ANALYSES OF MANUFACTURING OPTIMISATION OPTIONS ON THE HLFC-HTP

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Abstract

The major objective of the Clean Sky 2 HLFC-HTP project is to reduce viscous drag by establishing laminar flow at the Horizontal Tail Plane (HTP) of a long-range aircraft. In order to do this, a suction system integrated leading edge structure, that is suited for series production without trading in aerodynamic drag reduction potential, had to be developed. With respect to the enabling of laminar flow all former Hybrid Laminar Flow (HLFC) and Natural Laminar Flow (NLF) projects showed that meeting the very high demands of step, gap and waviness tolerances is a crucial hurdle that needs to be passed. The combination of a porous outer Titanium skin and a load bearing CFRP substructure was the most promising approach for the HTP Leading Edge (LE) even though CTE (Coefficient of Thermal Expansion) mismatch related challenges had to be considered. The manufacturing concept was basically a two-step approach based on a secondary bonding process for the joining of the porous Titanium skin to the CFRP substructure. To verify the feasibility of the two step approach several representative single curvature sub components (750 mm span) have been designed, manufactured and tested. Besides aerodynamic and weight efficiency the main driver for the load bearing leading edge sub structure were producibility and energy efficiency of the production process in order to meet the sustainability demands from an "Eco Design" point of view.

1. DRAG REDUCTION THROUGH LAMINAR FLOW

The basic Hybrid Laminar Flow (HLFC) idea is to safe fuel through drag reduction and establishing laminar flow is the technical approach to achieve the drag reduction. In comparison with Natural Laminar Flow (NLF) and Laminar Flow Control (LFC) approaches, HLFC concepts provide a large potential for structural adaption (sweep angle, Reynolds number, airfoil design) while keeping the technical effort at a reasonable level (Suction only at the leading edge). To further reduce technical effort, it makes sense to mainly consider cruise condition since this would bring the biggest over all benefit.

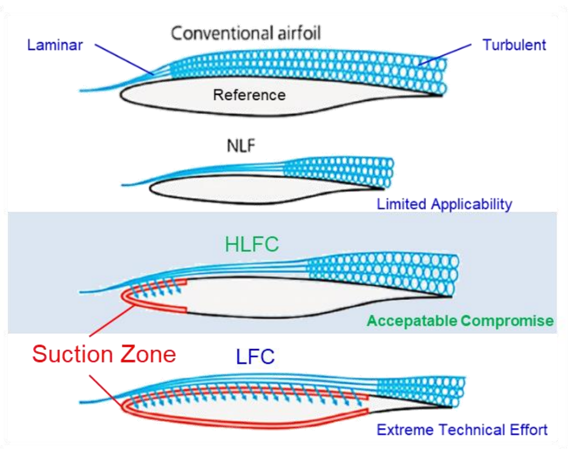

FIG. 1: NLF, HLFC and LFC Principles [1]

The smoothness of the aerodynamic surface is the major enabler for laminar flow but technical requirements like e.g. the overall built concept and repairability constrains are significantly limiting the potential for laminar flow at today's aircrafts.

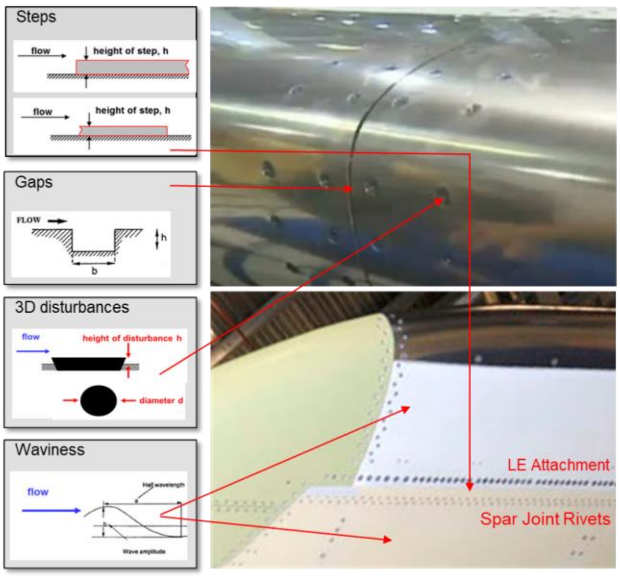

FIG. 2: Typical Surface Defects at an Airbus A350 HTP

The most challenging surface disturbance is a backward facing step because even small tolerances in the order of 0,1 mm may cause transition to turbulent flow. Application of filler to smoothen the surface has successfully been done in research campaigns but the related effort is extremely high and durability may not be sufficient for a series application.

