Efficient additive manufacturing of long fiber composite reinforcements using Fibre Patch Placement

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Abstract

Fibre-Patch-Preforming (FPP) is a novel process for automated manufacturing of complex CFRP parts. The developed robot system positions unidirectional long fiber patches at any position and orientation on a mold. FPP enables a unique laminate design and offers the possibility to locally tailor product properties through fibre orientation and part thickness. Thereby, the process aims to reduce manufacturing costs and structural weight and offers a solution to produce complex geometries and high performances CFRP structures. This paper intends to describe the process potential for improvement of CFRP production in the aerospace industry.

1. Introduction

The use of carbon composites in aerospace is driven by market needs for increased aircraft performances. Carbon fibre reinforced plastics (CFRP) demonstrated their potential for weight reduction in different structural airframe applications thanks to their high weight specific mechanical properties. With the growing airline demands for efficiency, composite structures have thus been gradually introduced into aircrafts design through a step by step approach and is currently representing respectively 50% and 53% of the structural weight for the recent 787 and A350XWB [1]. CFRP use allowed for significant weight reduction leading to increased range and fuel efficiency as well as reduction of the maintenance costs. This progressive evolution is however now challenged by some downsides inherent to the use of composites among which are the manufacturing costs and lead time.

Even though CFRP are proved capable of reducing significantly aircraft structural weight, their production must evolve and improve in order to remain competitive and satisfy the present challenging market requirements. Air transportation is indeed soaring. The traffic increased by 5,7% in 2013 and by 73% over the last ten years. Despite the recent crisis, the air transportation economy remained resilient, travel demand kept increasing and Airbus forecast future steady growth [2].
As a results Airbus activity reaches a new industry-record with a current backlog of 6,399 aircraft (as of 30 April 2015) that ensures approximately 10 years of continued production at current delivery rates for the jetliner families [3]. In order to better meet the demand, the lead time must be reduced. The A350 XWB for instance received already 780 purchases, the production rates are therefore steadily increasing and are now planned to exceed 50 aircrafts per month. Given the industrial context, CFRP solutions must align and offer cost-efficient manufacturing with shorter lead time.
Production efficiency needs to be achieved at all steps of the manufacturing chain. CFRP competitiveness improvement for aircrafts requires thus high performance materials at lower costs, automated lay-up technologies, reliable curing and assembly as well as automated NDT analysis. In order to achieve efficient manufacturing of CFRP components it is mostly crucial to introduce adapted automated manufacturing processes.

Automated CFRP manufacturing is already performed for some shell skin structures such as for the fuselage, tail and wings using automated tape laying (ATL) and automated fiber placement (AFP) technologies. These technologies offer great automation grade, part quality reproducibility, as well as generally good production rate.
These processes have nonetheless limitations, and when the structure complexity increases they become inappropriate. For complex geometries and/or lay-up featuring numerous local reinforcements ATL or AFP can be either inefficient or inapplicable. The ATL process is indeed limited to 2D or 3D geometry having slight single curvature given that the placed wide material stripes will wrinkle when steered. AFP places parallel narrow tows that are individually steered, started and dropped. It is therefore less sensitive to wrinkle and allows therefore more flexibility in part geometry and lay-up design. Its constraints are due to potential head collisions, roll compaction

capabilities, minimal cut size and material steering limitations. AFP is therefore efficient for most shell applications but not for production of small reinforcements or complex geometries as its production rate then drops drastically.

