Development of a Ecological friendly final consolidation step using Thermoplastic Fibre Placement for a helicopter door

Reporting

Project information

DEfcodoor

Grant agreement ID: 287103

Status
Closed project

Start date
1 September 2011

End date
31 July 2013

Funded under:
FP7-JTI

Overall budget:
€ 199 407,60

EU contribution
€ 149 553

Coordinated by:
TECHNISCHE UNIVERSITAET MUENCHEN
Germany

Final Report Summary - DEFCODOOR (Development of a Ecological friendly final consolidation step using Thermoplastic Fibre Placement for a helicopter door)

Executive Summary:

In order to reduce the environmental impact of the manufacture of products for the aircraft industry, it is necessary to reduce inputs (raw materials, energy, water, etc.), outputs and nuisances (waste, effluents, etc.) throughout the life cycle. The manufacturing technology currently used for helicopter doors is to place pre-impregnated sheets of carbon-fibre reinforced thermoset (prepregs) in the required fibre direction by hand. The subsequent curing of the carbon-fibre reinforced thermosets is performed in an autoclave. The highly energy-intensive autoclave cycles as well as the noxious effects due to processing thermosets require more ecological friendly solutions. If this procedure is replaced by laser-assisted Thermoplastic Fibre placement (TFP) with a thermoforming step in between, it would be possible to abandon the time- and energy-consuming autoclave process. The use of thermoplastics increase the potential for recyclability, which can be exploited in favour of a reduced environmental impact. The principal benefit of TFP is the possibility of in-situ consolidation, eliminating the need for bonding, riveting, bolting or other joining technologies. In addition, without the use of an autoclave faster cycle times can be achieved.

The project DEfcodoor comprises of the “Development of an eco-friendly final consolidation step using thermoplastic fibre placement for a helicopter door” and is part of the Green Rotorcraft 6 (GRC) programme of the EU research project Clean Sky. The laser-assisted TFP and thermoforming processes are combined to produce structures consisting of stiffener and skin for helicopter applications. Customised laminates with local reinforcements for example are manufactured by laser-assisted TFP and are then thermoformed into hat profiles. After insertion of a pre-cast core a skin laminate is joined in-situ to the thermoformed stiffener by TFP. The solulable core is removed and an in-situ joined part is obtained. The manufacturing steps of DEfcodoor are shown in Figure 1.

A thermoplastic matrix material suitable for aircraft applications had to be selected. Therefore, a trade-off between performance, availability and costs was made. Polyethersulfone (PES) was selected; an amorphous high-performance thermoplastics. The chosen thermoplastic material is commonly reinforced by AS4 fibres and is available in the form of unidirectionally pre-impregnated tapes. Carbon-fibres were selected due to their high strength and modulus in general.

To identify the relevant process parameters of the laser-assisted TFP technology with significant effect on the laminate quality, various testing methods were investigated. A modified T-peel test was chosen to find an optimum setting for the dominant process parameters in an efficient manner with respect to manufacturability and testing. The experimental setup of T-peel tests is presented in Figure 2.

The process parameters to be varied were the placement speed of the TFP head, the nip point temperature at the focal spot, the tool temperature of the heating plate, the tape tension and the consolidation force of the consolidation roller. After conducting several process parameter variations, tape tension and the consolidation force were found to have low influence on the laminate quality but are important parameters with respect to tape placement accuracy. With PES being an amorphous thermoplastic the tool temperature has no significant effect on the mechanical performance of the laminate. However, heated tooling decreases residual stresses that are conditioned by different coefficients of thermal expansion of carbon fibres and PES. Placement speed and nip point temperature had significant effects on the mechanical performance of the specimens. Sufficient energy was required to decrease the viscosity of the thermoplastic properly so that possible intralaminar and interlaminar voids can be penetrated by matrix material. The more time is available during laser-assisted TFP the higher the degree of bonding becomes. As soon as full contact was achieved between two placed tapes, diffusion of molecular chains across the interface can take place and strengthen the bond. Here, time and temperature are most influential factors. Besides the dominating process parameters the quality of the tape material had a significant impact on the laminate quality. Most of the employed tape spools showed non-uniform fibre-matrix distribution along tape width and thickness. As a consequence, dry spots with high agglomeration of fibres and resin-rich areas were detected. The non-uniform distribution of fibres and matrix within the tapes also resulted in a distortion of the tapes which affected the tape placement accuracy and handling.

The process parameter optimisation was conducted by varying one process parameter while keeping the remaining parameters constant. The evaluation of the T-peel test results was conducted in combination with microscopy and led to an optimum process setting which was then used for material characterisation of AS4/PES tapes. A standard testing program including tensile, compressive and shear properties was conducted to evaluate the performance of the chosen material. To classify the laminate quality upon processing with the laser-assisted TFP technology a comparison to post-consolidated specimens was made. The latter were manufactured with laser-assisted TFP first and then post-consolidated in an autoclave or press. In-plane shear tests were used to compare in-situ consolidated to post-consolidated specimens as primarily matrix-dominated and matrix/interface related properties are affected by post-consolidation. The test results exhibited an increase in longitudinal shear strength for the post-consolidated specimens by approximately 20 %. The reason for improved mechanical properties was found to be in a decreased thickness of post-consolidated specimens which is achieved due to higher pressures applied during autoclaving or press forming. A higher consolidation pressure enables the removal of air within tapes and between plies. The properties of in-situ consolidated specimens are expected to improve when tapes with high quality and low void content are processed. The low consolidation pressure during laser-assisted TFP is not sufficient to remove entrapped air within the tape material.

To obtain material properties on a subcomponent level, a demonstrator part (subcomponent) was designed and a test strategy developed. The subcomponent revealed a symmetrical cross-sectional area to avoid any influences due to asymmetries during mechanical testing. The test strategy comprised non-destructive inspection of laminates before and after thermoforming, mechanical testing of the finally in-situ joined subcomponent with a four-point bend test and examination by microscopy. Therefore, laminates were manufactured with laser-assisted TFP to thermoform them into symmetrical hat profiles to be the stiffener of the subcomponent. The quality of the laminates was examined with visual inspection and with dimensional inspection. A manufacturing concept for the core material was developed to ensure high dimensional accuracy. The core material used was Aquapour®, selected due to its high compressive strength as the core material needs to withstand the consolidation pressure during fibre placement. In addition, Aquapour® has a low environmental impact and is soluble in water. The fibre-placed laminates were successfully thermoformed into stiffeners as part of the subcomponent. The dimensional inspection of the stiffener showed that there was a decrease in thickness due to high pressures during thermoforming in comparison to fibre-placed laminates. Additionally, distortions of the stiffener due to residual stresses were not detected. Non-destructive inspection by ultrasound scanning was conducted and showed no major irregularities in the thermoformed laminate.