2. HLFC-HTP SMALL SCALE DEMONSTRATOR

To check the feasibility of the HLFC-HTP approach it is essential to analyse the interaction of aerodynamics, structure and systems. Furthermore, it has been decided to highly integrate aerodynamics, structure and systems because this offers the potential to minimise the size and the weight of the HLFC leading Edge. To minimise the power consumption of the compressor it was important to have a suction pressure adaption in chordwise and in spanwise direction.

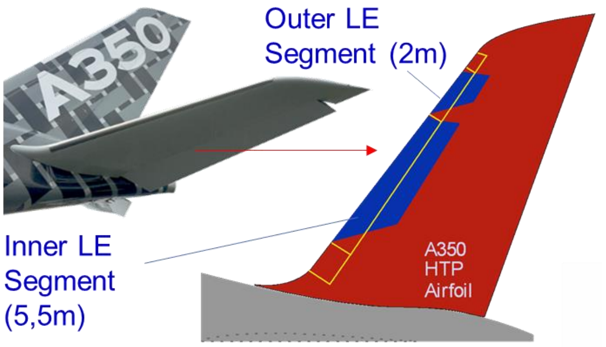

FIG. 3: Suction segments for the A350HTP

The final result of several optimisation loops was to skip suction at the tip end of the HTP (outer 500 mm) because of the highly double curved surface. A feasible compromise was to have a 2 m long outer suction segment and a 5,5 m inner suction segment with individually adapted plenum pressures. The inner section of the HTP is affected by the fuselage aerodynamics in a way that laminar flow is difficult to establish.

The remaining critical details, that need to be checked, are mainly geometrical accuracy aspects and also manufacturing aspects especially when the assembly is based on secondary bonding of materials with different CTEs. Acceptable blocking of the suction skin in the bond line area is also very limited and needs to be checked under realistic boundary conditions. In addition, space allocation aspects are very challenging at the outer LE segment, because the compressor shall be positioned within the plenum chamber with its outlet reaching through the HTP front spar.

Last but not least the sizing of the HLFC leading edge is highly dependent on its bird strike performance. The chosen design approach with a laser drilled Titanium skin, a CFRP substructure with integrated omega spacers and a secondary bonding based joining process is quite unusual and therefor a potential risk. Another uncertainty is that the Titanium suction skin and the omega spacers can not be considered as fully load bearing structures.

To check the different critical aspects, a representative Small Scale Demonstrator (SSD) has been designed. In order to analyse space allocation aspects a rather small cross section at the outer LE segment has been chosen. Other features that needed to be verified were the chambering concept and the pressure adjustment approach on the bases of drilled throttle orifices. The structural concept of the load bearing CFRP structure (skin and ribs) has been derived from the series A350 structure. Integrally manufactured, foam core filled, omega shaped spacers have been agreed on, to support the titanium suction skin and separate the suction chambers [3]. The bond line between the Titanium skin and the omega spacers is a compromise between minimizing blocking of the suction skin on one side but allowing sufficient load transfer on the other side.

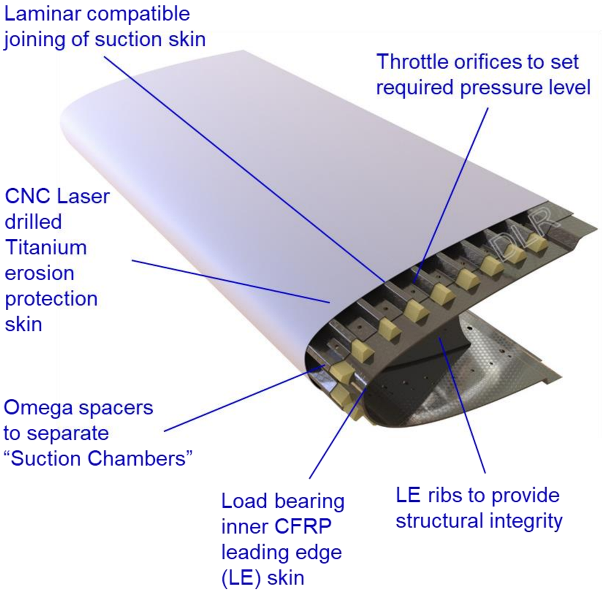

FIG. 4: SSD Features

The inner volume of the LE shall be sealed against the outside pressure and used as a large plenum chamber [4]. The main advantage of this approach is, that the compressor can then be installed directly inside the plenum chamber without the need of any pipes. By installing the compressor and the related electrical systems at the box front spar the HLFC leading edge structure can be exchanged without the need to disconnect any systems. The outlet of the compressor is directed through the front spar into the HTP box which is open to ambient pressure. This minimises the maintenance and repair effort.

