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Composites Part Production with Additive Manufacturing Technologies

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Abstract

Additive Manufacturing (AM) is of particular interest in the context of composite part production as AM promises the production of integrated, complex structures with low lead times. Currently, AM is used for tooling and sandwich cores with added functionalities. This paper presents four design principles that improve the production of composites parts during layup, handling, curing and post processing in the layup process. Design principles are applied to a hat-stiffener, a highly integrated aircraft instrument panel and a novel insert eliminating drilling operations. Results show that AM can reduce the part count, assembly steps and deformations during curing.

Keywords: Additive Manufacturing; Fiber-reinforced Polymers; Design for Processing;

1. Introduction

Recent advances in the field of Additive Manufacturing (AM) have generated increased interest in the context of Fiber-Reinforced Polymers (FRP) part production [1]. This is owing to the possibility of AM to directly produce geometrically complex structures at constant manufacturing effort. Current applications combining AM with FRP include layup tooling [2, 3, 4] and structural lightweight AM elements with added functionalities, such as AM honeycomb cores in Sandwich structures [5].

Lots of effort is observed in the development of thermally stable materials for the production of in-autoclave tooling with Fused Deposition Modeling (FDM) [6]. Stratasys published design guidelines for the design for FDM tooling and washout tools considering thermal expansion, accuracy and tool life [7]. Studies exist on the effect of thermal stresses for ULTEM 9085 by FDM at 121 °C and vacuum pressure [8]. For ULTEM 1010 by FDM, at 120 °C and bar pressure a minimal wall thickness of 12 mm is reported to keep tool deformations small [9]. These studies represent very important research towards the full understanding of FDM in the context of composite tooling. Most studies focus on the development of materials and their suitability under curing conditions.

Although curing is an important step in the manufacturing of FRP parts, AM can yield benefits along the whole processing route. To the best of our knowledge, there is no study systematically exploring AM design opportunities in tooling, layup, curing and post-processing of FRP parts.

This paper investigates how through *design*, AM can add value in the FRP layup process. Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are combined with a FRP layup process to produce highly integrated lightweight composite parts (Section 2). Four major AM design principles that could favorably impact the composite part production are presented and assigned along the main processing steps (section 3). Considerations relevant to the successful implementation of such design principles are presented. Case studies exemplify the embodiment of selected design principles and quantify the benefits of using AM in the processing of FRP (section 4). Section 5 concludes.

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2. Background information

2.1. Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is a powder bed fusion process where a laser is directed onto the powder bed and thermally fuses the powder layer to form the cross section of the part. The building platform is lowered and a new layer of powder is applied by roller. The process is repeated until the 3D part is built [10]. SLS shows high technological readiness and is considered to be the most favorable production technique for functional polymeric materials [11]. SLS doesn't require support structures and therefore allows the direct production of very complex geometries such as overhangs, internal channels and functional elements. The most common materials for SLS are polyamide 12 (PA12) and dry blends of PA12 accounting for approximately 90% of the industrial production [12].

2.2. Selective Laser Melting (SLM)

Selective Laser Melting (SLM) is a powder bed fusion process using a similar principle to SLS. A laser thermally melts the metal powder which then changes to a solid phase as it cools and forms the cross section of the part. The high melting point of metal powders leads to high thermal gradients and thermal stresses can result warping. Therefore SLM requires support structures for overhangs and anchors are used to attach the parts to the build plate. Typical materials are among others stainless steel, titanium and aluminum alloys [13].

2.3. Composite hand layup process

Fiber-Reinforced Polymers (FRP) consist of aligned, continuous fiber reinforcements that are embedded in a polymeric resin. For many high performance applications PREimPREGnated (prepreg) fibers are used. The autoclave prepreg layup process is a well-established and robust manufacturing route for the production of high performance lightweight structures. In this process prepregs are cut and laid down in the desired fiber direction on a tool. The layup is vacuum bagged and put in the autoclave where defined temperatures and pressures are applied for curing and consolidation of the part [14]. Figure 1 shows an adapted prerpeg layup process where complex elements made by AM are inserted during the layup. These elements can be tooling, structural cores or inserts made from polymers or metals. This approach enables the production of highly integrated, complex parts made of AM and FRP.

