Challenges for the Manufacturing of a Lattice Structure Fuselage Section with Prepreg Lay-up Technology

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1 Introduction
In aerospace industry an increasing number of metal structures are replaced by composite materials. Within an EU funded project a fuselage section is designed and manufactured as a full composite structure. A lattice structure is developed with potential to become the next step in aircraft design. Amongst others the automated fiber placement process is analyzed to manufacture different sections of the lattice structure, such as the crossing sections and the connection to the attachment frame [2].

2 Assumptions and determined parameters
2.1 Requirements definition
As reference aircraft the Piaggio Aero P180 is used. This aircraft has a fuselage radius from 0.90 meter. Within this project a metallic section of 2 m length is substituted by a carbon fiber fuselage section.

All required information about the load cases for the new lattice structure were taken from the P180. Different project partners were involved in the design process. In Fig. 2 a possible fuselage section design based on a lattice structure is shown.

2.2 Manufacturing processes
From the manufacturing point of view the project focuses on two different processes, wet filament winding (FW) [3] and automated fiber placement (AFP) with prepreg material. The Institut fuer Verbundwerkstoffe GmbH is work package leader for the “Wafer Section Manufacturing Design” and within this package responsible for the automated fiber placement process. All samples were manufactured with a lay-up test rig by hand or robot system. The automated robot systems and the lay-up test rig are originally designed for thermoplastic tape placement [4] and were modified for thermoset prepreg tapes. Therefore, all feeding guides were covered with a special coating film to reduce the tackiness between the prepreg material and metallic feeding guide. For an additional reduction of the tackiness mostly all components were tempered with a vortex tube. Inside this tube pressurized air is split in a cool airflow (up to - 40 °C) and a warm airflow (high than 50 °C). The cool airflow is used to cool the compaction roller, the feeding guides, and the cutting device inside the tape placement head. The protection film of the prepreg tape is stored in an optional material box.

2.3 Material selection
For the selected processes epoxy resin and carbon fiber (HTS040 / HTS 5631) were chosen. The brand name for the AFP prepreg material is MTM44-1 from CYTEC (formerly Advanced Composite Group). The material is an unidirectional carbon fiber tape with an epoxy resin (Tg from 190 °C - dry) 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. The curing cycle for the material is listed in Fig. 3.

The curing system “out of autoclave” required a heated tool or oven for the thermal energy input. Depending on the curing ramp the exothermal reaction of the material is different. In Fig. 3 the results of two DSC measurements (Differential Scanning Calorimetry) are plotted (heating ramp 2 °C/min and 5 °C/min). The exothermic reaction of the tests with 5 °C/min is higher than with 2 °C/min. For the manufacturing of a large test sample or a complete fuselage section the temperature distribution needs to be homogeneous. Different
exothermic reactions in one sample can result in residual stress. As a result of the DSC tests, the temperature distributions of the different heated plates were analyzed. For all tests an additional metallic plate were put on top of the heating plate to compensate non-homogeneous temperatures. For a further manufacturing process a lay-up tool needs to be developed with to homogeneous temperature distribution.

3 Results for the automated fiber placement process

3.1 Rib- manufacturing

Each of the two manufacturing processes (chapter 2.2) inside the project has their own requirements. For the AFP-Process it is not feasible to produce a rib with triangular cross section geometry. The used prepreg material is available in different width, but a permanent material change inside the lay-up process is not efficient. With this requirement the simulation and design partners developed a new lattice structure with only 1 ° draft angle, which is enough for the demolding of the part and fits to the AFP process requirements. 200 prepreg layers are necessary to realize the rib height. Considering the economical manufacturing it is not reasonable to compact after every 20 layers with vacuum before the next layers was layed-up. With well-chosen parameters the void content could be reduced to a minimum. The void content inside the manufactured parts depends from the part thickness and the used vacuum time. Fahrhag [6] shows the dependence between the vacuum time and the void content (Fig. 4). After 8 hours the minimum void content of the manufactured part is reached.