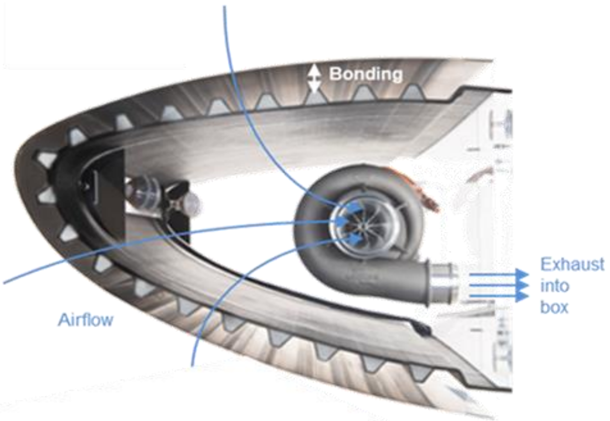

FIG. 5: SSD Compressor Integration

3. SSD MANUFACTURING

Multi-material structures do have the potential to combine individual material strengths but it is also quite likely that unknown effects cause unforeseen problems in a later stage of the project. In case of the HLFC-HTP leading edge the erosion resistance of the Titanium had to be combined with the geometrical flexibility and the light weight design potential of CFRP structures. Furthermore, the required surface smoothness asked for a bolt free joining solution like structural bonding which is also well known for unexpected effects.

3.1. Flat Manufacturing Trials

To get a first impression of the criticality of the chosen approach, small flat coupons with a quite representative material mix have been manufactured and analysed.

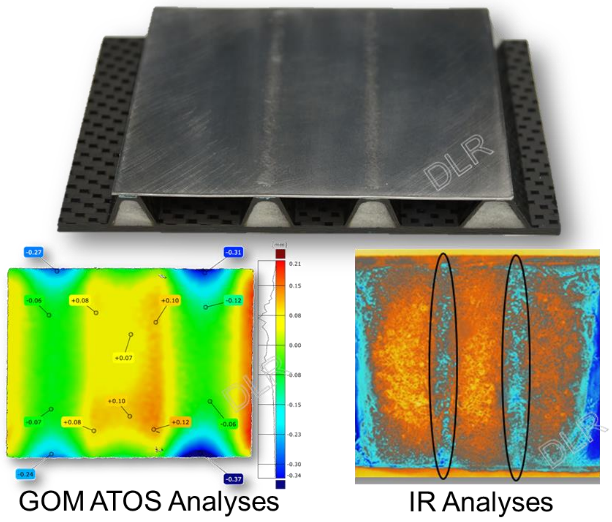

FIG. 6: Analyses of Flat Manufacturing Trials

With respect to the integral CFRP part the angle of the omega spacers has been varied and the best result was a combination of small spacers in the front section and wider (easier to demould) spacers in the rest of the structure. For the bondline a plateau of 7 mm width and 2x1 mm tolerance zone had to be provided to meet manufacturing and structural demands. The defined blocking zone of max. 9mm was acceptable for the aerodynamic HLFC layout and also for the required load transfer.

The geometrical analyses of the flat manufacturing trials showed a noticeable waviness in the Titanium sheet which needed to be kept in mind. The amount of blocking has been analysed with a specially developed infrared sensor setup and applied forced convection. The result here was that blocking was limited to the expected 9 mm zone on top of the spacer in spanwise direction. Even though blocking was acceptable, the thermal stress in the bond line was found to be critical. Further measures to reduce the thermal stress and improve the adhesion had to be developed. Another result was, that the chosen adhesive pultruded through the microperforation and was visible on the aerodynamic surface.

All the results and lessons learnt from the flat manufacturing trials were considered for the far more complex manufacturing of the Small Scale Demonstrators.

3.2. Small Scale Demonstrators

Although a closed mould Resin Transfer Moulding (RTM) process promised to be more efficient from an energy consumption point of view it has been decided to use an SLI (Single Line Infusion) autoclave infusion process for the prototype manufacturing because of the much cheaper and more flexible open mould tooling.

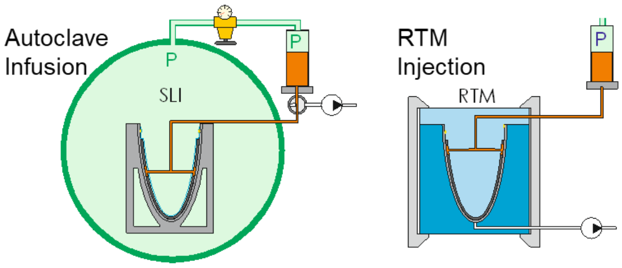

FIG. 7: Open and Closed Mould Processing Options

The complexity of the LE component also asked for a tooling with matching CTE (Coefficient Thermal Expansion) in order to avoid critical forces

