Composite thermoforming of surface functionalised stiffeners for aircraft structures

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Abstract:
As part of the EU project HERFUSE, innovative hybrid connections between composite thermoplastic stiffeners and clips and thermoset fuselage skins are being developed by the DLR to optimise weight and sustainability in aircraft structures. By modifying the joining surfaces with polyetherimide (PEI), the parts can be joined via welding, eliminating the need for traditional fasteners and adhesives. For the thermoplastic clips and stiffeners a thermoforming design and manufacturing workflow has been established. The workflow was first validated on the clips, including the manufacturing of preforms via Automated Fibre Placement (AFP), co-consolidating them with PEI and press forming, accompanied by iterative simulation and optimisation using AniForm and Ansys to minimise distortion. This process has subsequently been scaled up to the larger frame structure of the stiffeners. For larger parts, special care must be taken to ensure consistent part quality by achieving exact positioning on the mould and high temperature homogeneity of the part. An advanced multi-part mould design using passively driven sliders ensures sufficient compaction force on the flange surface, and separately controllable auxiliary heaters maintain ideal processing temperatures. After analysing the part quality using different non-destructive testing methods (NDT) and comparing the results with initial simulations, clips and frames can be joined with each other and the aircraft skin by welding the modified PEI-surfaces.
Keywords: thermoforming, thermoplastic composites, process simulation

Introduction

Composite materials often provide a good opportunity to save weight in aircraft structures, due to higher strength compared to commonly used metals like aluminium, among other properties. However, using the same material for different parts is suboptimal, since different parts have different requirements which can be better fulfilled by different materials. On the other hand, different materials can prove challenging when joining. The EU project HERFUSE (Hybrid Electrical Regional FUSelage & Empennages, supported by the Clean Aviation Joint Undertaking and its members, funded by the European Union under GA No 101140567) is focused on optimising weight, volume, safety, flexibility and sustainability in aviation by addressing challenges in layout, materials, components, manufacturing and assembly [1]. To develop the relevant technologies, a fuselage skin section demonstrator consisting of skin, stiffeners, stringers and clips welded together is being manufactured and tested.
The DLR is developing hybrid connections between thermoplastic stiffeners and thermoset fuselage skin, enabled through functionalised components. By blending of the stiffener component matrix materials using compatible amorphous thermoplastic surface modifications the hybrid joining technologies are made possible. Focus of the DLR Institute of Structures and design lies on manufacturing the thermoplastic composite stiffeners using thermoforming and stabilising clips and the welding process itself. The process is supported by extensive process simulations and non-destructive testing methods and microscopic examinations.

State of the art

For thermoforming a pre-consolidated organo sheet made from thermoplastic composites is heated above the matrix melting point, for example using infrared pre-heaters, and then inserted between a positive and negative mould in a heated press. The moulds are held at a temperature below the melting point. When the press closes, the organo sheet is formed and solidifies in the mould. After a short time, the part can be removed and cool down to room temperature [2]. This allows for fast cycle times and a high production rate. Since thermoforming is a highly complex process, accurate process simulations are challenging [3], but can often provide valuable insights, as shown in past projects [4]. Multiple companies provide solutions for different aspects, but complete simulation suites for all parts of the process are still uncommon.
In the same vein, AFP is also a highly complex but powerful process for manufacturing composite parts. The process also poses many challenges, which won't be the focus of this work [5].

Materials and methods

For the objective of joining thermoplastic and thermoset parts, a workflow for thermoplastic composite manufacturing was designed. The initial concept was tested on the clip that stabilises the frame against the skin (see Fig. 1). The clip exists in two symmetric variants using the same quasi-isotropic layup with 16 layers of carbon fibre reinforced low-melt polyaryletherketone (CF/LM-PAEK) with a layup of $[-45/0/45/90]_{2S}$ and a layer thickness of 0.145 mm with a fibre volume content of 66 % and an additional PEI-layer used for welding them onto the stringers and stiffeners with a thickness of 0.125 mm. Since a large number of clips is necessary, thermoforming has been chosen for manufacturing. The clip variants are similar enough that a single mould and preform design was chosen. After thermoforming the parts are trimmed into the final geometry.

