layers. However, with well-chosen parameters the void content could be minimized without compaction after several layers. The void content inside the manufactured parts depends on the part thickness and the used vacuum time. Fahrhang [6] shows the dependence between the vacuum time and the void content (Figure 5). As results of the researches from Fahrhang, all parts were cured after an 8 hours vacuum. The minimum allowed vacuum pressure for MTM 44-1 is 20 mbar. Within all curing cycles a standard vacuum pressure lower than 1 mbar could be reached. Figure 3 shows the vacuum curve during a curing cycle. After the curing cycle has started, the temperature rises and the vacuum decreases locally. This is due to decrease resin viscosity and the escape of entrapped air (voids).

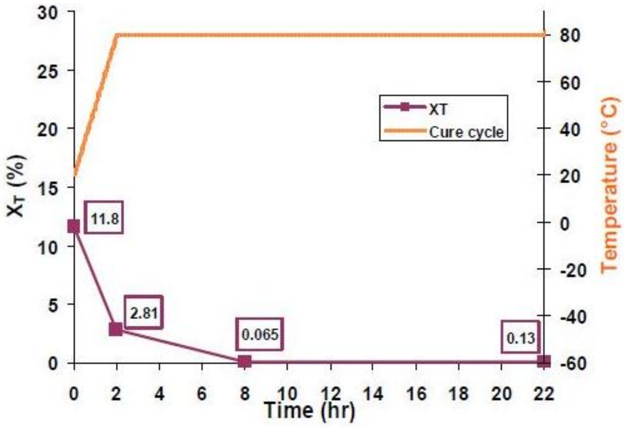


Figure 5. Void content depending on the time [6]

3.2. Crossing Sections

Crossing sections are significant for lattice structures [3]. In the crossing sections two or more ribs are crossing each other which results in a higher volume of fibers and matrix. To compensate the material increasing, the crossing area needs to be increased. All in all four different solutions for crossing sections have been analyzed. The solutions are shown schematically in Table 1 (top and side view of the crossing sections).

A metallic lay-up tool was utilized for the crossing section manufacturing. The rib geometry and the crossing section of the tool are the requested final rib geometry (6.35 mm in width, 20 mm in height, and with 1° draft angle). To achieve a better material compaction inside the ribs a silicon and a metallic X-structure is placed on top. The prepreg material is layed down inside the negative cavity of the tool and is covered by the silicon X-structure stamp. The second X-structure (metallic) is placed on top to distribute the consolidation pressure to the prepreg rib structure. The curing procedures: “Autoclave” and “Out of Autoclave” were compared to each other.

The void content inside the crossing sections was analyzed with a micro - computer tomography. For each sample the scanned pictures (maximum 1500) of the crossing section in thickness direction were statistically analyzed. The void content (grey scale) could be calculated with analytic software (Figure 6Figure 7). Table 1 shows the average void content for each configuration which is always less than 2 %.

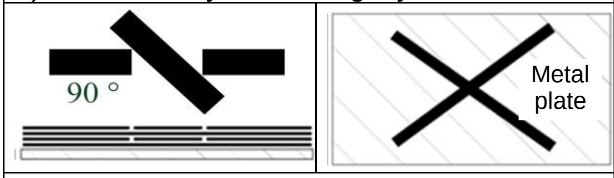
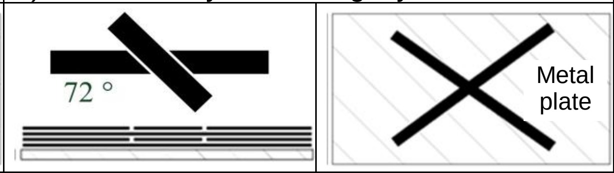
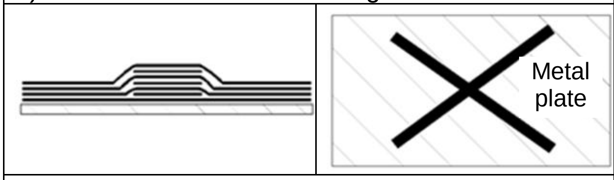
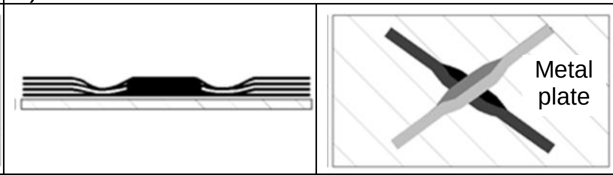
1) 90° cut every alternating layer	2) 72° cut every alternating layer
	