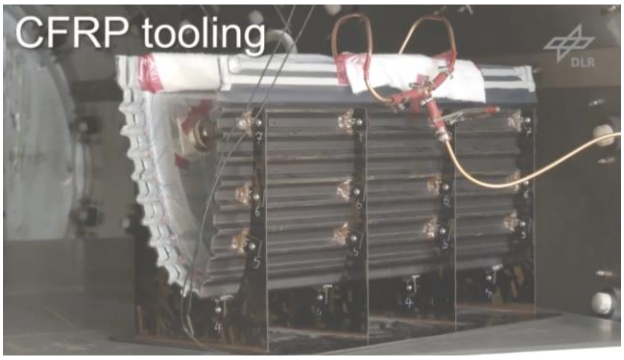

FIG. 8: CFRP Mould in Autoclave

Four demonstrators have been produced to check the various aspects of the multifunctional, multi-material HLFC leading edge component.

* “Trial 1” was mainly used to vary preforming options and to find a possible infusion setup.

FIG. 9: SSD Overview

“Trial 2” was the first CFRP component that was successfully infused even though especially the preforming procedure was still in a very provisional stage.

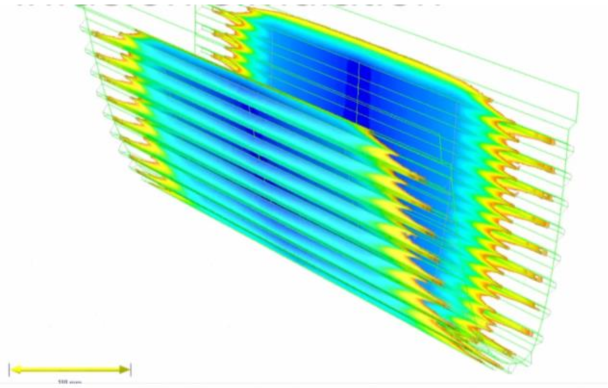

FIG. 10: Infusion Simulation for “Trial 2” SSD

Because fast microdrilling of large Titanium sheets was still under development it has been decided to use a non-drilled Titanium sheet for the bonding procedure. To control the deformation and the bondline stress of the later leading edge structure all spacers where bonded individually in a predefined sequence. A pressure hose has been used to apply a uniform compaction pressure in spanwise direction.

“Trial 3” was also successfully infused but it was mainly used to further optimize the CFRP part manufacturing process and to identify dominating cost drivers.

“Trial 4” was the first approach with a highly predefined manufacturing sequence for the CFRP part and a detailed analysis of the costs during prototype manufacturing. Furthermore, the first large microdrilled Titanium sheet was successfully bonded to the CFRP base structure.

FIG. 11: Bonding Process (“Trial 4”)

The “Trial 4” CFRP substructure had a number of drilled throttle orifices that were used to adjust the defined chamber pressure in a later functional test.

The final “Trial 5” SSD was optimised for a later series production and therefor a completely new and much simpler preforming approach has been introduced. In the earlier preform sequence a wavy fabric has been consolidated to build the omega spacers laminate. The main problem with this approach was, that tolerances and also the quite significant bulk factor of the fabric added up and caused significant shape uncertainties in the preforming process. The new solution for the omega spacer preform was based on braided glass fibre tubes that were used to wrap each individual foam core.

FIG. 12: Old and New Spacer Preforming Concept

The introduction of a newly developed infusion device was another decisive step towards a later series production. Besides the hot-swappable double container feature (used for continuous infusion) the highly responsive and powerful microwave resin heating system made a significant difference.

FIG. 13: Digital Infusion Center (DIce)

In addition, the Digital Infusion Centre is designed to control the infusion and curing process based on real time sensor information like flow front propagation and cure status. Heating and degassing of the resin system are fully automatic and controlled by integrated sensors. The Digital Infusion Centre is also fully integrated in the data network which means that it can be monitored from all connected terminals. Another specialty is that the mobile DIce can be used for pressurised and non-pressurised open and closed mould processes like LRI (Liquid Resin Infusion), RTM and Autoclave infusion. The machine has also an expert modus where all parameters can be set manually. This can be very helpful to counteract unforeseen developments (e.g. exothermal reaction of epoxy resin or blocked infusion lines) or when completely new procedures shall be investigated.

4. SSD RESULTS

The Small Scale Demonstrators have been manufactured and analysed to pass the TRL3 and TRL4 reviews and to support the TRL5 review for the HLFC-HTP leading edge.

4.1. Geometrical Accuracy

The comparison of the Catia geometry and the GOM ATOS scan of the “Trial 2” shows that there is a very good match and that there is no significant waviness. The deviations at the upper left edge of the structure are dedicated to a tooling deviation that has been detected, when the CFRP structure has been scanned before bonding. Compared with the formerly tested flat coupons the level of deformation is significantly lower and within a range that could be managed with less improvised production boundary conditions. In the intended RTM manufacturing approach with a rigid, metallic closed mould the geometrical tolerances of the CFRP structure will be even lower because the cavity is fully defined.