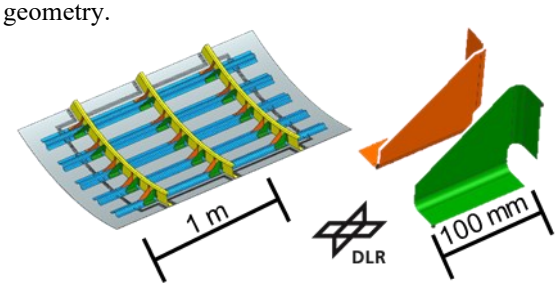


Fig. 1: *CAD of HERFUSE demonstrator and of both clip variants*

Before manufacturing, extensive process simulations have been iteratively conducted to adapt the mould design and minimise defects and warping. Two different simulation software products are used. AniForm simulates movement of the moulds and the forming process itself, while Ansys with Compro by Convergent Inc. as an addon handles the warping and spring-in simulations.

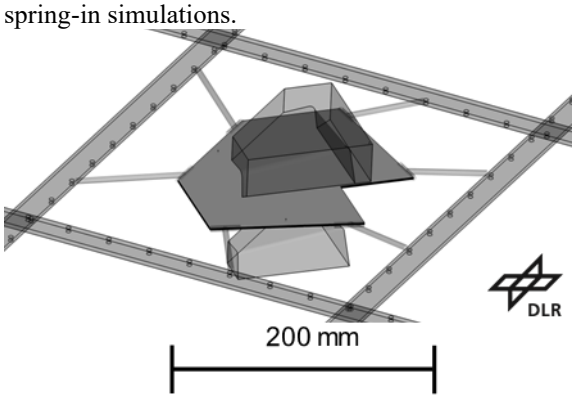


Fig. 2: *Simulation setup in AniForm with springs and frame*

The forming simulation emulates the procedures and parameters of the real thermoforming setup. The preform is modelled with triangular shell elements with an average size of 1.8 mm, is initially heated up to 385 °C and is given 2 s to deform in its mounting. Mirroring the real process, the mounting consisted of three fixed pins and six springs, which are all connected to a frame. The springs were removed for later simulations. The hot press then closes by moving the bottom mould up, placing the preform onto it and pulling the pins out of the preform in the process. The mould itself is held at a constant temperature of 220 °C. After closing, a thermal simulation runs for the remainder of the hold time of 120 s to evaluate the temperature changes. The material model for CF/LM-PAEK was provided by AniForm.

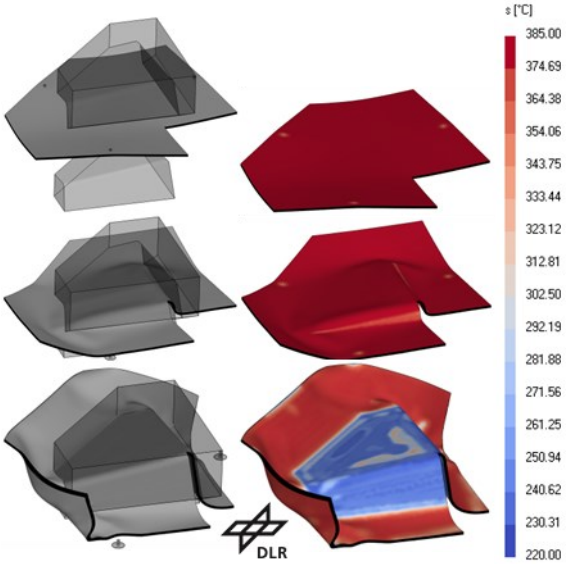


Fig. 3: *different stages during the forming simulation, left with transparent moulds, right with temperature overlay*

Special emphasis was placed on temperature distribution and wrinkling indicators like fibre compression and shearing. Additionally, the path where the laminate scrapes along the mould surface and edges was measured.