Void content: 2.0 %	Void content: 1.9 %
3) Fiber deflection into the height	4) Fiber deflection into the width
	
Void content: 1.0 %	Void content: 0.3 %

Table 1. Crossing section configurations with void content

In addition to the void content measuring different manufactured samples of each configuration were mechanically tested with a non-standard 3-point bending test. The maximum resultant loads and the mechanical behavior for each sample are shown in Figure 7. Both variants with 90° and 72° cut show lower load levels and lower displacements. Configuration 3 (fiber deflection into the height) and configuration 4 (maximum displacement) had the maximum load capacity.

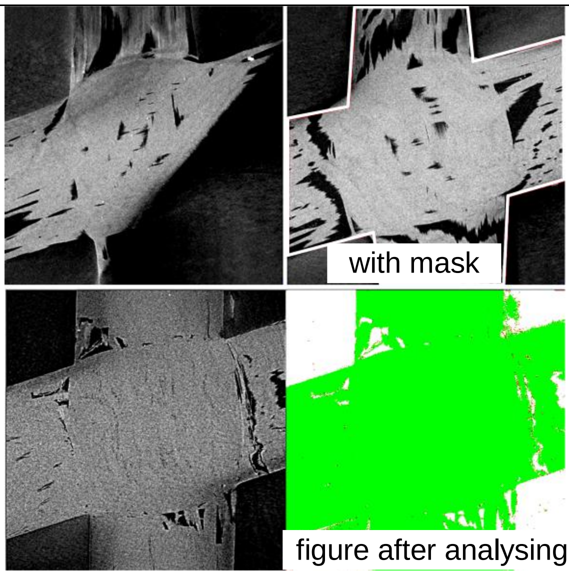


Figure 6. Void content analysis of a crossing section (µ-CT pictures)

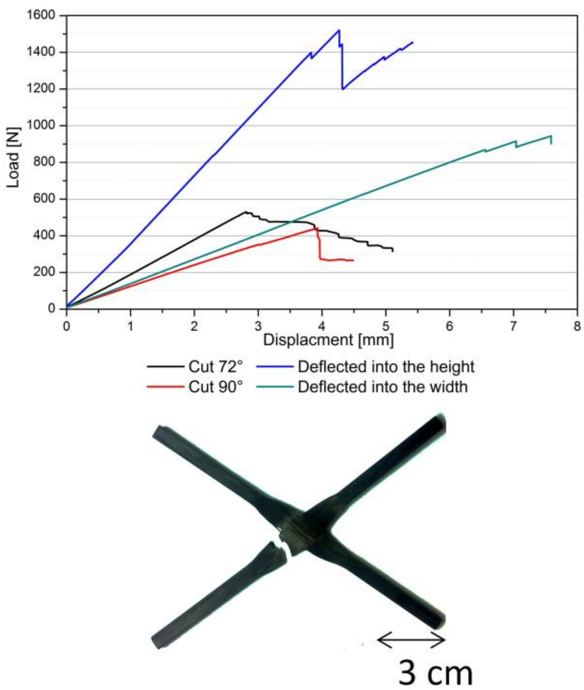


Figure 7. Crossing section configurations

3.3. Lay-up tools

Within the project a complete fuselage section (ribs and surface) should be manufactured in one step. The main focus is the compaction of the prepreg material inside the ribs, because of the “Out of Autoclave” curing. For the “Out of Autoclave” curing the maximum differential pressure is 1 bar. The vacuum bag needs to follow the decreasing rib. To compensate the behavior of the vacuum bag, the ribs in all samples were covered with a compression part. Different materials were analyzed as mold material and are described below:

Metallic:
To manufacture flat structures first tests were operating with a non-curved metallic tool and a non-curved metallic compression piece. For the manufacturing of non-curved panels a metallic mold works very well. Due to draft angles and undercuts of the isogrid fuselage design a metallic mold and compression part (stamp) are not suitable for curved panels. Besides, it is to expensive and complicated for handling and manufacturing.