As preparation for the in-situ joining of skin layers to the thermoformed stiffener, a tooling concept was designed and implemented as described in Figure 3.

The concept consisted of an arrangement of aluminium profiles which enabled the positioning of the thermoformed stiffener to be varied. The setup was covered with an aluminium sheet with a recess area for the thermoformed stiffener. In-situ joining of skin layers to the thermoformed stiffener required different process conditions than the manufacture of laminates with laser-assisted TFP. Typically, the desired nip point temperature is set and the laser power is controlled by contactless temperature measurement. The control of the laser power enabled adaption to variable tape quality and maintained the desired temperature. During in-situ joining, the TFP head passes different substrate materials such as aluminium, thermoformed AS4/PES and core material during in-situ joining. The resolution of the controller for the laser regulation was insufficient to maintain the correct nip point temperature at the thermoformed flanges. As a result, in-situ joining to the thermoformed stiffener was not achieved with regulated laser power, hence the laser power was set to constant values. This required the development of a further testing method to find the optimum parameter set to join skin layers to the thermoformed stiffener. The test setup was derived from the tooling concept for the in-situ joining to create process conditions close to reality. Test specimens were manufactured for short beam shear tests. The varied process parameters were laser power, tool temperature and angle of the laser optics. Latter is an important parameter with respect to adjusting the heat distribution to substrate and incoming tape and was previously set automatically by the laser power control. The evaluation of the process parameters resulted in an optimum parameter set which was employed on the thermoformed stiffener of the subcomponent. Since the thermoformed flanges of the stiffener were twice as thick as the short beam shear test specimens, they extracted more energy and required a further increase of the laser power. Skin layers were successfully joined to several thermoformed stiffeners by using one tape spool only. When the empty spool was replaced with a new one, the process settings did not lead to continued success with joining. Process- and material-related reasons were investigated to find the reason for the poor joining. The highly variable tape quality was found to be the reason that reproducible in-situ joining process was not possible. Applying constant process settings is not possible with high variability in the tape quality. Hence, process parameters would need to be changed for each spool. It is assumed that the in-situ joining process works well when tapes with constant quality can be supplied and when the response time of controller at the TFP head is increased.

As the successfully in-situ joined stiffeners were investigated under the microscope and more stiffeners could not be joined successfully, mechanical testing of the demonstrators could not be conducted. However, three-point bending tests were conducted to compare thermoformed specimens to in-situ consolidated specimens. Specimens were cut from the crown and the flanges of a thermoformed stiffener to investigate the effect of thermoforming on the laminate quality. Similarly to post-consolidated specimens the flexural strength of the thermoformed specimens was increased by 21 % compared to in-situ consolidated specimens.

The subcomponent consisted of 2D laminates manufactured with laser-assisted TFP that were thermoformed to symmetrical hat profiles. The last demonstrator within DEfcodoor, the feasibility article, revealed a complex unsymmetrical cross-sectional area and double-curvature. The design of the feasibility article was based on the current helicopter door of EC 135. Since thermoforming of UD laminates into complex double-curved structures is highly challenging, a concept with optimized fibre orientation was developed to be manufactured with laser-assisted TFP. 0° plies of the layup were steered along the curvature of the feasibility article as can be seen in Figure 4.

Standard laminates without fibre steering were manufactured to compare them after thermoforming. The results from thermoforming both laminate types were examined visually and under the microscope as shown in Figure 5.

A slight increase in number of wrinkles was detected for the standard laminate. Under the microscope strong deviations from the original lay-up were observed for the standard blanks. Micrographs of laminates with fibre steering showed that the fibre orientation of the 0° plies was maintained along the curvature of the feasibility article. Steering of 0° plies had a positive effect on fibre orientation. However, the positioning of the laminate in the mould during thermoforming was found to be a highly influential factor on the laminate quality.

Project Context and Objectives:

Project context

The state-of-the-art manufacturing process of fibre reinforced polymer helicopter doors currently utilises pre-impregnated thermoset fibre reinforced polymers (prepregs) that are subsequently cured in an autoclave. Since the complete helicopter structure consists of a multitude of parts, the manufactured autoclaved components must later be joined by mechanical fastening or utilising adhesive bonding.

The use of thermoplastic prepregs in this process provides numerous advantages. Most importantly, their short forming and consolidation times are exploited, eliminating the use of an autoclave during the process, considerably reducing the energy consumption and cycle times. Additionally, they have an unlimited shelf-life and are able to be welded, allowing weight and cost savings when the composite parts are joined.

The laser-assisted TFP process, using unidirectionally carbon-fibre reinforced thermoplastic tapes, is a recent development of automated manufacturing processes. During the laser-assisted TFP, the tape is in-situ bonded to the substrate under application of heat from a diode laser and applied pressure. The laser ensures heat application with a very short reaction time, good controllability and high efficiency. Using this process, customised laminates with improved mechanical properties can be produced in a single step method by locally adding tapes according to the load distribution. In contrast to as-received thermoset prepreg or thermoplastic sheet material, near-net shape laminates can be manufactured using laser-assisted TFP, enabling scrap and weight reduction.

In the DEfcodoor approach, the advantages of the laser-assisted TFP are combined with the thermoforming technology. Using this manufacturing approach, demonstrator parts with a skin and a stiffener structure are produced that are representative of helicopter doors. 2D customised laminates are manufactured with laser-assisted TFP. The customised laminates are then thermoformed to 3D hat profiles. Core materials are inserted into the hat profiles enabling laser-assisted TFP of skin layers to the top of the flanges. This enables the in-situ joining between the flanges and the skin without the need of other joining technologies. The single manufacturing steps of the DEfcodoor manufacturing approach can be seen in Figure 6.

In comparison to the previously described state-of-the-art manufacturing of helicopter doors, the DEfcodoor manufacturing approach enables environmentally friendly, scrap-reduced manufacture of complex hollow carbon-fibre reinforced thermoplastic structures. In addition, weight savings can be achieved when the joining of helicopter parts is done without mechanical fasteners.

Project objectives

The main objectives within this research project can be broken down into technical, scientific as well as ecological ambitions and are listed below:

Technical objectives:

- Development of a new final consolidation technique
- Development of core concepts for TFP
- Development of lay-up strategies for core structures
- Weight reduction by 20 % of final integrated structure

Scientific objectives:

- Parameter study on mechanical and physical properties of in-situ placed laminate
- Parameter study on mechanical and physical properties of in-situ final consolidation
- Parameter study on different post consolidation steps
- Feasibility to perform a final consolidation without special surface treatment

Ecological objectives:

- Reduction of scrap by 15 % compared to current thermoset prepreg production
- Out-of-autoclave manufacturing of high-performance composite structures
- No need for bagging and other consumables

One of the objectives of this research project is to eliminate the autoclave out of the manufacturing process, saving time, energy and being more cost efficient. In order to achieve this objective, different post-consolidation steps are screened during this research project.