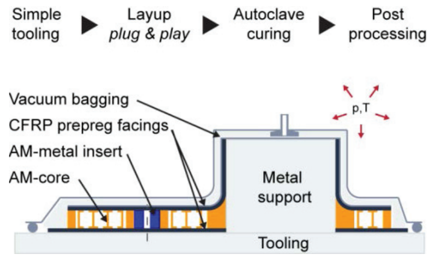


Fig. 1. Hand layup process route combining additive manufacturing and FRP.

3. AM design principles for the composite part production

This section introduces four major design principles that support the processing of FRP parts. They are based on two fundamental characteristics of additive manufacturing: The first one, is the possibility to design very complex geometries, often referred to as *complexity for free*. From this follows the second advantage, that is the integration of various functions into one single part.

3.1. Positioning and fixation elements (pre-assembly)

In the manufacturing of composite parts reinforcement plies, inserts for load introductions, attachment points or structural cores are subsequently added to form the part. The positioning and fixation of such elements is crucial to meet design tolerances for the attachment of further components (e.g. instruments) or the integration of the part in a superior assembly.

In honeycomb sandwich structures the positioning and fixation of inserts is effortful and requires many process steps. The installation of a molded-in fastener into a conventional honeycomb structure requires the following steps: First, a hole is drilled into the honeycomb, then a potting resin is applied. The insert is placed in the hole and a temporary tab is used to hold and fix the fastener during the potting process [15].

With AM, *positioning and fixation elements* can directly be integrated into the additive core or tooling (Fig 2). Design embodiments of such elements can broadly be divided to:

- Connection elements: snap fit, puzzle joints, etc
- Positioning elements: pockets with form fits, spacing elements (e.g. defined bonding gaps)

The integration of such elements potentially reduces the number of assembly steps and thereby the assembly time. In sandwich structures, this allows for a quick pre-assembly of structural elements including AM core elements and inserts (e.g AM cores, inserts) before going on to the layup of the facings. AM tooling could include such elements for the positioning and fixation of conventional honeycombs and inserts. However, a few considerations must be accounted for: On one hand, tolerances are crucial in the design of AM positioning elements. For AM, dimensional tolerances vary depending on the process and the building orientation. Due to the mechanical anisotropy of AM [16], material and building orientation of load bearing connection elements such as snap fit joints should be considered [17].

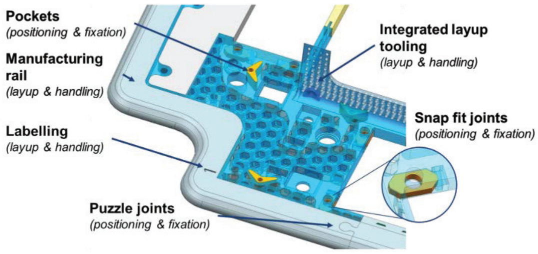


Fig. 2. Examples of layup, handling, positioning and fixation aids.

3.2. Layup & handling aids (layup and demoulding)

Layup processes are very labor intensive and labor costs are 50 to 100 times greater than high volume processes. However, the process offers great flexibility and complex shapes with high fiber volume fractions can be produced. Solid laminates with various fiber materials and orientations, as well as sandwich constructions with foam or honeycomb cores are possible. The prepreg layup process is considered to be a robust manufacturing route for the production of high performance parts, which is why it is very common in the aerospace industry.

During the layup process, a number of prepregs plies are laid in a dictated sequence and orientation on top of an open mold. Common errors during layup are mistakes in the ply sequence and fiber orientation. Common defects are folds, wrinkles, fiber misalignments and shear deformation that occur as a result of draping plies in tight radii or on single and double curved surfaces. There is a high number of possibilities to drape woven reinforcements over a 3D geometry and the fiber directions are significantly different giving different mechanical responses [18].