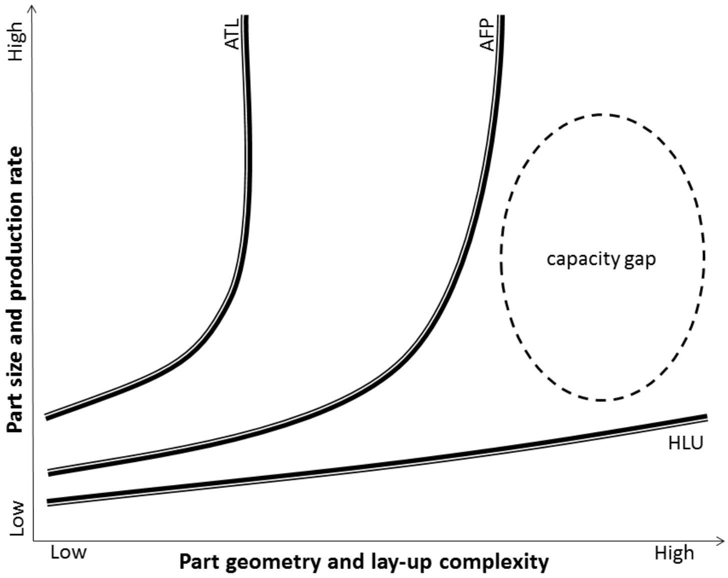


Figure 1: Illustration of efficient application area of state-of-the-art production processes

For these reasons the hand lay-up of prepregs (HLU) and autoclave cure is still a widely established manufacturing process for such CFRP components because its limitation are only due to the material drapability. The manufacturing is consequently costly due to high labor efforts and is not suitable for high volume. There is therefore currently a capacity gap for the efficient manufacturing of high volume complex CFRP parts. ATL and AFP are not efficient when the part to produce is too small and/or too complex. HLU is acceptable for small sizes and low volume production rates but is expensive and not adapted for high volume production. Therefore aircrafts still contain significant number of machined metallic components for such applications. New production technologies are required to enable future suitability of CFRP designs given the current production requirements.

1.1 Fiber Patch Placement (FPP) / Process description

Fiber Patch Placement (FPP) is a novel process that proposes a solution for efficient manufacturing of small reinforcements and complex geometry parts. The process was invented in 2008 by the R&D department Airbus Group Innovations [4] and developed in cooperation with the automation company Manz. The developed robot system enables automated and controlled lay-up of unidirectional discontinuous long fiber cuts at any position and orientation on a mold. The system combines three cooperating unites: material supply, a four-axis pick-and-place robot and a six-axis tool manipulation robot.

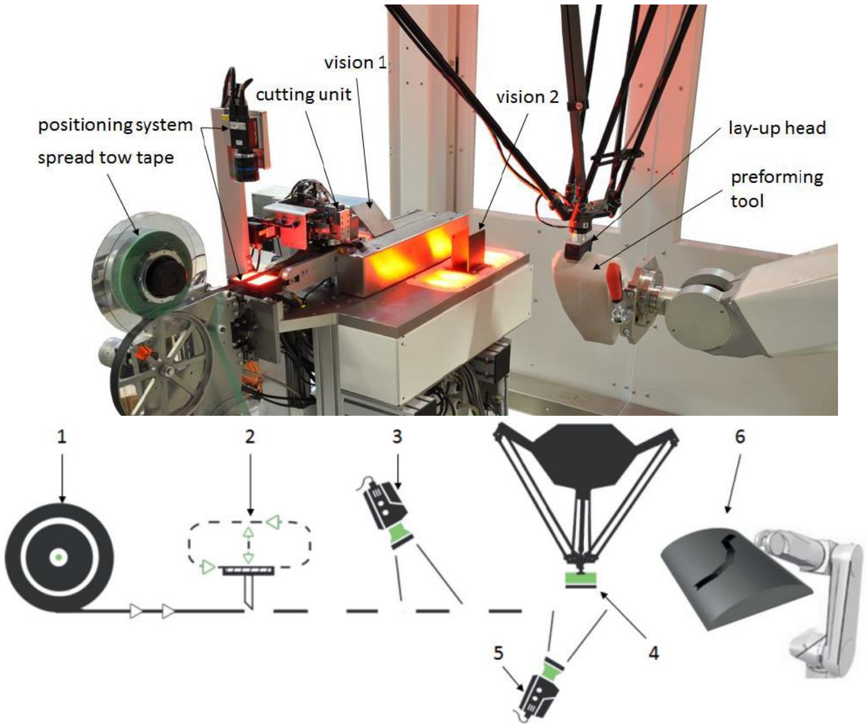
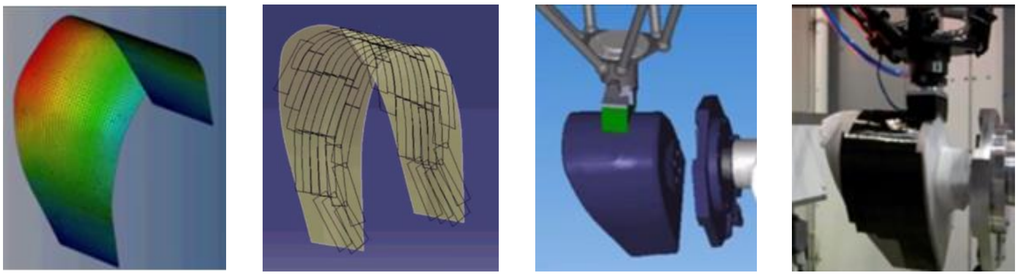