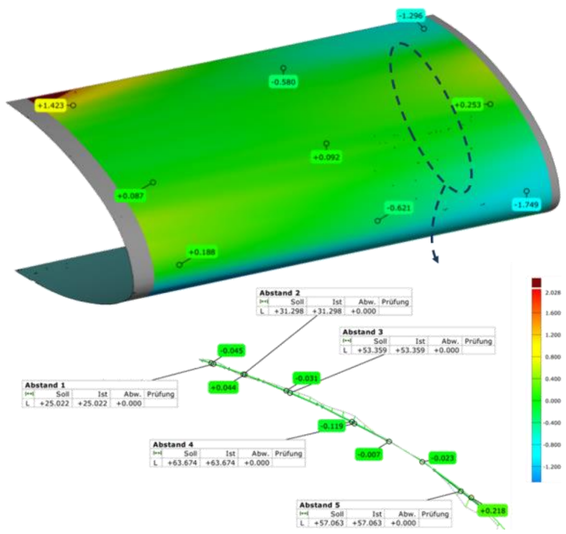

FIG. 14: GOM ATOS Scan Geometrical Accuracy

4.2. Cost Assessment

A detailed cost assessment for the CFRP substructure and the bonding process has been done during the manufacturing of “Trial 4”. The effort and resources of each individual production step have been analysed and listed. To estimate the cost saving margin of a series production with 15 a/c per month, potential series effects and automation options have been taken into account for a virtual production of the same “Trial 4” component. For specific tooling and jigs a depreciation time of 5 years has been chosen. For production equipment like e.g. an autoclave a 10-year depreciation time has been used for the assessment.

4.2.1 Prototype Production Assessment

As expected the main production cost drivers during autoclave infusion were the tooling costs and the manual set up effort to prepare the life data sheet and other documents. Preforming costs and also autoclave costs were also dominating cost drivers because still a lot of manual adaption was required. The bonding process was a critical cost factor because of the manual bonding procedure that had to be applied to each individual spacer.

4.2.2 Series Production Assessment

An RTM production scenario has been considered for the series production cost estimation because this is the production method that is currently used for the production of the A350 HTP leading edge.
Even though the estimated series production costs are 80% lower than the prototype production there is still a cost saving potential in the consolidation phase due to today’s highly conservative heat up and cool down ramps that cause extreme long machine times. By applying a more accurate nesting and near net shape processes there is also a remarkable margin for a more efficient exploitation of fibre and resin semi-finished products.

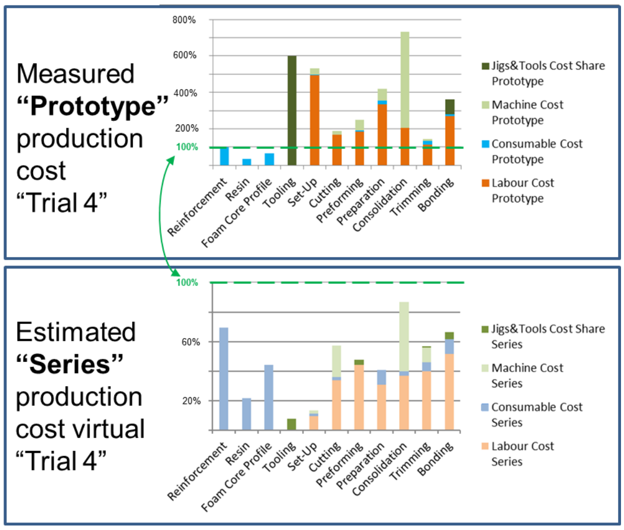

FIG. 15: Cost Driver Analyses

4.3. Functionality Tests

To carry out basic functionality tests a representative Fischer compressor (EMTC 150 AIR) has been installed at an improvised front spar.

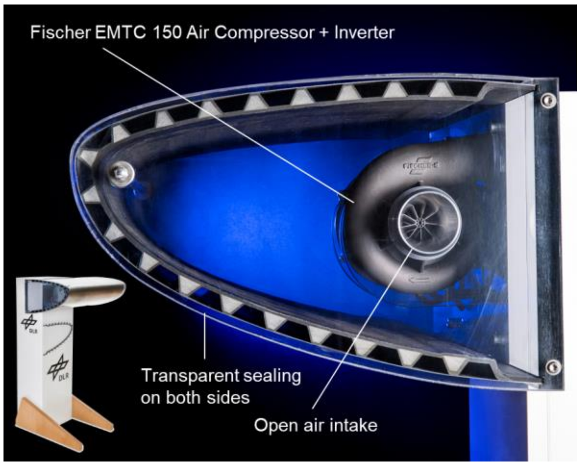

FIG. 16: Functional Demonstrator

The sides of the “Trial 4” demonstrator have been sealed with silicon films and polycarbonate boards to simulate the intended situation in the future HLFC-HTP. Small pressure sensors were installed to check the functionality of the plenum chamber, the throttle orifices and the suction skin. Thermocouples were used to monitor the compressor temperature and also the temperature of the compressed air at the compressor exhaust.