Additive Manufacturing allows to *integrate layup and handling aids* into the tooling to assist the operator in labor-intensive steps, such as the ply layup or demolding. AM layup and handling aids may be classified into:

- Layup reference
- Manufacturing rail
- Numbering / labelling
- Integrated layup tooling

In this context, a *layup reference* is a set of integrated edges or pockets with form fits that define the starting point and the development of the drape across the tool to minimize fiber misalignment. It should assist the operator when laying down a reinforcement ply where necessary to ensure that the actual and the desired layup correspond. The *manufacturing rail* is a tool that allows for near net-shape fabrication of composite parts and compensates a laminate offset for complex parts. After curing, the rail is machined away to give the part its final shape. It also structurally supports the layup during curing and consolidation. *Numbering* or *labelling* is an easy way to define or to refer to a sequence by directly placing the information on the tool/core and thereby minimizing possible assembly errors. Finally, the layup process offers the possibility to integrate *layup tooling* made by AM that support the operator in laminating complex-shaped areas such as tight curvatures and radii.

The design engineer should consider that the geometrical complexity of AM elements should remain within the possibilities to drape FRP. As a rule of thumb, radii should not be smaller than 5 mm for easy lamination of complex geometries.

3.3. Structural curing aids

In the curing stage, pressures ranging from 1 up to 10 bar and temperatures ranging from 24 °C - 180 °C are applied over time to process the composite layup. The cure cycle depends on the application, the resin material, the thickness and the geometry of the part. In the combined approach the AM elements should withstand these processing conditions without showing severe deformations, collapse or undesired surface effects such as telegraphing.

With AM, *structural curing aids* can be integrated to support the hybrid layup during the curing stage. *Structural curing aids* are oriented support structures, designed to absorb the processing loads and to keep the reinforcements from deforming. In this research we propose the following types of structural curing aids:

- Oriented support structures
- Temporary support structures (core saver)
- Anti-telegraphing structure

The first consists of *structures with oriented mechanical properties* that are opposed to the direction of the processing pressure vector. The processing pressure acts normal to the surface of the part which is why the support structures should exhibits strong properties normal to the outer part surface. The second type consists of integrated *temporary support structures* that are removed after curing. They should be selectively added to the design in areas where the structure necessities additional support during processing. The third type are *anti-telegraphing structures*. Telegraphing is an undesired effect in curing sandwich structures, where the reinforcements deform within an individual cell as a result of a too big cell size and applied pressure. The resulting out-of-plane deflection of the fibers reduces the compression strength of the composite. With AM anti-telegraphing structures such as crosses or grids can be generated to support the layup during the processing. While oriented support structures keep the global shape from deforming, anti-telegraphing structures prevent from local defects and are designed in contact areas with the layup.

General considerations during curing AM with FRP are the difference in the coefficient of thermal extensions (CTE) of polymeric ($47 - 88\ \mu m/mC°$) and FRP $8\ \mu m/mC°$ materials [3]. Furthermore, polymeric AM materials show a visco-elastic material response and creep at elevated temperatures may deform the AM structure. We therefore recommend to mechanically characterize the AM material for FRP processing conditions (creep stiffness, creep strength).

3.4. Postprocessing aids

Most composite parts are post-processed to create holes and other features, generate the desired tolerance in the component, machine the part to the final shape, prepare the surface for bonding or perform surface finishing actions. Machining operations are necessary to perform most these post-processing objectives and machining cost has become a major production cost factor in aerospace applications. A wing on an aircraft has as many as 5000 holes and a transport plane has between 1,000,000 and 2,000,000 holes [19]. Typical challenges during machining composites are fiber discontinuities affecting the performance of the part, delaminations at the cut edges and reduced tool life due to the abrasive nature of the composite [20].

With AM, 3D solid structures can be created that reduce or even eliminate post-processing steps. These post processing aids can be temporary structures that are removed during the post processing of the composite part. Among many possible design principles, an AM element with a *rated breaking point* is presented in section 4. The element has the potential to eliminate drilling steps in the production of composite parts.

4. Case studies

This section presents three case studies where AM is used to improve the processing performance in the context of composite part production.