Figure 2: Illustration of the FPP process components and manufacturing steps [5]

In the material supply unit a unidirectional carbon fiber tape is guided through a feeding system into the machine (1). The fiber tape is then cut into regular long fiber cuts called patches (2), typical machine settings enable delivery of patches with 10-20mm of width, and 40-100mm of length. The correct patch geometry is ensured by an optical system that rejects imperfect ones (3), this guarantees the compliance with tolerances of ± 0,2 mm in length and width . An end-effector mounted on the pick-and-place robot picks up the patch by vacuum (4). The position of the patch on the end-effector is checked by a second optical system that detects any deviation in order to correct the patch deposition point, and ensures a positioning repeatability of ± 0,3 mm. (5). The end-effector is highly flexible and deforms according to the mold surface. It includes a system to heat the tape material required to bind it to the mold. The mold is manipulated by a six-axis robot enabling manufacturing of 3D structures (6). The sequentially stacked patches then create the 3D Lay-up. The extremely quick movement of the pick-and-place robot ensures high productivity. The pick-and-place robot reaches a deposition rate of one patch per second while the mold is independently moved. Thanks to the continuous patch delivery of the supply unit the deposition rate can be maintained even for a part with high geometrical complexity.

To ensure a simple and efficient use of the technology, which is crucial for its success, software modules are provided by the software and process consulting company CENIT. A first module is the dedicated design module, integrated in the Catia V5 CPD workbench supporting the development of specific FPP laminates. It uses CAD functionalities to automatically arrange several layers of patches on 3D surfaces. An algorithm automatically defines the patch arrangement based on user inputs in order to optimize the laminate properties. After the optimization the laminate arrangement is visualized in the software.

The second module is offline programming the machine control for the lay-up using a machine simulation software. The machine configuration is simulated in the software, the mould and patch data are imported and positioned. Based on this information the program defines the lay-up position of each patch as well as the motion of the pick-and-place and mould manipulation robots. The manufacturing is then simulated to validate the calculated robot motions and detect potential collision. Alternative motions can be created if necessary. Once verified the program can be exported to the manufacturing cell. During the generation of the machine program the software internally optimizes the position process to reach a high lay-up quality and productivity. The software takes into account the draping of the end-effector on the tool in order to correct the lay-up position and ensure good positioning tolerance.