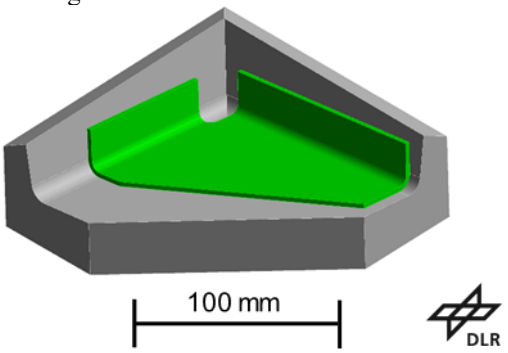


Fig. 4: *Ansys simulation geometry; second mould hidden*

The warping simulation with the Ansys-plugin Compro was performed in two steps. First the thermal history was created in a transient-thermal analysis. This was used in a structural analysis as input to calculate process-induced warping. Both simulations use the final part geometry for the clip because it is expected that trimming releases internal stress and affects warping. Since the geometry of the final part is relevant for designing the part, this approach was chosen.

Compro is used for accurately simulating material behaviour of the semi-crystalline matrix material. The crystallisation behaviour was developed by Gordnian at the University of British Columbia (UBC) for PEEK [6] and adapted to LM-PAEK by Teltschik at the DLR in Stuttgart [7] [8]. The model calculates the current crystallisation rate depending on the degree of crystallinity and temperature and adapts the material parameters including density and modulus accordingly. An example of an average history of temperature and degree of crystallinity is shown in Fig. 5.

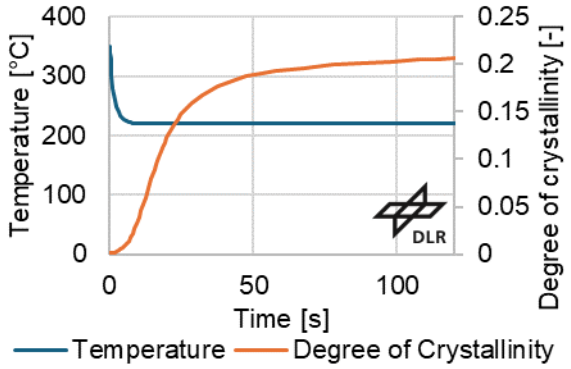


Fig. 5: *Average simulated temperature and calculated degree of crystallinity in the closed mould*

The part was meshed with a solid mesh with an average edge size of 3 mm and at least one element per layer. The simulation starts at the moment the mould is fully closed. To simplify the process, the laminate starts at 385 °C except in the outer layers which have contact with the mould surface. The mould itself starts at 220 °C and is held at the opposite contact surfaces at this temperature, with additional convection boundary conditions at the other free surfaces. The structural simulation in contrast fixes one mould and applies the consolidation pressure onto the second mould. MPC contacts are used to connect moulds and laminate.

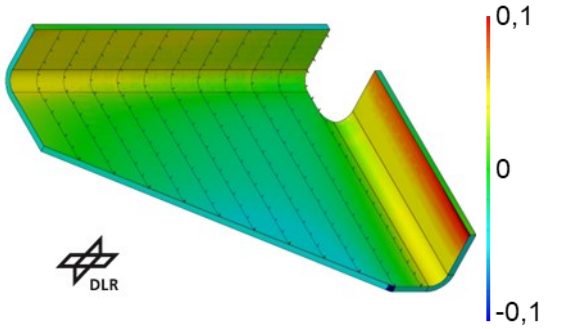


Fig. 6: *Comparison of warping simulation result and target geometry with proposed reference lines for spring-in angle measurement; legend shows deviation in mm*

For result evaluation, the deformed mesh was compared with the target geometry and deviations were noted. These deviations were reverted and implemented into a new mould generation, and the simulations were repeated until the deviation between simulation result and target geometry was negligible. For a simplified process only the spring-in angles can be measured and compensated. Since the warping can be irregular, an average spring-in angle can be evaluated by setting cuts in regular distances to each other and measuring the angle in discrete locations (see Fig. 6).