4.1. Lightweight stiffener profile

Figure 3 shows a lightweight stiffener profile consisting of a core made by SLS and carbon FRP (CFRP) prepreg facings. The AM-CFRP structure could be used to selectively stiffen CFRP panels in compression and bending loading of complex shaped structures (e.g. winglet). Conventional hat-stiffened panels use an over-laminated foam core to increase the bending stiffness of the panel. The foam core is machined and consequently most stiffeners exhibit constant mechanical properties along the longitudinal axis of the stiffener. Using an AM core gives design freedom in selectively adapting relevant geometric parameters, namely the height and the width of the stiffener to local loads.

The AM core of the stiffener features integrated processing aids consisting of positioning and fixation elements, layup and handling aids and structural curing aids. The AM core is split in two pieces to fit into the building chamber of the SLS machine. A slide connector with a 0,5 mm deep groove is integrated in one half and a 0,8 mm thick tongue is embodied on the other half, forming a defined gap of 0,3 mm. A high temperature epoxy adhesive is applied in the gap. The amount of adhesive is defined by the integrated bonding gap and thereby it could improve the reproducibility and the quality of the adhesive bond. A layup reference with two pockets is used in the SLS core to reduce fiber misalignment during layup. In this example, the layup reference supports the laminator in the starting and the finishing point of the layup.

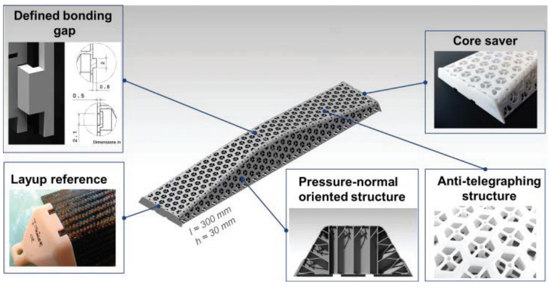


Fig. 3. Lightweight stiffener profile with processing aids

The layup is co-cured for 180 min at 100 °C and at a total pressure of 2,5 bar consisting of 1 bar vacuum and 1,5 bar autoclave pressure. To withstand the processing conditions three structural curing aids are used in this example. The mechanical concept of the core are 3D printed honeycombs that are oriented normal to the layup plane.

To reduce structural deformations in the curing stage, structural cured aids could be integrated into the AM design. For example, a core saver is a temporary edge rail, that is directly produced with the AM core and is removed by machining in the post processing stage. Fig. 4 shows the deformation of the edge of the core without (left) and with a core saver (right) at a pressure of 2,5 bar. The FEM simulation shows deformations amounting up to 0,156 mm without and 0,078 mm with the core saver. The core saver seems to introduce the pressure more evenly into the core structure. An anti-telegraphing structure using crosses are used to keep the layup from deforming locally.

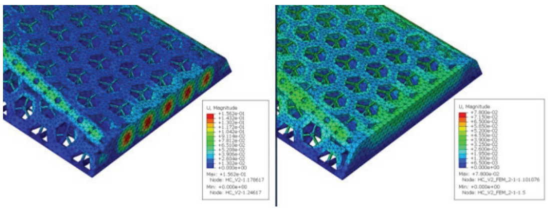


Fig. 4. Deformations as a result of the processing pressure without (left) and with (right) an integrated structural curing aid.

4.2. Aircraft instrument panel

This case study builds on previous work exploring the design potentials of combining AM with CFRP by developing a novel instrument panel for a small multi-purpose aircraft. [5]. The reference panel displayed in Fig 5 is made of aluminum and its main function is the attachment of various instruments ranging from radio equipment to GPS. The structural concept is a sheet metal design. It consists of three sheet metal parts and 115 joining elements such as rivets, rivet nuts and turn-lock DZUS fasteners, resulting in a total of 118 parts to provide 49 attachment interfaces for instruments. Further 8 interfaces connect the support straps to the sheet metal base plate. The base plate is integrally machined down to a thickness of 3,2 mm and the structural weight of the aluminum panel amounts to 1481 g.