Desin optimisation Patch Design Process simulation Automated lay-up

Figure 3: Illustration of the FPP product development steps

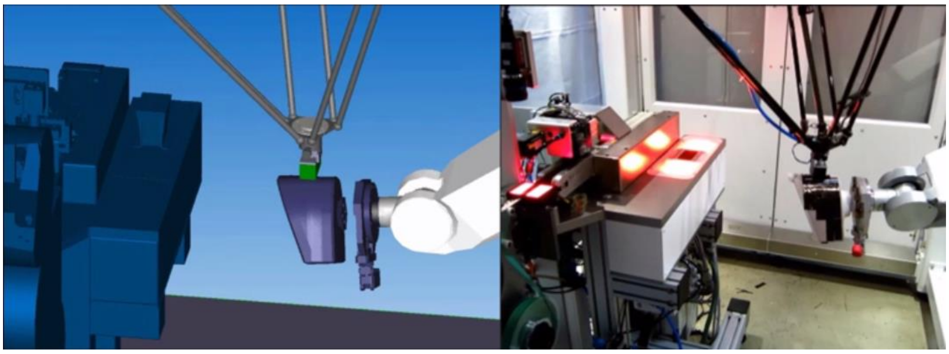


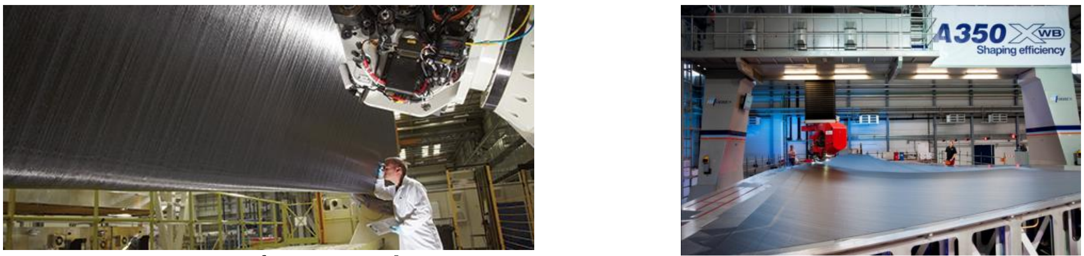
Figure 4: Illustration of the FPP process simulation and the automated lay-up [6]

The FPP technology has a high potential to improve the manufacturing of complex geometries and high performance CFRP parts featuring local reinforcements. The characteristic patch by patch stacking offers many ways to customize part properties, to locally tailor product properties through fiber orientation and part thickness. Costs can be kept low as the part lay-up is fully automated, the process generates low waste and the required investment are much lower than for standard AFP, or ATL processes. Thereby the process aims to reduce manufacturing costs and reduce structural weight for the small and complex applications.

1.2 Efficient reinforcements manufacturing

To be successful a CFRP design has to be producible, that means its production must be cost-efficient at the targeted production rate. Aerospace structure design is generally highly optimized given the high benefit of weight savings. The resulting production cost and time are therefore important, as they are mostly increasing with the part complexity. The production method and specific design must also consider the production rate at early stage in order to avoid uncontrolled delay or cost increase during ramp-up phases.

ATL and AFP are successfully used in production of CFRP aerospace structures. Significant investment are required but these processes are the most effective for manufacturing of large shell components thanks to their high lay-up rates, from 2 to 100kg/h depending on the application.



wing spars manufacturing with AFP wing covers manufacturing with ATL

Figure 5: Illustration of machinery used for production of A350XWB CFRP shells [7]

Even if they are mostly efficient, their production rate can drop significantly below 2kg/h when laying local reinforcements. Small reinforced areas are widely present in aerospace CFRP structures. Local reinforcements are widely present in optimized structures and are typically present in rim and joining areas as well surrounding cutout

areas. The lay-up of such small reinforcements leads to a drastic reduction of AFP production rates. This results in reduction of AFP cost-effectiveness and in increased lead time. When high production rates are required, the purchase of second machines and tooling for manufacturing in parallel can therefore be necessary.
Unlike AFP and ATL, the FPP process is efficient for the lay-up of small reinforcements. In order to avoid ineffective manufacturing of small reinforcements, FPP can be combined with AFP, and used to manufacture reinforcement stacks. These can be manufactured in parallel, pre-compacted and then assembled to the base laminate.