The results of the functional tests were all within the expectations and no critical aspect has been found.

4.4. Bonded GFRP Spacer Concept

The variation of the preforming approach from shaped CFRP fabric to braided glass fibre tubes (“Trial 5”) proved to be highly efficient and reproducible. The problem with resin rich areas in the bonding zone on top of the spacers, that have been observed at the former trials were no longer existing. The glass fibre omega laminate was slightly thinner than the carbon fibre omega laminate so that no additional weight had to be taken into account. From a cost point of view there is a significant advantage for the braided glass fibre tubes because of the much lower raw material price and because there was nearly no scrap during production. The wrapping of the foam cores has been done manually but the simple wrapping procedure could easily be automated.

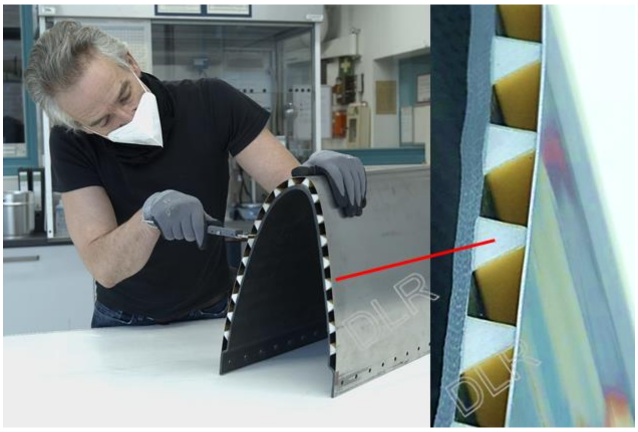

FIG. 17: GFRP Spacer Strategy (“Trial 5”)

The bonding procedure that has been used for Trial 2, 4 and 5 proved to be very reliable. The distribution of the Solvay FM94 film adhesive in spanwise direction was very homogenous and within the predefined 9mm width range (aerodynamically accepted non- suction zone).

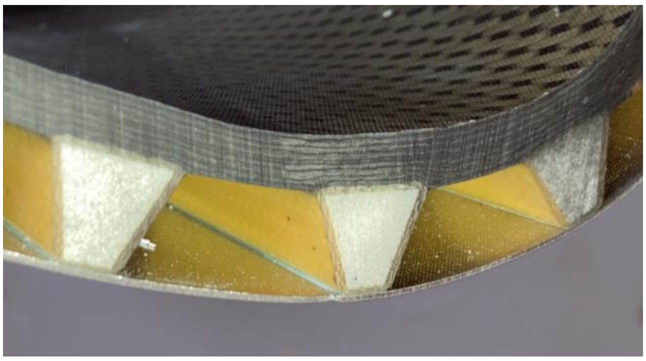

FIG. 18: Spacer Bond line (“Trial 5”)

4.5. Impact Test

Finally, an impact test with an artificial polymer impactor has been carried out at the DLR Institute of Structures and Design in Stuttgart to check the structural integrity of the bonded multi material leading edge structure

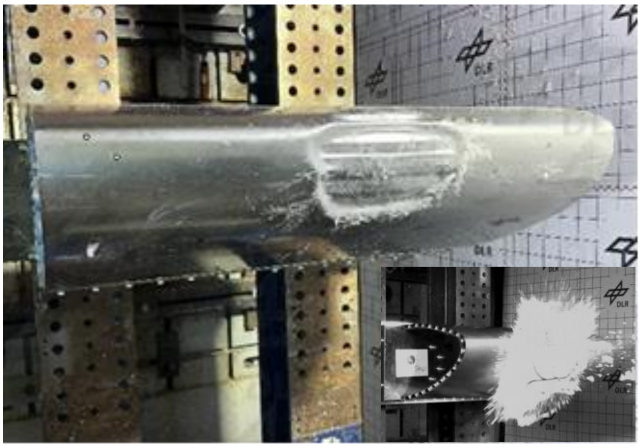

FIG. 19: “Trial 5” SSD After Successful Impact Test

The result was very positive because the damage was only locally in the direct impact zone. Furthermore, the impact energy was mainly absorbed by the Titanium-Spacer-Structure. No visible degradation of the load bearing inner CFRP laminate has been detected and also the bondline between the Titanium sheet and the GFRP spacer seems to be unaffected outside the direct impact area.