All manufactured samples were cured after an eight hour vacuum. The minimum allowed vacuum pressure is 20 mbar (material datasheet). Within all curing cycles a standard vacuum pressure lower than 1 mbar could be reached. In Fig. 5 the vacuum curve during a curing cycle is plotted. After the curing cycle has started, the temperatures raised and the vacuum decreases. The reason for this effect is the decreasing resin viscosity and the entrapped air (voids) can escaped.

3.2 Crossing Sections

For lattice structures the crossing points of ribs are significant. [3] The crossing results in a higher volume of fibers and matrix. For example the crossing of two ribs doubles the material at the crossing point. To compensate this, the crossing area needs to be increased. Four different solutions for the alternative crossing sections were analyzed. All solutions are shown schematically in Table 2 (top and side view).

The lay-up tool for the crossing section manufacturing is shown in Fig. 6.

In figure A a negative metallic tool for configuration 4 is shown. The rib geometry and the crossing section are the requested final rib geometry. For a better material compaction a silicon X-structure (B) was manufactured as stamp. In figure C the curing setup is shown. The prepreg material is layed down inside the negative metallic tool and covered by the silicon X-structure stamp. In figure D the complete buildup is shown. On the top of the silicon tool an additional metallic X-structure was used to distribute the consolidation pressure to the prepreg rib structure. Two different curing procedures were used: “Autoclave” figure E and “Out of Autoclave” figure F. The cured sample is shown in figure G (e.g. sample with the fiber deflection into the width configuration 4).

With a micro - computer tomography the void content was analyzed inside the crossing sections. For each sample the pictures (maximum 1500) of the crossing section in thickness direction were statistically analyzed. With software the void content (grey scale) could be calculated (Fig. 7).

Configuration 1 (90 ° cut) shows for all examples the maximum void content of 2.0 %. The examples with cut fibers in 72 ° have a void content of 1.9 %, Configuration 3 (deflection into the height) 1.0 % and the minimum void content inside the crossing section shows configuration 4 (deflection into the width) with 0.3 %.

In addition different manufactured samples of each configuration were mechanically tested with a non-standard 3-point bending test (Fig. 8). The maximum loads and the mechanical behavior for each sample were shown in Fig. 9. The first two variants (90° cut and 72° cut) shows lower maximum loads and lower
displacements. The maximum load is shown in configuration 3 (fiber deflection into the height) and configuration 4 (maximum displacement).

Considering the side views in Table 2 a combination of configurations 3 and 4 should be the optimum for this crossing section. The reason is that the crossing section of configuration 3 is higher than the ribs which leads to manufacturing problems during the lay-up and problems during the assembly of the interior of the aircraft. The combination of configurations 3 and 4 results in a nearly constant cross section and rib height.

3.3 Lay-up tool

The complete fuselage section with ribs and surface sheets should be manufactured in one step. This results in different problems. The main focus is the compaction of the prepreg material during the “Out of Autoclave” curing process. Due to the material compaction during the curing process the prepreg height of a rib decreases (maximum 20 %). For the “Out of Autoclave” curing the maximum differential pressure is 1 bar. The vacuum bag needs to follow the rib decrease. As described before the crossing section samples were manufactured with a metallic tool to distribute the consolidation pressure. Due to the draft angle and the undercuts of the design a metallic stamp is a very expensive and complicated choice for a suitable fuselage manufacturing process.

Different tool materials were analyzed and tested. As tool material Elastosil ® C1200 (silicon with a Shore A of 25), Aquacore TM, Aquapur TM, and a salt material were tested. Salt, Aquacore TM, and Aquapur TM are all lost tool materials. The test with the silicon material is shown in Fig. 10 and Fig. 11.

The rib was placed on a metallic plate covered with a glass fabric, peel ply, and a silicon tool on top. A standard vacuum bag covered all. A low Shore A value in combination with different design variants (Fig. 11) should permit the compaction of the material while the rib geometry is almost trapezoidal. Due to the vacuum pressure the rib was compacted but lost its dimensional accuracy.

Fig. 12 shows the undefined rib geometry (no trapezoidal geometry). The handling of both state of the art lost core materials (Aquacore TM and Aquapur TM) shows some disadvantages for a fuselage section manufacturing process. Salt as a tooling material for the FRPC production is new. The used experimental material is not commercially available and shows nearly perfect surface and handling properties. The quality of the manufactured part shows the high potential of this tooling material, but the manufacturing process for a salt tool needs to be optimized for the requirements of FRPC parts. In further projects the material may be a good tooling material for complex parts.