Using the results of both forming and warping simulation, the final press moulds can be designed and machined. Meanwhile the preforms were manufactured by placing large panels via thermoplastic AFP for the initial CF/LM-PAEK-layup. Afterwards, the panels were co-consolidated with a PEI foil on a heated vacuum table, combining the PEI with the laminate. Since the laminate is consolidated after the process, no heated table is necessary for the AFP process. The final preforms were cut from the panels using a water jet cutting machine.

A RUCKS KV33.000 press was used for the forming process. The main focus of the forming process is, in particular, the rapid transfer into the press, in order to minimise the temperature loss of the organo sheet as much as possible. With hybrid organo-sheet, the challenge is to keep the laminate as cold as possible for forming, whilst ensuring it is warm enough to guarantee optimal sliding between the individual layers. To this end, preliminary tests were carried out on an organo-sheet of a similar size. The PEI layer was briefly heated to 380°C, whilst the core of the laminate was heated to 390°C. Another focus is on rapid heating while maintaining a homogeneous temperature across the part thickness. To this end, the infrared heaters were set to 450°C. The heating process was ultimately set at 165 seconds. Fig. 7 shows the temperature history during the calibration.

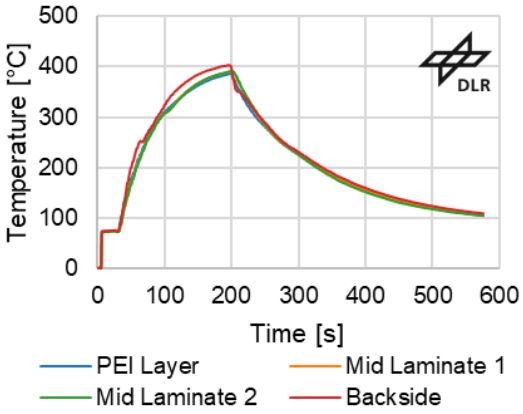


Fig. 7: *Heating calibration plot*

To protect the functional surface, this area was covered with a thin layer of Upilex film. Since the simulation shows potential risks for the surface due to a long gliding path of the laminate along the mould surface, the film provides additional protection

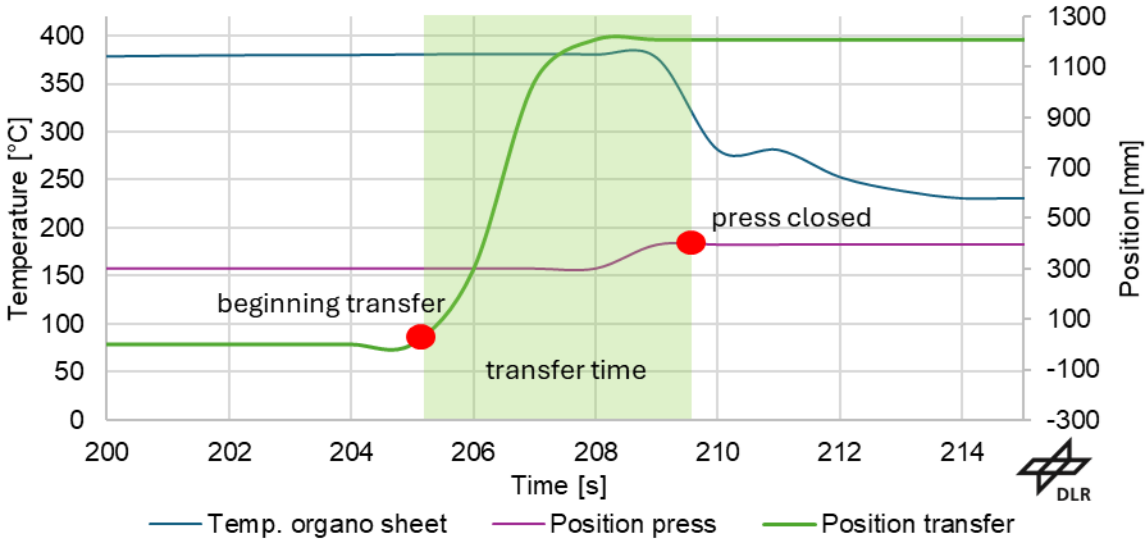


Fig. 8: *Transfer timing and movement of the press during clip manufacturing, with key time stamps marked*

against abrasion during forming. A functional surface is essential for subsequent joining.