Overall strategy within DEfcodoor

Figure 7 shows the overall strategy within DEfcodoor. Once a suitable material is chosen and the relevant process parameters of the laser-assisted TFP technology are identified, material characterisation on coupon level can be performed.

Within a next step, the flat laminate manufactured by laser-assisted TFP is thermoformed to a 2D demonstrator part. This demonstrator is used to develop core concepts and to develop a process to place the skin layer. After manufacture of the 2D demonstrator parts, a test strategy is developed to perform mechanical testing and to determine material properties on subcomponent level. In order to demonstrate the feasibility of the DEfcodoor manufacturing approach for helicopter applications, a complex 3D shaped component with double-curvature, derived from an actual helicopter door design, is manufactured.

Project Results:

Screening and optimization of process conditions on coupon level

Within the first work package of the research project DEfcodoor, the object was to optimise the process parameter during the laser-assisted TFP and the final in-situ consolidation.

Material selection

In this first task, the project coordinator screened different thermoplastic matrix materials together with the industrial partner to come into consideration for the thermoplastic helicopter door. For the aircraft industry and the helicopter industry respectively, only high-performance thermoplastic materials are applicable due to a number of requirements which are shown in Figure 8.

Due to their high mechanical properties polyetherimide (PEI), polyether sulfone (PES), polyetheretherketone (PEEK) and polyphenylene sulfide (PPS) were preselected first. The major criterion for this pre-selection was an operation temperature as high as possible. After a detailed evaluation of all properties and requirements of the preselected matrix polymers, the amorphous thermoplastics PEI was chosen as preferred matrix material. Polyether sulfone PES was selected as an alternative to be used as matrix material in case of any delivery difficulties of PEI since it provides similar mechanical properties like PEI. Both thermoplastics are commonly reinforced by AS4 fibres and are available in form of unidirectionally reinforced pre-impregnated tapes. AS4/PEI is supplied by TenCate, Netherlands and AS4/PES tapes by Suprem, Switzerland. The emphasis of this investigation is put on the matrix behaviour and processability so no particular requirements referring to the fibres have to be considered why standard modulus fibres were chosen. Carbon fibres were selected for their very good values in strength and modulus in general.

For easy and reproducible processing PEI and PES being amorphous polymers are favoured. The choice was made in favour of amorphous polymers in anticipation of finding processing windows easier and to be able to reproduce a certain homogeneous laminate quality as crystallization does not need to be taken into account during this first feasibility study. At this point it shall be underlined that this decision does not imply a categorical exclusion of semi-crystalline polymers at a later stage and potential following projects. Another reason why amorphous polymers are favoured represents their lower processing temperatures as energy consumption is an important aspect within this project.

Due to difficulties in delivery of the originally preferred pre-impregnated AS4/PEI tapes, the DEfcodoor consortium decided in favour of AS4/PES tapes together with the industrial partner to avoid any longer delays of the actual project start. The material data can be referred to Table 1.

Process development of laser-assisted TFP

Furthermore a literature research on the process conditions of TFP was performed by the TUM and supplemented by the know-how of AFPT. The most dominant process parameters on the consolidation quality were identified and are listed below:

- Nip point temperature (temperature at the focal spot of the laser),
- Tool temperature (temperature of the heated plate on which laminate is placed down)
- Consolidation force of the consolidation roller
- Placement speed and

- Tape tension (adjustable at the front and rear brake at the TFP Head)

Figure 9 shows all relevant components of the used AFPT TFP Head and highlights the dominant process parameters. Upon selection of a suitable matrix material, a testing method has to be developed which enables the evaluation of effects resulting from process parameter variations on the laminate quality upon processing with laser-assisted TFP. To identify the optimum combination of the dominant process parameter a wide range of variations has to be performed. Thus, the testing method to be developed was supposed to enable efficient manufacturing and testing of the various process parameter sets. Different testing methods were screened. Finally, a modification of the T-peel test according to the ECD standard HS 7100-Q-011 was chosen since it enables a quick manufacture and testing of specimens. Figure 10 shows the conduction of a T-peel test.

Due to the testing length of 150 mm enough data is generated to allow an evaluation of the process stability of each parameter set.

Within two parameter studies the optimum setting for each process parameter was found and compared to autoclaved specimens. The autoclaved specimens showed higher peel forces and very high scatter at the same time. Fibre bridging was assumed to be the reason for both effects. Fibre-placed specimens show higher stability in test results. In addition, the absolute minimum value for the peel force of autoclave-consolidated coupons was found to be lower than the mean average of fibre-placed coupons.

In addition, the general influence of each varied parameter on the consolidation quality was finally assessed. The tape tension and the consolidation force were found to be less influencing the consolidation quality of laminates manufactured with laser-assisted TFP. However, both process parameters affect the placement accuracy. As PES being an amorphous thermoplastic the tool temperature had low impact on the laminate quality. However, by heating of the tool on which tapes are placed down the temperature gradient is decreased between incoming tape and tool. Big temperature gradients result in considerable distortion of the coupons due to the different coefficients of thermal expansion (CTE) of carbon fibre and PES. The bigger the temperature gradient is between tool surface and incoming tape, the bigger the discrepancy in the CTEs and thus the resulting deformation. Heating up of the tool is recommended when perfectly flat laminates are required (e.g. for mechanical testing). When the laminate is processed in subsequent manufacturing steps as thermoforming, heated tooling is not necessary and energy input can be saved.

In contrast to the previously discussed process parameters tape tension, consolidation force and tool temperature, the placement speed has got a significant influence on the consolidation quality. The more time is available to melt the matrix material the better voids can be filled up due to the lower viscosity of PES. Hence, lower placement speeds benefit a good consolidation in general. In addition, it was found out that high placement speeds provide too little time to melt PES properly to enable a good consolidation. The temperature in the focal spot of the laser turned out to be an important process factor of the laser-assisted TFP as well. The focal spot is of rectangular shape and is directed to the incoming tape as well as to the substrate. The variation range from 350 °C to 440 °C revealed the limits of the processing of CF/PES. A temperature of 350 °C was not sufficient to melt the incoming tape as well as the substrate. On the contrary, a temperature of 440 °C leads to beginning degradation of the matrix material that can be seen by significantly increased scatter of the T-peel test results.

Table 2 summarizes the optimum parameter set that was found by the conduction of parameter study II. Additionally, the parameter set for production of testing plates to gain material properties are given in this table.