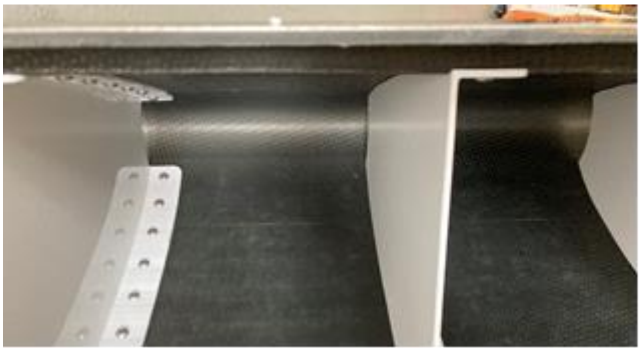

FIG. 20: Load Bearing CFRP Skin After Impact

The very promising results of the impact test have also been used to calibrate the impact simulation that has been setup by the DLR Institute of Structures and Design.

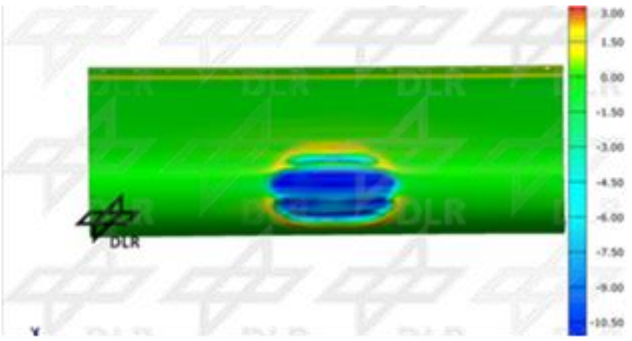

FIG. 21: Impact Simulation

5. NEXT STEPS / OUTLOOK

The “European Green Deal” is targeting at a reduction of net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels and for Europe to become the first climate-neutral continent by 2050.

For the aerospace business this means that every aspect from raw material over production and service to the end of life needs to be optimised to meet this challenging demand. Reducing aerodynamic drag through laminarisation is a very powerful measure that contributes to eco efficiency on each and every flight

Even though first promising laminarisation experiments have been conducted during World War II there is no series application available for large commercial aircrafts until today.

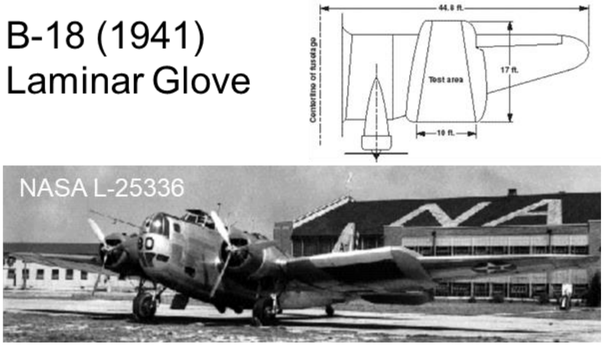

FIG. 22: Early NLF and HLFC Investigation [8]

Especially the complexity of HLFC systems and the related risk during operation was a major uncertainty.

FIG. 23: Do 228 HLFC test aircraft [7]

The consequent simplification of the HLFC system that has been achieved within the HLFC-HTP project may therefore be a decisive step towards energy efficient future aircrafts. The next challenge in the running project is TRL 5. To pass this review in the coming month a retrofit A350 outer HTP-LE-Segment will be manufactured and tested with all the features that have been developed at SSD level.
In comparison with a laminar empennage (vertical and horizontal tail plane) the drag reduction effect of a laminar wing is much higher and therefor it is the next step to transfer the results of the simplified HLFC-HTP to a HLFC wing.

5.1. HLFC Wing

With respect to a HLFC Wing the major difference that needs to be dealt with are the additional wing systems [2]. Especially the high lift system and the WIPS (Wing Ice Protection System) are directly impacting the suction system and have a higher priority because they are relevant for flight safety. Furthermore, it is necessary to avoid contamination by insects during take-off and landing at the laminar leading edge. This is usually done by applying a Krüger high lift system that can be configured as an effective shielding system when deployed.

FIG. 24: Principle Clean Sky 2HLFC-WIN Concept

The related project within Clean Sky 2 is called HLFC-WIN and it will follow the same Small Scale Demonstrator approach that proved to be successful in the HLFC-HTP project.