Due to the deflection angle of the ribs and other restrictions of the project silicone was chosen as tooling material. Also the manufacturing method was changed to the method which is shown in Fig. 14. Five different silicon materials were analyzed (Table 3). To test the stability of the tooling and the surface quality of the part different simple test samples were manufactured. The surface quality was measured on a cured prepreg fabric with a “White Light Profilometer” (FRT MicroProf® MPR 1149). The maximum resolution in z-direction (roughness of the surface) is 3 nm (3 x 10^-6 mm). For the surface roughness determination a scanning area of 4 x 4 mm was chosen. Depending on the toughness of the tooling material the fabric structure is more or less distinctive (Fig. 13). All silicone materials consist of 2 components expected for silicon E. This silicon is available as silicone mat. With a higher Shore A value the surface quality and the accuracy of the geometry increases. The best value was achieved with a silicon pad (type E). Due to manufacturing restrictions (draft angle and a required thickness of 25 mm) the finished silicone mat could not be used. For all further tests the second best silicon ZA 50 LT from Zhermack was used.

The manufacturing method for the test panels (a curved section of a fuselage with a radius of 900 mm, length and width 1100 mm) is shown in Fig. 14. For the panel manufacturing the lay-up robot system stands next to the concave lay-up tool. The manufacturing process starts with the lay-up of the surface. After completion of the surface layers the ribs are manufactured.

The accuracy of the rib geometry is important for the stability and the reliability of the manufacturing process. Due to the draft angles and undercuts the free space between the ribs needs to be filled with precisely fitting silicon tools made of the chosen
silicone material ZA 50 LT. To achieve the required geometry the silicone is formed in a separate tool. Based on the rectangular ribs on the surface and the undercuts the tooling for the silicon was printed with a 3D printer. First tests with the silicon tool were successful. After completing the ribs an additional pressure piece was placed on top of the ribs and used to get a better compaction beneath the vacuum bag. Due to the concave lay-up system the compaction of the ribs (< 20 %) had no negative influence for the outer fuselage surface. Nevertheless, this can results in some difficulties for the manufacturing process of a complete fuselage section:
- The lay-up system (AFP robot) needs to work inside the fuselage
- silicon tools for ribs need to be fixed (gravity)

In view of the described problems another lay-up tool is required for the manufacturing of a complete fuselage section. Using a convex lay-up tool the manufacturing process starts with the lay-up of the ribs and ends with the lay-up of the surface (Fig. 15).

During curing of the material especially the ribs are compacted resulting in an inhomogeneous outer fuselage surface, which is unacceptable. A new manufacturing and compaction method has to be developed. In combination of a special lay-up tool and an additional pressure system the compaction of the material (especially the ribs) can apply without fiber deflection on the outer fuselage surface. The new manufacturing system starts with the lay-up of the ribs on a convex tool, which is followed by the surface layers. To apply the pressure to the ribs from the inside to the outside a separate pressure system is required. With a new test tool (Fig. 16) it is possible to apply a pressure on the rib during the “Out of autoclave” curing. The test tool consists of different metallic plates. On the base plate all additional plates were fixed and positioned. As second plate (spacer plate) was fitted in to apply the additional pressure system. The maximum usable size for the additional pressure system was set to 20 x 20 mm. In the third plate the rib is placed. The draft angle from 1° on each side opens to the fourth plate (Fig. 16).

All additional pressure systems were tested on a real rib structure (cured dimensions: 6.35 mm on the short side, draft angle 1° and 20 mm high). For all systems compressed air were used to apply the additional pressure on the rib. In Table 4 the different tube diameters are shown. All tubes have a Shore A value of 55.

In Table 5 different pressure systems and the final rib height are shown. The uncured rib is 25 mm high. The compaction depends strongly on the used material and applied pressure. Higher inside pressure leads to higher compaction and lower void content but due to an OoA process with vacuum compaction the maximum possible applied inside pressure has to be less than 1 bar. Otherwise the additional applied pressure is higher than the outer pressure of the vacuum.