During the parameter studies it was revealed clearly that there is a considerable influence of the spool quality on the consolidation quality measured by the peeling force. This influence was discovered by producing T-peel coupons with a standard parameter setting applied to different spools which led to highly varying test results. The micrographs of the tested spools showed differences in tape thickness and fibre-matrix distribution. When the fibres and the matrix are distributed evenly along tape width and thickness, medium values for the peeling forces can be expected but low scatter. Variations in thickness and in fibre-matrix distribution lead to dry spots and resin-rich areas all over the tape. Low consolidation pressure and high placement speed cannot decrease the viscosity of the matrix material sufficiently so that dry spots with high fibre agglomeration are filled up with matrix. As a consequence, voids which are present in the tape material before processing can be found in the final product after processing. This mean the tape quality directly influences the quality of the final component.

Considering the micrographs of the various spools in Figure 11 it can be seen that all examined spools except spool 26 show uneven distribution of fibres and matrix material along the tape width.

During tape production, a non-uniform fibre-matrix distribution leads to distorted tapes upon cooling due to the different CTEs of fibre and matrix. Mainly, two different types of distorted cross-sections were observed: u-curved and s-curved cross-sections. Figure 12 is a schematic sketch of a u-curved cross-section conditioned by one side which reveals more fibres than matrix material (upper side in Figure 12) and the opposite side (lower side in Figure 12) which is rich of resin.

Besides, there are also spools with an s-curved cross-section. In contrast to tapes with a u-curved section, there is also a change in fibre-matrix distribution across the tape thickness. Figure 13 shows such a distorted spool cross-section. Basically, an s-curved cross-section acts like two u-curved cross-section with a transfer of the resin-rich side in the middle.

Material properties of CF/PES

In-situ consolidated specimens

After determination the optimum parameter set for laminates by using laser-assisted TFP, testing plates were manufactured to conduct mechanical tests. To determine the elastic properties in the longitudinal and transverse direction with regard to the orientation of the fibres, tensile tests were conducted following the test standard DIN EN ISO 2561 B for longitudinal tests and DIN EN ISO 2597 B for transverse tests.

Compression tests according to DIN EN ISO 14126 1 A using the Celanese test fixture were carried out in order to determine the material behaviour of CF/PES under compressive loading.

Post-consolidated specimens

Within DEfcodoor a classification of the laser-assisted TFP process was aspired with respect to commonly used manufacturing technologies as autoclaving or press-forming. Usually, the highest performance of carbon-fibre reinforced thermoplastics can be achieved by processing them in an autoclave due to the high applied pressure. The most significant difference in the said manufacturing technologies is the applied pressure during processing which affects the matrix-dominated mechanical properties most. In-plane shear tests can be conducted by tensile loading of specimens with symmetric -45°/+45°-lay-up. In this way, matrix-dependent and matrix/interface dominated mechanical properties can be determined. Hence, this testing method was chosen in order to compare in-situ consolidated specimens manufactured with laser-assisted TFP to specimens post-consolidated in a press and in an autoclave. Three testing plates were manufactured by using the laser-assisted TFP technology and employing the optimum parameter set. One plate underwent an additional post-consolidation in an autoclave applying the following autoclave cycle:

- Heat up to 380°C with heating up rate of 15 K/min
- Holding 380°C for 30 minutes
- Cooling down to 60°C (no definite cooling rate)
- Holding the pressure constant at 10 bar during the entire autoclave cycle

The next plate was post-consolidated in a press following the press cycle below:

- Heat up of preheater to 470 °C for 80 s
- Preheating of fibre-placed laminate for 220 s at 470 °C
- Transfer of preheated laminate to mould heated up to 170°C
- Holding 170°C at a pressure of 60 tons for 60 s

All testing plates were cut to the desired dimensions and equipped with biaxial strain gauges in order to perform in-plane shear tests according to DIN EN ISO 14129. The results from in-plane shear testing of specimens post-consolidated in a press show an increase of the mean average longitudinal shear strength by approximately 16 % towards in-situ fibre-placed specimens. Specimens that were post-consolidated in an autoclave show an increase in mean average longitudinal shear strength of approximately 21 % compared to in-situ fibre-placed specimens.

Both times, this effect correlates with a decrease in the consolidated ply thickness of post-consolidated specimens. This is explained by higher pressure applied during autoclave processing or pressing than during TFP. Intralaminar voids within tapes as well as interlaminar voids between plies can be removed more successfully due to high consolidation pressure in an autoclave or in a press. The high compaction results in reduced thickness of post-consolidated laminates. As a consequence the fibre volume content of the post-consolidated specimens increases and in turn the longitudinal shear strength and the shear modulus increase.

It is interesting to note that the scatter of the test results for post-consolidated specimens in an autoclave is nearly four times higher than for in-situ consolidated specimens. The test results for specimens post-consolidated in a press show the lowest standard deviation over all tested specimens. However, the test results from in-situ consolidated specimens are nearly as stable as the results from specimens post-consolidated in a press.

Process development: Thermoforming of UD laminates

Preliminary tests

To develop process parameters for thermoforming fibre-placed laminates made from CF/PES tapes, a mould for a symmetrical hat profile ("in-situ article") was used which was already available at DTC. The composite material was dried at 120 °C for over 12 hours before press forming. For the thermoforming trial components several settings have been used which can be seen in Table 3.

Cirex release agent was used on the mould. It was visually judged that a part heated for 5:00 minutes with 470 ºC heater setting, a dwell of 60 seconds and a press force of 60 ton looked good for the first trials. These settings have been determined based on the material properties as far as they were known and previous press forming experience.

Subcomponent

This demonstrator part represented the next step within the development of the DEfcodoor technology. The design of the subcomponent differs from the in-situ article by increased dimensions in depth and width. The finally in-situ joined subcomponent, the cross-section of the thermoformed stiffener and the correspondent dimensions of the subcomponent can be seen in Figure 15.

The laminates to be thermoformed to subcomponent stiffeners were manufactured by laser-assisted TFP using the optimum parameter set (Table 2) as can be seen exemplary in Figure 16.

12 blanks in total were produced to be thermoformed subsequently. An aluminium tooling was designed and manufactured at DTC (Figure 17) to thermoform the fibre-placed laminates into hat profiles.

After some preliminary trials, nine laminates were successfully thermoformed to hat-shaped stiffeners. Table 4 shows the used press settings for thermoforming blanks to subcomponent.

The thermoformed hat profile (subcomponent) can be seen in Figure 18.

It can be derived from the figure above that both flanges rest on the table and no distortion can be detected.

The quality of the stiffener was examined by the use of visual inspection, non-destructive inspection (NDT) and dimensional inspection. The surface of the material becomes smoother due to press forming, which not only improves the visual appearance but also the inspectability by NDT via ultrasound. Dimensional inspection suggests compaction of the laminate occurs during press forming, since the average thickness decreased towards the nominal thickness. The quality inspection of the blanks and final components by ultrasound scanning remained inconclusive because no standard is available. NDT of the fibre-placed laminates would also require a smoother surface.

Core insertion

To enable in-situ placement on top of the flanges of the thermoformed component, a core with high dimensional accuracy is to be manufactured to generate an even plane with the flanges. This is especially important at the curved transfer from web to flange of the thermoformed component highlighted in Figure 19.