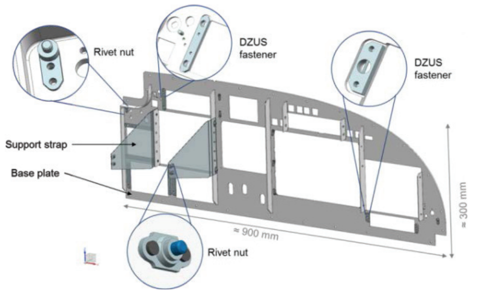


Fig. 5. Aluminum aircraft instrument panel

The novel aircraft instrument panel is a highly integrated lightweight structure using AM and FRP in a way to benefit from the advantages of each material and production technology. The underlying structural concept is a sandwich construction, where CFRP prepregs constitute the facings. The core consists of eight pre-assembled multifunctional honeycombs made by SLS in areas with many functions to integrate and conventional nomex honeycombs in other areas. The following functions are integrated in the SLS core: positioning and fixation elements for inserts, sealing and manufacturing rails and layup tooling. Snap-fit joints are used to hold inserts for the turn-lock DZUS fasteners (Fig 2). Pockets are used for most of the SLM inserts (Fig 6) and the SLS core elements are connected with puzzle joints using a tolerance of 0,05 mm on each side. To manufacture a complex, integrated lightweight part, the support straps are integrated. Therefore, the layup tooling is integrated on top of the AM core. The bottom facings are brought upwards and are laid down on the aluminum tool. The top facings are laid down on top of the AM layup tooling and the bottom facings to form a uniform support strap. The AM-CFRP instrument panel is co-cured in an autoclave at 100 °C and 1,5 bar. The part is demolded and the final contour is machined.

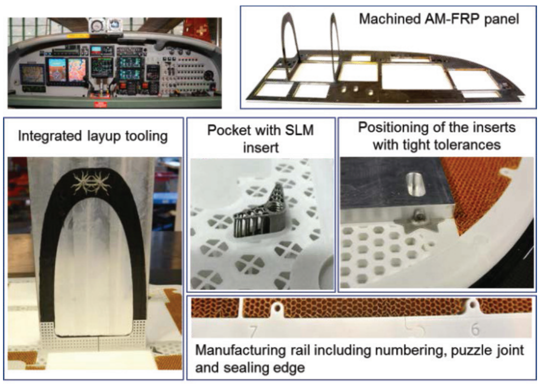
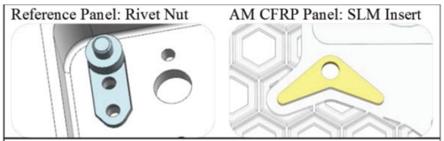


Fig. 6. Processing aids in the AM-CFRP aircraft instrument panel.

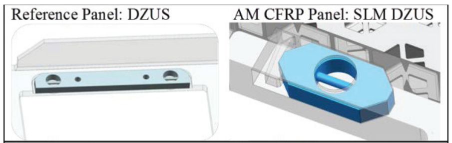
The AM-CFRP panel weighs 880 g, which corresponds to weight savings of 40,6%. Most weight savings arise from the sandwich concept. The number of parts could be reduced by 50%, from 118 to 59 parts. It is composed of 8 AM honeycomb core elements, 7 nomex honeycombs, 2 CFRP facings and 42 inserts. The number of *parts per interface (PPI)* is used to assess the added value of AM in the processing of composites: The aluminum panel uses 115 parts for 49 attachment interfaces and 8 interfaces for mounting the support straps, resulting in approximately 2,02 parts per interface. The AM-CFRP panel manages 49 interface points with only 42 AM inserts, resulting in 0,86 PPI. This is around 2,3 times less PPI. Due to the possibility of integrating layup tooling, the interface points for the support straps could be eliminated.



Reference Panel: Rivet Nut	AM CFRP Panel: SLM Insert
1x positioning 3x drilling 2x riveting	1x positioning 1x drilling through hole 1x tapping a thread
6 steps per interface	3 steps per interface
x 23 rivets	x 23 inserts
138 work steps	69 work steps
⇨ Work steps reduced by 50%	

Fig. 7. Number of work steps necessary to mount an interface with thread in the aluminum (left) and additive (right) version of the instrument panel.