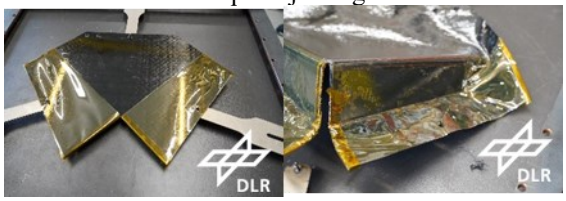


Fig. 9: *Part with Upilex film before and after forming*

Given the complex geometry, it is necessary to ensure that the organo sheet could be positioned consistently onto the mould. To this end, the organo sheet was aligned using four removable locating pins in the mould during the set-up process, shown in Fig. 10. During production, the organo-sheets were simply hooked onto three pins on the transfer frame with minimal play (see left picture of Fig. 9). The repeatability of the transfer frame ensures that the positioning remained constant throughout the production run.

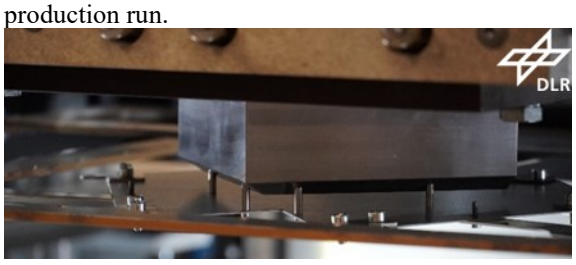


Fig. 10: *Preform alignment*

Prior to the pressing process, the organo sheet was heated for 165 s as described. The transfer into the press until the mould was closed took approximately 4 s (see Fig. 8). The organo sheet continued to cool for approximately 1 min inside the heated mould. The component could then be removed. The process took a total of approximately 230 s and consumed just 0.7 kWh of electricity per part.

To ensure optimum part quality, one part was cut into smaller pieces after forming and analysed with a microscope. Emphasis is placed on the integrity of the PEI layer and on obvious defects like pores or delamination. An analysis of the micrographs revealed very good quality (compare Fig. 11). It was confirmed that the PEI layer remained intact in the area of the outer radius. Furthermore, the targeted design of the tool radius ensures optimum compaction within the radius.

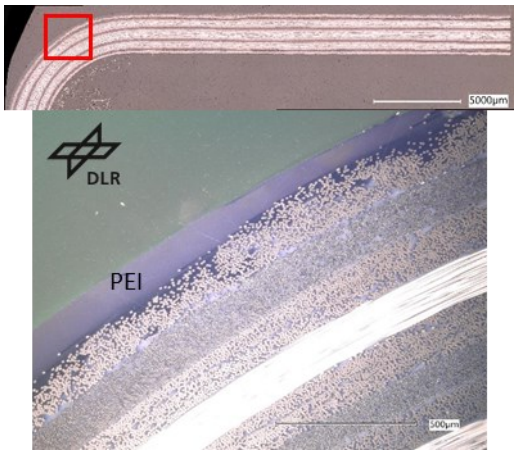


Fig. 11: *Micrograph of a clip section, with a detailed view of the PEI layer*

After manufacturing, all clips were scanned using a GOM Atos 5 3D-scanner. This serves two goals: the process simulation results could be validated against a large number of parts, and the deviation of all parts could be statistically analysed (compare Fig. 16 in the results). The focus during this analysis is placed on consistent spring-in angles.