The used core material is Aquapour ® which provides high compressive strength to withstand pressure during a new placement on top of core and thermoformed flanges. Aquapour ® is soluble in water.

A setup to manufacture customized cores has been developed. After mixing the core material with water at the required ratio, the material has a pasty texture and is ready for filling. For every demonstrator one thermoformed component each serves as mould in which the core material is filled in. To maintain a core free of bubbles and with high surface quality the material is filled in the mould vertically. The mould is aligned upright such that the front end touches the underground. At the same time a steel plate is clamped to the flange surface of the thermoformed stiffeners to generate a closed opening. In addition, the open hole of the setup acts as feeder to supply liquid core material to the hardening core to compensate for shrinkage. The setup for core manufacture can be seen in Figure 20.

The procedure to manufacture a matching core is summarized hereinafter:

- Mixing of core material in powder form with water at the ratio of 55 % Aquapour ® and 45 % water
- Filling into the mould with aligned steel plate
- Drying of core material in closed mould for 1.5 hours at room temperature
- Demoulding of core material and complete drying of core material for 4 hours at 135 °C

By following this approach cores were manufactured which show high dimensional accuracy and precise transfer from core to the thermoformed flanges.

Process development for final in-situ joining

Manufacturing concept

In order to perform the in-situ joining process a setup was developed to position the thermoformed hat profiles properly. The setup is shown in Figure 21.

The sketch above shows the demonstrator (1) first. When the demonstrator is positioned between two solid aluminium profiles (2) the flanges rest on these profiles whereas the crown is suspended in air. Then, the pre-cast core is inserted into the hollow of the thermoformed stiffener (3). To extend the area for TFP the preliminary setup is surrounded by four more hollow profiles which are of equal height like the solid profiles (4, 5). To overcome the step generated by the wall thickness of the demonstrator, an additional aluminium sheet covers the whole setup. This sheet has the same thickness as the thermoformed component and a recess area leaving the flanges and the core uncovered for fibre placement of the skin (6). The whole setup is arranged on a heating plate. Thus, the thermoformed flanges can be heated up indirectly through the solid aluminium profiles. The hollow of the surrounding profiles is filled with air and has an insulating effect which prevents heat extraction. By doing so, the flanges can be heated up to 150 °C maximum. The aluminium sheet is coated with black baking enamel to reduce reflections of the laser beam. These reflections would generate more heat input on the incoming tape and then result in overheating of the incoming tape.

Changed process conditions

When blanks are manufactured which are subsequently thermoformed (in-situ placement process) the nip point temperature is set to the desired value. An infrared camera mounted to the TFP head measures the second highest temperature which occurs in the nip point region. The actually measured temperature is used for regulating the laser power and is calibrated to the emission coefficient of carbon-fibre reinforced thermoplastic tapes. When the measured temperature is higher than the set value the laser power is decreased automatically. If the target temperature is not reached the laser power is increased. The on-line and contactless temperature measurement is currently the unique feature of the AFPT technology comparing to other TFP technologies. The laser power can even be adapted to highly variable tape quality which requires different laser power settings.

The resolution of the controller which processes the information from the infrared camera is relatively low. Hence, the measuring distance needs to be sufficiently long to provide time for regulating the laser power. Considering the in-situ joining process, the TFP head passes different substrate materials during fibre placement of each track. These are the aluminium sheet, the first thermoformed flange (CF/PES), the core material (Aquapour®) and finally the second flange (CF/PES). This is shown in Figure 22 schematically.

Every substrate material has got a different emission coefficient and different reflection behaviour which prevents a correct temperature measurement of the infrared camera. In addition, the flanges are about 20°mm in width which are not long enough to enable good laser regulation according to the measured temperature within time. Even though a very low placement velocity was applied to provide more time for temperature measurement the control path remained too short for real-time regulation.

To overcome these issues aforementioned, the laser power and the optics angle are set to a constant value for the in-situ joining process. This represents the difference to the in-situ placement process. Due to setting two parameters to a constant level, the optimum parameter set for the in-situ placement process cannot be used for the in-situ joining process why further process parameter variations need to be performed.

The dominating process parameters for the in-situ joining process are listed in the following with their effects in parenthesis:

- Optics angle (distribution of heat input)
- Laser power (heat input on incoming tape and substrate)
- Tool temperature (indirect heating-up of the flanges)

Development of test setup and test results

Similarly to the in-situ placement process to produce laminates before thermoforming a testing method is required which enables a fast manufacture of test specimens and quick conduction of the testing. In addition, the testing method and the way of manufacture of the specimens should be close to reality. Hence, an abstraction of the manufacturing concept was made which is shown in Figure 23. The aluminium sheet surrounding the flanges of the thermoformed component was simulated by mounting small fibre-placed pieces (extracted from fibre-placed UD laminate) between two strips of aluminium. Hereby, the two strips shall act as surrounding aluminium sheet, the embedded fibre-placed piece represents the flange.

Since the core was also coated with black baking enamel just as the aluminium sheet for coverage of the setup, the reflection behaviour was assumed to be similar. This is why an additional investigation of the transfer from flange to core was disregarded.

The dimensions of the “flange” pieces are designed such that two coupons can be extracted after fibre placement of the skin suitable for testing according to test standard DIN EN ISO 14130 to determine the apparent interlaminar shear strength (ILS). In order to generate the required amount of six test specimens in accordance with DIN EN ISO 1430, the original setup was repeated two more times by arranging them one after another. The test setup is shown in top view in Figure 24.

After testing various parameter combinations according to DIN EN ISO 14130 the highest interlaminar shear strength was reached using the setting stated in Table 5.

Influence due to surface treatments of thermoformed flanges

Besides various parameter combinations of optics angle, laser power and tool temperature, the effects of different surface treatments of the thermoformed flanges on which the skin layers are placed was investigated. Due to the previous thermoforming step involving the use of release agent, the surface character of thermoformed flanges has changed. Since residues of release agent on the flange surface can hinder a sufficient consolidation to the skin laminate, several surface treatments were investigated. Previously fibre-placed plates were press formed by DTC applying the following modifications:

- With commonly used release agent Cirex (no surface treatment)
- With Cirex and subsequent grinding step
- Without Cirex but with Kapton foil instead to enable demoulding
- Without Cirex but with Kapton foil and with a loose piece of pure PES foil on top to establish a resin rich surface PES foil

In further test series, small pieces were cut from plates with different surface treatments mentioned above and placed between the aluminium strips of the test setup (Figure 24).All press formed pieces were in-situ consolidated by applying the optimum parameter set arising from previous coupon testing. After testing all coupons according to DIN EN ISO 14130, the test results from the optimum parameter set for fibre-placed coupons are compared to surface treated coupons as shown in Figure 25.