Lost Core Materials:

Lost core materials form the mold structure during the part manufacturing process. The materials are usually destroyed in the demolding process. Three different materials were investigated: Aquacore ™, Aquapour ™, and salt. The materials (Aquacore ™, Aquapour ™) are blended with water and filled up in a negative tool. After a short drying, the solvable core can be removed. In contrast to this, the salt material is delivered in flat pieces. To create the form the salt pieces needs to be machined. All presented lost core tooling’s can be applied for the lay-up of prepreg material. The solvable tool can be easily washed out with water after the prepreg curing. It was found that both Aquacore ™ and Aquapour ™ did not meet the requirements because of the geometric accuracy. Only the salt material meets all the requirements, but is not yet available commercially.

Silicone:
A number of different removable silicone mold materials were investigated, too. It was detected that a hard material with high geometric accuracy is most desirable. Table 2 shows different silicone materials, which are ordered by the geometric accuracy. The best material “Silicone 60” from Beyer was only available as flat sheets. Due to the required 3D geometry with undercuts the Silicone 60 could not be chosen. ZA 50 LT was the second best choice. This silicone consists of two components, which are mixed together in a ratio of 1:1 and can be filled in each negative mold. A perfect matching 3D silicone form for between the ribs is the result. Tests with this material proceed very well.

Table 2: Evaluation of silicon mold material

Brand name	Shore A	Geometric accuracy	Supplier
Elastosil C120	25 ± 2	--	Wacker
ZA 22	21 ± 2	--	Zhermack
TCF4011	35 ± 2	+	Trollfabrik
SF 45	43 ± 3	+	Silikonfabrik

ZA 50 LT	50 ± 3	++	Zhermack
Silicone 60	60 ± 5	++	Beyer

After evaluation of the three different classes of mold materials it was decided that the tooling should be manufactured from ZA 50 LT silicone rubber due to its relatively low costs and the simple manufacturing while still achieving good geometric accuracy and surface finish.
For the manufacturing of the large demonstrator panel (Figure 8) the 1.4 m wide, 1.4 m long tool base with a radius of 900 mm was produced with a 2 mm thick stainless steel sheet for the surface and a wooden rib support structure. Silicone inserts were used to fill the space between the lattice structures. To manufacture these inserts a casting mold was created using extrusion deposition 3D printing so that the removable silicone mold parts would conform to the radius. The mold parts were produced with a metal insert in the center of the part. The metal insert could be removed prior to make the demolding process easier. The cavity containing the metal insert was filled with silicone. The part was removed from the mold after curing. Four different triangular silicone designs, all in all 32 silicone forms, were required to create the mold for the large panel (Figure 8).

To construct the demonstration panel a layer of glass fiber weave followed by a layer of peel ply was laid onto the base radius. The six layer carbon skin was then placed onto this. Holes were made in the skin to match those in the mold, reels were located over these holes and secured with a bolt and nut. The nut was sealed underneath the mold using tacky tape. Tapes were then laid onto the skin to form the ribs. After the ribs were completed the silicone inserts were placed into the mold in the appropriate location followed by the compression strips. Layers of glass fiber and peal ply were placed on the top of the part. The entire mold was then enclosed in a vacuum bag and evacuated before being cured at elevated temperature.

Figure 8. Curing of demonstration panel

4. Summary

The manufacturing of isogrid lattice structures for a fuselage section with the AFP process was analyzed and described. Different designs for rib crossing points are proposed and experimentally analyzed. A void content lower than 2 % was achieved by using optimized process and curing parameters. Solutions for convex as well as concave tooling concepts are explained and partly tested. Specific core materials and additional rib compaction leads to best results in part as well as surface quality. The investigations show the potential of AFP to manufacture lattice structures for new aerospace fuselage designs. All manufactured samples were mechanically tested from a project partner.

5. Acknowledgment

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