The techniques developed during clip design and manufacturing were also applied to the thermoplastic stiffeners. During design, simplified versions of the forming and warping simulations were implemented. Since the stiffener geometry is complex in comparison to the clips, wrinkles are expected during forming, so emphasis is placed on positioning of the mounting of the preform. The goal is minimising the

wrinkles by increasing the tension in the flat organo sheet.
During forming, the frame holding the stiffener preform is lowered onto the positive mould. After that, the press closes from the top, with a final step where the sides of the mould also move to provide additional pressure onto the flanges. This also had to be reflected during the forming simulation

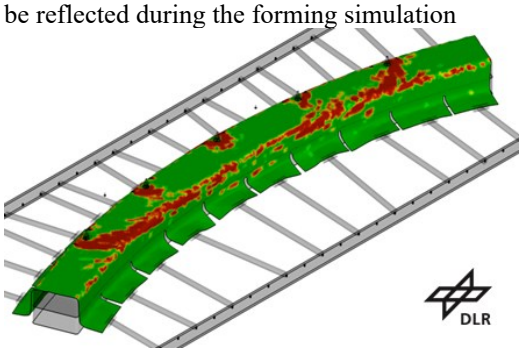


Fig. 12: *An early version of stiffener forming simulation with prevalent wrinkling*

After the forming simulations, warping simulations similar to the clips were performed. Due to the complexity of the part, the simulations were simplified and only the spring-in of the flanges was measured. The mould was subsequently modified with a global spring-in compensation angle.

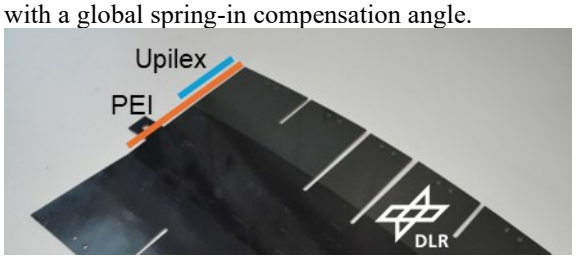


Fig. 13: *Distribution of PEI layer and Upilex foil on the stiffeners*

Similar to the clips, the outer flange of the stiffener was modified with an additional Upilex foil to protect the functionalised PEI layer during thermoforming. While the foil on the clips was placed by hand after co-consolidation of the preforms with PEI, the foil of the stiffeners was applied during the same step. This reduced manual effort and reduced the influence of the foil on surface wrinkling. The hybridisation was only applied on the sides of the frame which will be used for joining. Additionally, the organo sheets were dried at 80 °C for 48 h before thermoforming to remove residual moisture from the PEI which would result in degradation.

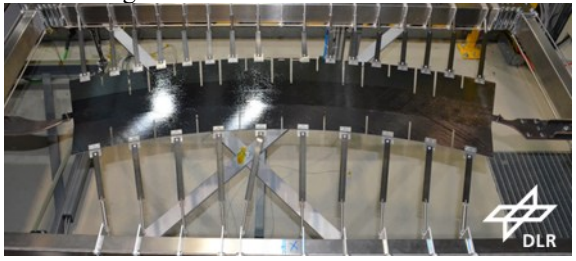


Fig. 14: *Mounting concept of the stiffener organo sheet with pins on both ends and springs on the sides*

Similar to the clips, the positioning of the stiffeners on the mould was achieved by fixed pins at the short ends of the organo sheets. They unhook when the organo sheet is placed on the bottom mould.

Results

The forming simulations for both the clips and the stiffeners show the rapid cooling of the laminate after first mould contact. While wrinkling remained non-critical, the temperature distribution showed that tooling contact rapidly cools the laminate below the matrix melting point. Fig. 15 shows an example of the simulated temperature profile in the clip radius during forming. Due to the high forming speed, the clip only cooled down to 350 °C before the mould is fully closed, but any delays might move the lowest point below the matrix melting point. Therefore, high process speed shown in Fig. 8 is necessary reducing wrinkles and improving consolidation quality in the radius.