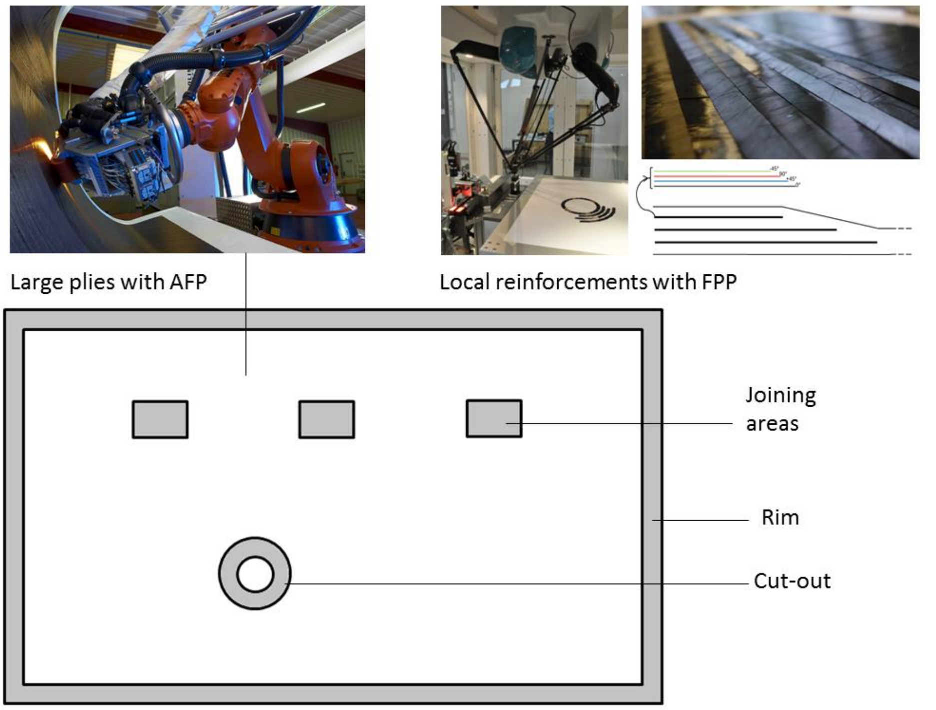


Figure 6: Illustration of methodology for use of FPP in combination with AFP

The benefit of this strategy is that expensive AFP machines are not misapplied to the manufacture of small reinforcements with poor production rates. The local pad-ups are manufactured with efficient machinery with lower costs and avoiding bottleneck in the part lay-up. The overall increase of productivity helps to achieve shorter lead time and can avoid the need of a second production line. Figure 7 depicts FPP performances compared to the state-of-the-art processes for small reinforcement manufacturing. The process achieves for such application comparable quality and material performance as AFP with a higher production rate with lower investment costs.

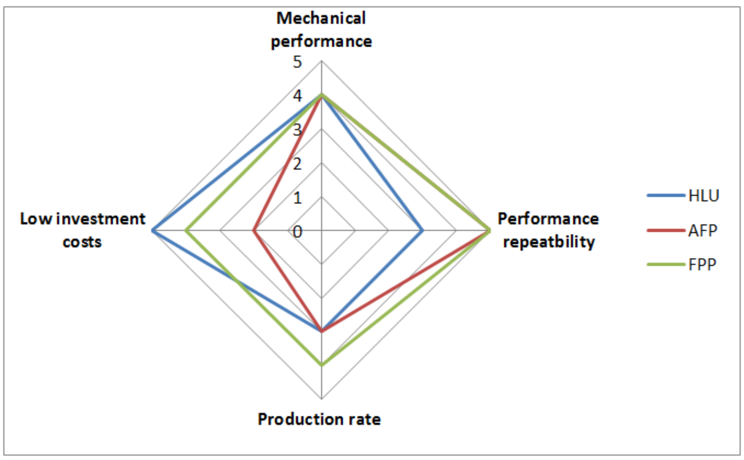


Figure 7: Comparative evaluation of process performances for manufacturing small reinforcements of aerospace CFRP structures

Thanks its flexibility, FPP can also be applied widely and be used for reinforcement of more complex geometries, this has been demonstrated with the 3D direct reinforcement of a braided frame.