The diagram (Figure 25) shows that the highest interlaminar shear strength occurred upon grinding the surface of the thermoformed flanges before placement. However, the scatter of these results is considerably high which was likely to arise from the used tape spool which showed a highly non-uniform fibre-matrix distribution.

In addition, the second best results were gained by providing a resin rich surface due to an additional PES foil on top of the flange surface. Here, the standard deviation is very small. Conversely, it has been found that it is difficult to place a pure PES foil properly on top of the fibre-placed blank before thermoforming. The foil slipped easily and led to an inhomogeneous surface so that reproducibility cannot be guaranteed. Hence, this surface treatment is disregarded in further trials.

The lowest apparent interlaminar shear strength was reached by using flanges without any surface treatment.

For all subsequent trials the flange surface of thermoformed stiffener was cleaned and grinded since the highest ILS results were achieved with this surface treatment.

Optimum setting

The results from the ILS test helped to determine general effects due to the dominating process parameters for the in-situ joining. Since constant values for the laser power and the optics angle require adaption as soon as changes of the test setup are made, the optimum setting had to be developed further for demonstrator production. The flanges of thermoformed stiffener are twice as thick as the fibre-placed pieces of the ILS coupons and require more energy to get heated up. Eventually, the final optimum parameter set for the in-situ joining process could be determined by fibre placing on a thermoformed stiffener. Starting from the optimum setting arising from coupon testing, the laser power was gradually increased until enough heat could be supplied to melt the substrate. It was found out that an uneven heat distribution in favour of the incoming tape prevents overheating of the substrate. The final optimum parameter set arising from demonstrator tests is shown in Table 6.

Results

This optimum parameter set was used for final joining of the thermoformed stiffeners of the in-situ article by using laser-assisted TFP. By applying the optimum parameter set arising from demonstrator tests (Table 6), three stiffeners of the in-situ article were successfully final joined. Figure 26 shows a stitched micrograph of the joined in-situ article with details of the joint.

The detailed views of the flanges reveal that the joint cannot be distinguished from the remaining fibre-placed plies anymore. Interlaminar voids occur particularly when two tapes with dry spots are placed onto each other and matrix material cannot fill up this area. Air that is entrapped during tape production can hardly be removed during fibre placement due to low consolidation pressures. Due to the high applied pressure during thermoforming the stiffener in Figure 26 shows fewer inter- and intralaminar voids than the fibre-placed skin.

Since the employed tape spool was empty after final joining of three stiffeners of the in-situ article, the spool was replaced with a new one. Thenceforward, the previously applied parameter set did not lead to a successful joint anymore. The trials were repeated first with different tape spools and different stiffeners whereby successful in-situ joining could not be restored. In addition, process parameters were again varied extensively but the originally successful in-situ joining could not be achieved.

Several process- and material-related reasons were investigated to restore the previously successful process. The constant setting for the laser power and the optics angle prevents dynamic adaption of these process parameters to changing condition of tape or thermoformed stiffeners. Since one tape spool only was used for determination of the final optimum parameter set, which led to successful joining of three demonstrators, it is assumed that the change of a tape spool requires an adaption of the process parameters. This would mean one process parameter set only is not sufficient when several different tape spools are needed for manufacture as long as the quality of the semi-finished products shows as high variability in quality as the used CF/PES tapes. Hence, the current tape quality does not enable reproducible in-situ joining by employing constant settings for laser power and optics angle. Regulated laser power and optics angle cannot be applied to achieve in-situ joining as the controller cannot react to quickly changing substrate material in real time. These limitations in equipment need to be overcome to establish a stable and reproducible in-situ joining process. In addition to the need for technological advancements, the quality of the tape material must improve a lot since it is the most influencing factor for the component quality.

Besides process-related reasons, also effects due to the thermoformed components on the in-situ joining process were investigated. Since fibre placement on top of press formed and fibre-placed pieces of material succeeded when providing a longer distance for fibre placement, the poor joining might be partially attributed to the width and the surface of the thermoformed flange. In addition, the inhomogeneously distributed matrix material within tapes can lead to beginning degradation of the tape material due to local overheating during thermoforming and inhibits in-situ joining. However, the influences due to the use of different spools within the same batch were even bigger than due to the substrate materials why a clear conclusion on the reason for poor in-situ joining cannot be drawn.

It is assumed that the highly varying tape quality is the reason for the poor in-situ joining. Successful in-situ joining of several omegas is explained by the use of a tape spool that revealed suitable and stable quality.

Material properties on subcomponent level

As described in the previous section, final joining of the subcomponent could not be completed and hence, the anticipated testing of finally in-situ joined subcomponent elements could not be conducted (referencing document EC1124-042-01_Test Definition Plan). However, another test was chosen to investigate the effect of thermoforming on the laminate properties. It was decided in favour of the three-point bending test according to DIN EN ISO 14125 which resembles the original test plan for the subcomponent. In addition, the specimen dimensions are small enough to extract test specimens from the flanges and the crown of a subcomponent stiffener. In addition, specimens were cut from two plates that were manufactured with laser-assisted TFP to represent the skin of the subcomponent. Table 7 gives an overview of the sampling points of all tested specimens.

Figure 27 shows the sampling points for the three-point bending test specimens at the subcomponent stiffener.

The thickness of the specimens (thermoformed stiffener) differs from the commonly used dimensions stated in DIN EN ISO 14125. That is why the dimensions of the specimens were re-designed in accordance with the guidelines of the applied test standard.

The load-displacement curves and all test results of fibre-placed specimens manufactured with spools of different material batches can be seen in Figure 28.

The gained results for the flexural strength of both test series pictured above are almost identical and amount to 489.94 MPa (batch 3) and 489.80 MPa (batch 4) in average. However, test series made from batch 4 is subjected to higher scatter than specimens made from batch 3. In addition, the load-displacement curves indicate different failure modes for both test series. Specimens made from batch 4 imply a higher breaking elongation and a higher flexural modulus than specimens made from the third batch. This is explained by the use of IM7 fibres in batch 4 which have a higher Young’s modulus than AS4 fibres applied in batch 3. Previously, the tape material for DEfcodoor always comprised AS4 fibres and was also used for the material characterisation. After intense examination of the tape material the DEfcodoor consortium and the industrial partner discussed the highly variable tape quality with the tape manufacturer. As a result of this discussion, IM7 fibres were used instead of AS4 fibres to enhance the tape quality. The IM7 fibres are available without sizing which helps to strengthen the fibre-matrix interface and the impregnation behaviour.

In the following, Figure 29 – Figure 31 show the load-displacement curves as well as the test results for specimens extracted from both flanges and the crown of a thermoformed subcomponent stiffener.