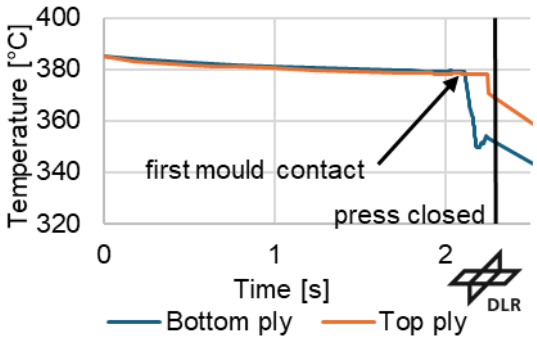


Fig. 15: *Simulated temperature history during clip forming in the radius*

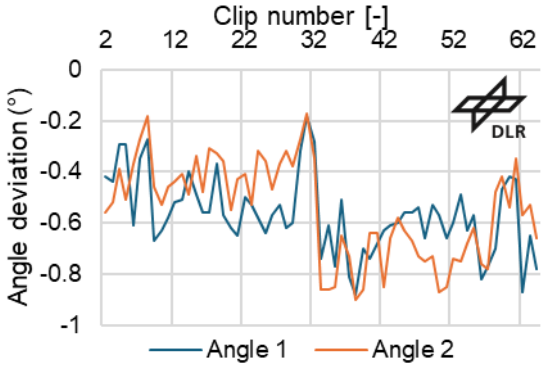


Fig. 16: *Deviation of both flange angles for all manufactured clips*

Additionally, wrinkle prediction of the simulations aligns with real wrinkle distributions on initial real parts, showing the validity of the simulation results
The warping simulations proved very valuable in reducing spring-in. Validation of the simulations using 3D-scans show a slight under-compensation of the compensated spring-in angle of 0.8 °, resulting in an average deviation of the design angle of 0.4 °-0.5 ° (see Fig. 16). Between clips 33 and 34 the production was halted for a few weeks, and the second batch

shows a slightly different spring-in angle. The cause is currently being investigated.
For both parts the Upilex foil proved capable of protecting the functional PEI layer. Both optical inspection (see Fig. 17) and micrographs (see Fig. 11) show no defects in the affected parts.

Conclusion

The designed workflow proved capable for manufacturing the hybrid thermoplastic composite parts for HERFUSE. The extensive simulations for designing the manufacturing process of the clips successfully reduced part deviations, while simultaneously the large number of parts can be used for statistically validating and improving the simulations.

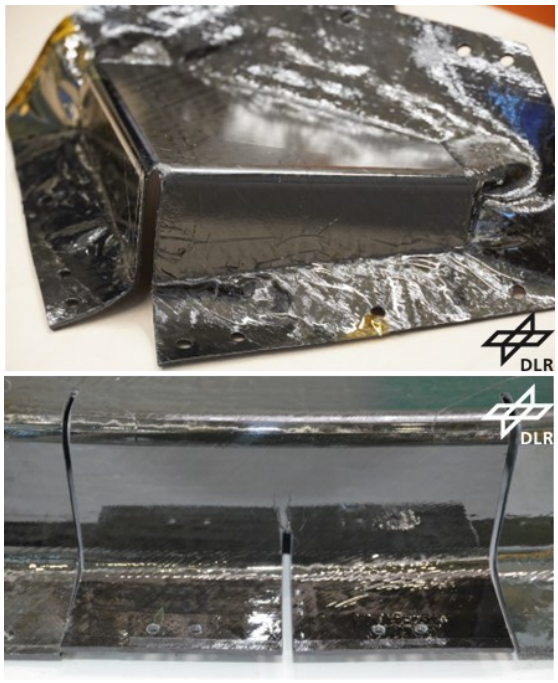


Fig. 17: *Clip (top) and stiffener (bottom) detail of the functional PEI surface*

The process chain of AFP, co-consolidation and thermoforming could be successfully conducted. The co-consolidation of LM-PAEK and PEI posed little problems, and the PEI layer could be protected successfully during thermoforming. While the placement of the protective Upilex foil by hand required additional effort, co-consolidating the foil during PEI implementation reduced the additional work.
The final part showed few wrinkles and good consolidation and provided valuable data to further improve both the simulations and the process itself.
In the next steps, the parts will be trimmed and joined with the thermoset composite skin.

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