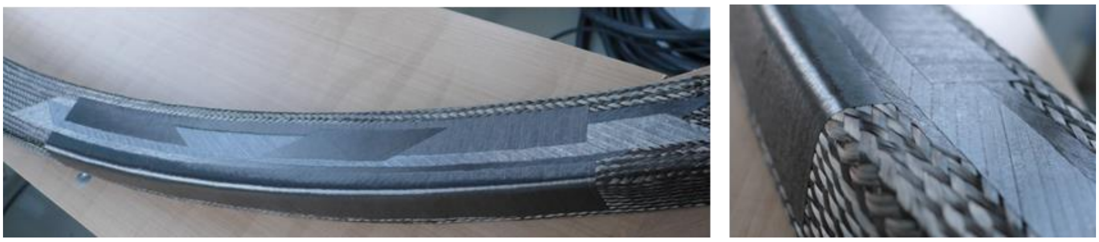


Figure 8: Direct 3D local reinforcement of a complex braided frame using FPP

1.2 Efficient additive manufacturing of complex geometries with long fiber composite

ATL/AFP cannot be used for the manufacturing of complex shaped parts due to the restrictive process and material limitations. For such applications the use of discontinuous fiber is the only possibility to enable light CFRP structures with reduced costs and lead time. Discontinuous fibers induce a strong decrease in in-plane mechanical properties but allow to get rid of the draping issues that strongly limit the producible part geometries. New manufacturing technologies using discontinuous fibers are emerging and create potential efficient production solutions.

Discontinuous short fibers composites have typically fibers with less than 1mm of length. There in-plane properties are very low (maximal 200MPa of tensile strength). They are used in injection molding processes that allows for relatively good fiber dispersion with steady anisotropic properties. Thermoplastics material (such as PEKK) with very short fibers can also be used with laser sintering processes in order to manufacture complex parts with almost no design constraints. These processes enable very high shape complexity but given the low material properties they cannot yet be applied for structural elements. Therefore they are currently used for non-structural elements such as air ducts, electrical assembly elements or interiors.

Oxford performance materials' installation brackets Stratasys' air duct

Figure 9: Illustration of 3D Printed aerospace parts.

Discontinuous long fibers (DLF) offer another alternative for applications where short fiber composites lack sufficient performances. Such materials have fibers ranging typically from 1 to 100mm of length. Parts manufactured with short fiber cuts are usually compression molded in net-shaped parts. That process is adaptable for thermoplastics and thermosets. When using the dry textile manufacturing routes it is also possible to spray the fibers in order to automate the lay-up for larger parts. Discontinuous long fiber composites target secondary and primary structure applications, and especially parts such as brackets, fittings, clips.

This process is flexible, enables efficient manufacturing of complex parts with integrated elements and it also reduces waste. Even if the process can get accurate overall resin content and fiber length, it is difficult to have predictable material performances as the fiber distribution and orientation can poorly be controlled. This result in high design safety factors due to the important variation in mechanical properties. Therefore even if DLF materials have a high potential for efficient manufacturing of complex parts its use in aerospace structural applications is still restrained. Adapted design, prediction and certification methodologies are still needed to allow its implementation.

Figure 10: Illustration of parts manufactured by Green tweed using Xycomp DLF materials

The FPP process enables the manufacturing of complex shaped parts with discontinuous long fibers (length typically 40-100mm). In opposition to traditional DLF processes, the fiber architecture is precisely predicted and controlled. The fiber distribution is even calculated with dedicated software in order to optimize the laminate strength. The additive patch by patch manufacturing ensures a high quality laminate production with reduced drapability issues and with low fiber undulation. Also the laminate properties can be tailored with local modification of the part thickness or fiber orientation.

Lay-up head adaptability　　　　Manufacturing of a complex T-Joint structure

Figure 11: Illustration of the geometrical flexibility of the FPP process

Figure 12: Illustration of complex parts manufactured with the FPP process.

The FPP process enables therefore manufacture complex shaped shell parts with high repeatability and high in-plane properties. While traditional DLF laminates have tensile strength of ca. 300MPa, FPP QI laminates can achieve more than 600MPA. Manufacturing costs can as well be kept low through the use of inexpensive fibre material and automated robotic production.