Comparing the load-displacement curves above, no significant differences can be seen between the different sampling points. The failure modes indicate a lower breaking elongation than fibre-placed specimens. However, the test results of all thermoformed specimens scatter less than fibre-placed specimens. In addition, the test results for specimens extracted at the flanges are very similar. Specimens extracted from the crown show an increase of the flexural strength by about 5.30 % and the lowest standard deviation in comparison to the flange specimens. This might be explained by more matrix flow at the flanges during thermoforming. This effect is also indicated by decreased thickness at the flanges in relation to specimens sampled at the crown.

Figure 32 compares three-point bending test results of all tested specimens.

The overall comparison of the test results above reveals that the mean average in flexural strength of thermoformed specimens is increased by 21.85 % compared to fibre-placed specimens. This kind of difference was also investigated on coupon level when fibre-placed specimens were compared to specimens post-consolidated with press forming.

Feasibility article

In first steps 2D laminates manufactured by using the laser-assisted TFP technology were thermoformed to symmetrical hat profiles (subcomponent) successfully. The feasibility article instead comprises a complex unsymmetrical cross-sectional area and double-curvature. This demonstrator part was derived from the current door design of the helicopter EC 135 as can be seen in Figure 33.

The detailed design of the feasibility article stiffener can be seen in Figure 34.

The manufacture of the double-curved stiffener of the feasibility article is presented hereinafter.

Fibre placement strategies

Since double-curved structures with a varying cross-sectional area are most challenging with respect to thermoforming, concepts for the manufacture of special blanks with the laser-assisted TFP technology were developed. Two different blank types were designed to facilitate the subsequent thermoforming step. Thereby, wrinkles and tearing apart of material due to limited movement of single plies shall be prevented. For means of comparison also standard blanks (blank type 1) were manufactured employing 1inch tapes only and in a non-steered manner. The second blank type involved steered fibre placement of the 0° plies along the curvature of the FA. For this ¼ inch CF/PES tapes were used. Another significant advantage of steering 0° plies is that the lay-up is maintained at every position of the curved structure. Table 8 compares both blank types including lay-up and used tape width.

All in all, 4 blanks of each blank type were manufactured. Figure 35 gives an impression of manufacturing blanks comprising fibre placement of 1 inch tapes only.

Regarding the second blank type, the double-curved feasibility article was anticipated to be pressed to a flat laminate to estimate the width, length and curvature of the area which has to be covered by ¼ inch tapes. After fibre placement of the first two 45° plies using 1inch tapes, the first curved 0° ply was placed on top of them employing ¼ inch tapes. The thickness and the consolidation of both plies were sufficient to enable steered fibre placement. To allow a high degree of movement of the tape underneath the consolidation roller a placement speed of 5cm/s was applied. Figure 36 shows fibre placement of curved 0° plies with high accuracy during manufacture of 4 laminates of blank type 2.

A detailed view (Figure 37) of the fibre steering reveals small wrinkles at the inside radius of each track since the critical energy for the elongation of the fibres was exceeded.

Since the material gets molten during fibre placement the out-of plane wrinkles can be pressed flat by the consolidation roller which results in in-plane fibre waviness.

This indicates that the design of the curvature would need to be adapted to the bearable elongation of the fibres in future since wrinkles and fibre waviness affect the material properties negatively.

Thermoforming of 2D blanks into double-curved component

In the following the process development for thermoforming the feasibility article is presented. Table 9 shows the press settings for thermoforming of the feasibility article.

The aluminum tool to thermoform the feasibility article was designed and manufactured by DTC as shown in Figure 38.

A big challenge is to position the blanks in the mould properly. Two blanks of blank type 1 and 2 could not be positioned well in first place. After some trials, the blanks could be positioned in the mould well and wrinkles could be reduced significantly as can be seen in Figure 39. Here, a laminate of blank type 2 was used.

Summarizing the thermoforming of fibre-placed blanks into the double-curved feasibility article, it was difficult to position the blank on the tool very accurately. This had a considerable influence on the amount of wrinkles in the part. Comparing the best parts from quasi-isotropic standard blanks and blanks with fibre steering, the product from fibre steered material looks a bit better since fewer wrinkles are detected. However, improvement for both parts is still possible and the current level of information is too little to draw clear conclusions regarding the influence of the fibre steering on the reduction of wrinkles.

Additionally, a CF/PEI fabric was thermoformed to compare the results to forming of fibre-placed laminates.

Particularly fibre-placed UD laminates can move less than e.g. fabrics during thermoforming to prevent wrinkling. One reason is the lower cohesion between UD tapes in transverse direction as e.g. in a woven fabric so that the material can tear apart at locations with high deformation degrees. Comparing UD with fabric (figure above), the fabric could be thermoformed much better. Hardly any wrinkles are observed but also for this part there is room for improvement.

Quality inspection of the feasibility article

The results of thermoforming both blank types was investigated via visual inspection and microscopy. Figure 41 compares the results from thermoforming both blank types. Both stiffeners are positioned such that the crown faces the bottom.

Differences were observed on a macroscopic level. The thermoformed feasibility article made out of blank type 1 without steering of fibres shows a higher amount of wrinkles at the end of the structure with high degree of deformation (highlighted in red). The stiffener upon thermoforming blank type 2 reveals fewer wrinkles in this area (highlighted in green).

Additionally, more wrinkles can be observed at the outer flange and in the crown for blank type 1 than for blank type 2. When both stiffeners are aligned such that the flanges face the bottom, similar observations can be made as Figure 42 shows.

The picture above reveals that more defects like wrinkles can be observed for blank type 1 than for blank type 2. Unlike the bottom side of the flanges, the upper side of the thermoformed blank type 1 exposes wrinkles at the inner radius of the component as well.

Investigating the thermoformed stiffeners with respect to residual stresses a similar magnitude of unevenness could be observed for both blank types due to residual stresses. Figure 43 shows both thermoformed stiffeners in lateral view.

In addition to visual inspection, micrographs were obtained at both ends of each feasibility article stiffener along the cross-sectional area. Figure 44 refers to the position where the first set of micrographs was sampled.

As highlighted above, the micrographs were extracted at the straight part of the feasibility article first. Since this region is free of curvature fewer deviations of the fibre orientation were expected here. The cross-section of the feasibility article was divided into five pieces to enable mounting of the specimens in silicone dies for micrograph preparation. For each thermoformed stiffener made out of blank type 1 and 2 five pieces each were obtained and examined under the microscope. In the following, the comparison of both blank types can be seen with reference to the actual position of extraction. Exemplary, the region of the angular shear web and the crown are shown for each blank type since these are the areas with a high deformation degree.

Figure 45 refers to the transfer from angular shear web to flange. The left micrograph of blank type 2 shows that the original fibre orientation of each ply could be maintained despite of the degree of deformation. However, the changed reflection of the right micrograph of blank type 1 implies a deviation of the fibre orientation from the original lay-up. In addition, plies in the middle of the specimen reveal considerable waviness. It can be assumed that the undulation has a significant effect on the mechanical properties of the stiffener.