Fig. 7 shows the work steps for mounting one insert using a rivet nut and an AM insert. For the aluminum panel, the rivet nut is positioned, three holes are drilled and the rivet nut is fixed with two riveting operations, resulting in 6 work steps per interface. The panel features 23 rivets, resulting in a total of 138 work steps. In the additive version, the insert is positioned in the pocket of the AM core and after curing the facings are removed by drilling, before tapping the thread. The number of necessary work steps amounts to 3 per interface or 69 in total, corresponding to a work step reduction for the mounting of connection points by 50%.



Reference Panel: DZUS	AM CFRP Panel: SLM DZUS
1x milling the recess 4x drilling 1x positioning 2x riveting	1x positioning in snap-in 1x drilling through facings
8 steps per interface	2 steps per interface
x 10 DZUS fastener	x 18 DZUS fastener *
80 work steps	36 work steps
⇨ Work steps reduced by 55%	

Fig. 8. Number of work steps necessary to mount a DZUS interface in the aluminum (left) and additive (right) version of the instrument panel.

The second category of interfaces are metal rails featuring a metal wire to mount turn-lock DZUS fasteners, displayed in Fig 8. In the aluminum version, a recess is milled into the sheet metal part to ensure the correct distance of the insert to the fastener. Then, 4 drilling operations are performed and the insert is positioned and riveted to the base plate. The number of work steps amounts to 8 for every interface or to 80 work steps for the whole aluminum panel. In the additive version, certain rails are split to save weight. The metal wire is directly

3D printed into the SLM insert. It is positioned using a snap-fit joint in the SLS core. After curing, a drilling operation is performed to remove the facings. Using integrated snap fit joints reduces the number of work steps to two per interface or 36 for the AM-CFRP instrument panel. This corresponds to a work step reduction of 55%.

4.3. Lightweight insert with integrated break-away pin

Figure 9 shows a lightweight insert made with SLM. It is inserted into the pocket of the AM core of the aircraft instrument panel described in the section above and is used as a load introduction element. The insert features lightweight vertical trusses that merge into arcs and so, it is manufactured without supports. The wing shape gives the connection element additional rotational strength. In the center, a bore hole with the core diameter of the desired thread is printed. The insert features a multifunctional pin on top of it. A sharp tip punctures the FRP layup and pushes the reinforcing fibers around the pin. The layup is deposited on the insert, with the pin looking through it. Below the tip a spanner gap is integrated into the pin. After curing, the location of the inserts is visually apparent and the pin can be broken away by applying a torque on the rated breaking point with an open ended spanner. The bore hole is released and is resin-free. Drilling through the hole is not required and the only necessary machining operation is tapping the thread. The reinforcement fibers remain continuous as no drilling is performed, resulting in a mechanical performance advantage compared to discontinuous FRP load introductions. This example shows how AM can be used to *design for part performance* by using lightweight structures and to *design for processing*: In this case the latter approach reduces the time and the number of post processing steps while preserving the performance of the fibers.

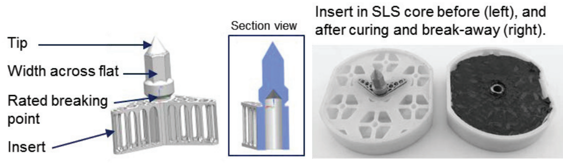


Fig. 9. Lightweight insert made by SLM with a pin featuring a predetermined breaking point to avoid hole drilling

5. Conclusions

This study investigated how through *design,* AM can support the production of composite parts along the whole process chain ranging from tooling to post processing. Major AM design principles that improve the processing of FRP can be classified into integrated positioning and fixation elements, layup and handling aids, structural curing aids and post processing aids. Case studies showed that structural curing aids can reduce part deformation, but require knowledge about the material behavior at curing conditions. The example of an aircraft instrument panel made by AM and CFRP showed that the integration of positioning and fixation elements could reduce the number of parts by 50% and the number of work steps to mount an interface by up to 55% compared to an aluminum reference panel. A novel type of insert with a predetermined breaking point, eliminating the need for drilling through CFRP facings is presented. These examples, show that AM can offer advantages in the performance of the part and in its fabrication if major processing principles are considered during design.

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