To achieve the required accuracy a pressure plate at the outside of the part is essential.

4 Summary
The manufacturing of lattice structures for a fuselage section with the AFP process was analyzed and described. Different configurations for rib crossing points are proposed and experimentally evaluated. Void content of less than 2 % is achieved due to 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.

5 Acknowledgment
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References
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[6] Fahrhang, L.; Fernlund, G.: Void Evolution and gas transport during cure in Out-Of-Autoclave Prepreg Laminates; Department of Materials Engineering; The University of British Columbia; Vancouver, British Columbia; V6T 1Z4, Canada

Fig. 1: P180 Section

Fig. 2: Lattice structure designed by KhAI (outer diameter 1800 mm)

Fig. 3. DSC-results for different heating ramps

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Fig. 4: Void content depending on the time [6]

Fig. 5: Measured curing cycle (temperature and vacuum pressure)

Fig. 6: Manufacturing process for the rib intersection
Fig. 7: Void content analyses of a crossing section (µ-CT pictures)

Fig. 8: Non-standard 3 point bending test

Fig. 9: Results for the 3 point bending test

Fig. 10: Silicone compression test

Fig. 11: Different silicone design variants

Fig. 12: Silicon tooling block
Fig. 13: Surface roughness from two different tooling materials (silicone B left, silicone D right)

Fig. 14: Tooling and sketch of the panel lay-up

Fig. 15: Manufacturing sketch – fuselage lay-up

Fig. 16: Test tool for applying an additional pressure

Pressurized air inside the additional pressure system applies the compaction force on the rib

Table 1: Curing cycle MTM 44-1 [5]

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Room temp. → 130°C</td>
<td>1-2 °C/min</td>
</tr>
<tr>
<td>2 130 °C</td>
<td>120 min</td>
</tr>
<tr>
<td>3 130 °C → 180 °C</td>
<td>1-2 °C/min</td>
</tr>
<tr>
<td>4 180 °C</td>
<td>120 min</td>
</tr>
<tr>
<td>5 180 °C → Room temp.</td>
<td>Not defined</td>
</tr>
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</table>

Table 2: Crossing section configurations

1) 90° cut every alternating layer

2) 72° cut every alternating layer

3) Fiber deflection into the height
4) Fiber deflection into the width

Table 3: Tooling Material and surface qualities

<table>
<thead>
<tr>
<th></th>
<th>Shore A</th>
<th>Surface roughness Ra [µm]</th>
<th>Rz [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>ZA 22 Mould</td>
<td>21 ± 2</td>
<td>1.160</td>
</tr>
<tr>
<td>B</td>
<td>TCF 4011</td>
<td>35 ± 2</td>
<td>1.066</td>
</tr>
<tr>
<td>C</td>
<td>SF 45</td>
<td>43 ± 3</td>
<td>0.928</td>
</tr>
<tr>
<td>D</td>
<td>ZA 50 LT</td>
<td>50 ± 3</td>
<td>0.981</td>
</tr>
<tr>
<td>E</td>
<td>Silicone 60</td>
<td>60 ± 5</td>
<td>0.877</td>
</tr>
</tbody>
</table>

Supplier: 
A, D) Zhermack / B) Trollfabrik / C) Silikonfabrik 
E) Beyer

Table 4: Silicon tube parameter

<table>
<thead>
<tr>
<th></th>
<th>Outer Diameter [mm]</th>
<th>Inner Diameter [mm]</th>
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<tbody>
<tr>
<td>Silicone tube 1</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Silicone tube 2</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>Silicone tube 3</td>
<td>21</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5: Results of different analyzed pressure systems

<table>
<thead>
<tr>
<th>Pressure System</th>
<th>Applied Pressure [bar]</th>
<th>Rib height [mm]</th>
<th>Void Content [%]</th>
<th>Problems</th>
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<tbody>
<tr>
<td>Silicone tube 1</td>
<td>1</td>
<td>25.0</td>
<td>3.88</td>
<td>Air leakage</td>
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<tr>
<td>Silicone tube 1</td>
<td>1</td>
<td>20.8</td>
<td>0.73</td>
<td>-</td>
</tr>
</tbody>
</table>

AIRTECH, Advanced Materials Group