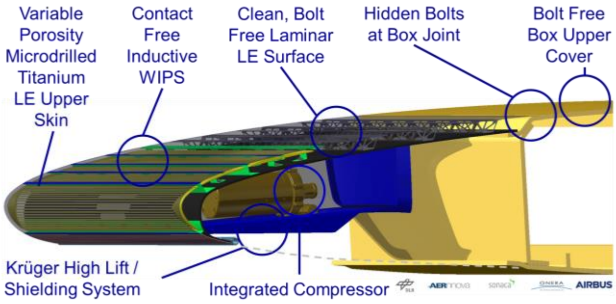

FIG. 25: Planned HLFC-WIN SSD

The most obvious communality of the HLFC-HTP and the HLFC wing approaches are the distributed, small but extremely powerful compressors that can directly be integrated in the structure without the need of complex piping systems.
In case of the WIPS a new approach based on contact free, inductive heating has been chosen to avoid any additional blocking in the suction skin.

5.2. Cycle Time Reduction

Compared with “drag reduction through laminar flow”, an energy optimized aircraft production scenario has a much smaller potential contribution to the “European Green Deal” target. On the other hand, if energy optimization can be combined with a significant cycle time reduction it may be attractive from a general competitiveness point of view.

The basic idea is to significantly increase heat-up and cool down rates and to terminate the cure phase based on the individually sensed cure status. In case of the RTM scenario an isothermal process will be investigated where thermal cycling can be fully avoided or at least reduced to a minimum.

Today’s composite processing requirements are mainly optimised for the production of prepreg components where e.g. the correct dwell time for debulking is very important. Furthermore, heat-up and cool down rate specifications are kept linear (e.g. 2K/min) maybe to simplify programming. Tolerances with respect to resin crosslinking characteristics and autoclave temperature scatter led to very conservative cure time specifications to ensure the required degree of cure in the produced composite component.

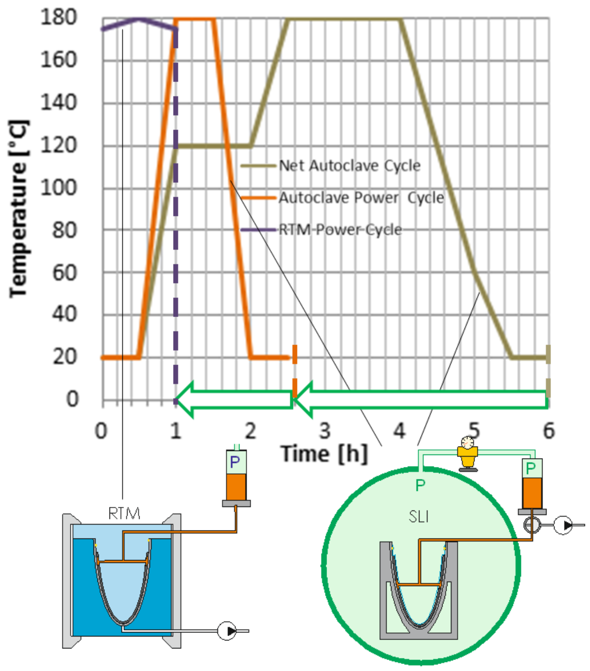

FIG. 26: Cycle Time Reduction Strategy

In case of LRI (Liquid Resin Infusion) processes, the debulking characteristic is very different from prepreg since no entrapped air in a high viscosity matrix needs to eliminated. Instead the porosity of the produced component is highly dependent on the flow front propagation and on the pressure boundary conditions during curing. If these process conditions are set and controlled in the required way even heat-up and cool down rates of up to 10K/min can be applied when aerospace resins like e.g. Hexcel RTM 6 are used. To reduce internal cure shrinking related stress, especially the early stage of the cool down phase needs to be well defined and controlled.
From a technical point of view, it can be expected that the next generation of technical equipment (autoclaves, presses, infusion devices etc.) can be used for individually sensor-controlled processing which in turn would unleash the above described potential to minimise cycle times and energy consumption.
Accompanying sensor updated, real time simulations (especially flow and cure simulations) can be utilised to predict the imminent process development and provide data for precise process parameter tuning [6].
The DigiCOMP research platform has been setup to further investigate digitalisation options for future composite production scenarios.

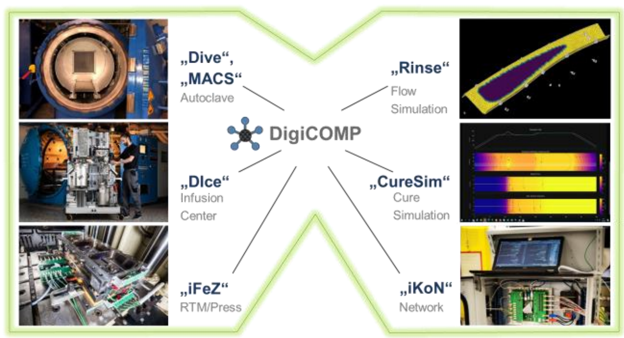

FIG. 27: DigiCOMP research platform

Acknowledgments

The authors would like to thank for the support from EU CleanSky2 ECHO (JTI-CS2-CPW01-LPA-01-02) project.

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