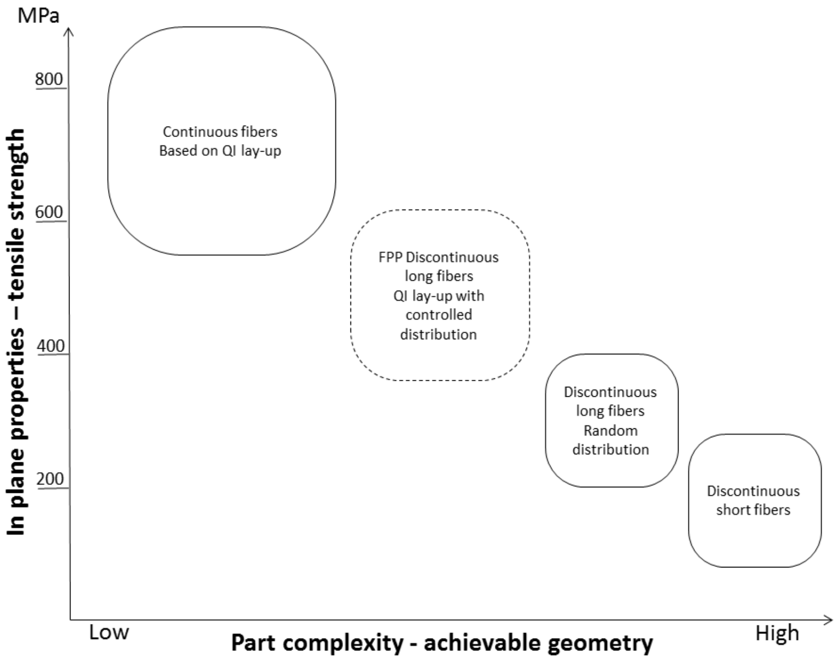


Figure 13: Illustration of mechanical perfomances and flexibility of the considered materials and processes

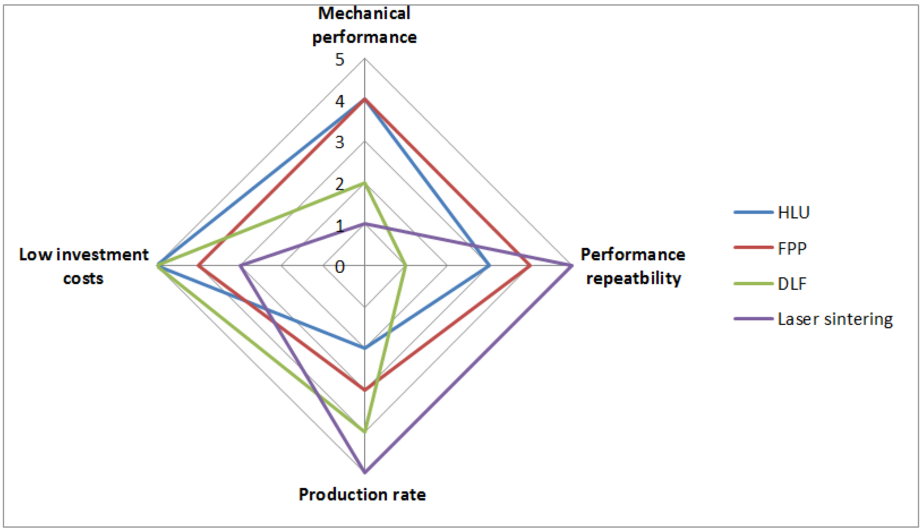


Figure 14: Comparative evaluation of process performances for manufacturing of complex aerospace CFRP parts

In contrary to the other processes using long fibers, FPP can ensure in the same time high repeatability, high mechanical performances and good geometrical flexibility. Therefore it offers a suitable solution for the efficient, automated production of high volume complex CFRP structures, that is required given the present challenges in the aerospace industry.

References

[1] K. Edelmann. 2012. Automatisiert - CFK-Thermoplast-Fertigung für den A350 XWB. Lightweight Design. 42 Produktions- und Fertigungstechnik.

[2] Airbus Global Market Forecast 2014-2033

[3] http://www.airbus.com/company/market/orders-deliveries/

[4] http://www.airbusgroup.com/int/en/innovation-environment/airbus-group-innovations.html

[5] Image source from the University of Munich, Institute for Carbon Composites, http://www.lcc.mw.tum.de/

[6] Image source from the company Cevotec, http://www.cevotec.com/

[7] http://www.compositesworld.com/articles/a350-a400m-wing-spars-a-study-in-contrasts