Slight undulations at the outer plies and entrapped air between top and second layer are detected related to blank type 2 (Figure 46). The lower micrograph shows strong deviations from the original lay-up all over the specimens and irregularities in thickness in the transfer from crown to angular shear web of the feasibility article.

All micrographs above were extracted from the straight part of the feasibility article. Hereinafter, the micrographs were cut from the other end of the demonstrator part – at the area with the highest degree of deformation. Figure 47 refers to the sample position.

In contrast to the first set of micrographs, both blank types are expected to reveal deviations from the original lay-up. This is because the feasibility article underwent a considerable degree of deformation by what the lay-up at the beginning (straight part, highlighted in Figure 47) cannot be maintained at the end of the demonstrator part (highlighted in Figure 47). Nevertheless, the 0° plies within blank type 2 should appear in an original manner since they were steered along the curvature of the feasibility article. Exemplary, the region of the angular shear web and the crown are shown for each blank type since these are the areas with a high deformation degree.

Figure 48 shows the microscopic comparison of both blank types at the transfer from flange to angular shear web. It can be clearly derived from this comparison that plies at the lower side differ from the original lay-up in relation to blank type 2. In addition, deviations in thickness resulting from shifted plies can be noticed. Also some waviness can be observed for blank type 2 in the middle of the angular shear web. The darker reflections in the mid of the lay-up of blank type 2 can be referred to 0° plies. By this it can be stated that the steered 0° plies help to maintain the original lay-up.

The micrograph of blank type 1 of the transfer from angular shear web to crown revealed a strong wrinkle (highlighted in orange, Figure 49). It is noted that no air is entrapped in this wrinkle and that no irregularities in thickness is caused by the wrinkle as it was filled up by melted matrix material during thermoforming.

Upon visual inspection of the thermoformed stiffener of the feasibility article only slight differences in the use of various blank types could be noticed. Blanks with steered 0° plies showed fewer wrinkles at the outer radius of the demonstrator part than blanks without fibre steering.

However, the examination of cross-sections under the microscope upon thermoforming two different blank types revealed that the fibre orientation could not be maintained in case of laminates without fibre steering. It is noticeable that even strong deviations in thickness and waviness could be observed for blanks without fibre steering at the straight part of the feasibility article. At this area the feasibility article is 2D curved only. In case of thermoforming laminates with steered 0° plies no significant undulations, deviations in fibre orientation or irregularities in thickness could be observed.

The end of the feasibility article shows the highest deformation degree and here strong wrinkles and ply undulations were noticed for blanks without fibre steering. In addition, the fibre orientation highly deviated from the original lay-up. Regarding laminates with steered 0° plies it could be observed that the orientation of the steered plies was maintained at the end of the feasibility article. However, the orientation of the non-steered plies was changed.

All in all, it can be summarized that steering of plies has a positive effect on the laminate quality upon thermoforming into 3D shaped structures. Fibre steering not only affected the ply orientation positively but also hindered the evolvement of wrinkles and undulations. However, final conclusion cannot be drawn that fibre steered laminates can be thermoformed better than non-steered laminates in general and further investigation is needed. A significant effect on the thermoformed product is attributed to the positioning of the pre-heated blank into the mould.

Potential Impact:

Environmentally-friendly technology

The potential impact of the project DEfcodoor was anticipated to benefit from the advantages of using thermoplastics. Employing such matrix materials, storage with climate control as used for thermosets becomes needless and hence lowers the environmental impact. Apart from cleaning the surface of the thermoformed stiffener before in-situ joining with isopropyl no chemicals were used for manufacturing components with the DEfcodoor approach. Since the production of matrix material and carbon fibres is highly energy-consuming and involves big use of resources, the components made out of CFRP should involve as few scrap as possible. The use of automated TFP is one possibility to do so. The automated TFP process enables the production of customised blanks with exact fibre orientations and if required with local reinforcements. Using this technology flat laminates which were subsequently thermoformed and skin laminates were manufactured near net shape to decrease the amount of scrap.

In addition, the scrap can be used for the production of smaller components by e.g. injection moulding or compression moulding since thermoplastics can be melted several times. The recyclability and the reusability of parts manufactured with the DEfcodoor approach is currently investigated in another CleanSky project called “Disacop”.

Furthermore, consumables and auxiliary materials as needed for vacuum bagging of thermoset prepregs for autoclaving is not required when thermoplastic composites are produced by TFP and thermoforming.

Specimens post-consolidated in an autoclave yielded an increase of about 20% in comparison to in-situ consolidated specimens. However, the main reason for the offset was found to be the insufficient quality of the unidirectionally reinforced tapes. It is assumed that a post-consolidation step in an autoclave can be eliminated as soon as the tape quality improves.

Maintaining cost-efficiency

When consumables and resources can be cut down not only an ecological effect can be seen but also an impact on the processing costs. One of the main cost drivers during the currently used manufacturing process of helicopter structures is assembly. By bonding the skin directly to the thermoformed stiffener an intense surface preparation and mechanical processing for bolts, rivets, screws or adhesives can be abandoned. By implementing this step up to 40% of the total costs can be saved. This can be attributed to the fact that no load carrying fibres are cut and no expensive titanium bolts are required, saving both weight and costs.

Furthermore, no intermediate or post consolidation in an autoclave is required when the DEfcodoor approach is used for aircraft components. On the one hand the high investment costs for an autoclave and on the other hand long cycle times and high energy consumption let the component costs increase when an autoclave is used. As previously mentioned, post-consolidation of fibre-placed laminates will become needless when the tape quality is increased.

Summary

In the proposal of DEfcodoor a reduction of scrap by 15% was estimated. After analysis of the collected data for life cycle assessment, a scrap rate of 10% was determined for the DEfcodoor manufacturing approach. The commonly employed manufacturing process consisting of hand lay-up of thermoset prepregs with a subsequent autoclave process has estimated scrap rate of 20%. Hence, the scrap could be reduced by 10% during manufacture with TFP. However, it is assumed that the scrap rate can be further decreased when the TFP technology is continuously advanced.

The DEfcodoor approach can be stated as an out-of-autoclave process as soon as the quality of the semi-finished products (tapes) can be significantly improved. Air entrapped in the tapes can be removed when high pressure is applied as during press forming or autoclaving. The consolidation pressure during TFP is insufficient to squeeze out entrapped air. It is assumed if tapes with low void content are supplied the mechanical properties of in-situ consolidated specimens become equal to specimens post-consolidated in an autoclave.

Use and dissemination of foreground

An abstract was submitted to the conference “Greener Aviation 2014” where Clean Sky breakthroughs and worldwide status will be reported. The title of the abstract is “Novel environmentally friendly manufacturing approach for helicopter doors made out of thermoplastic composites”. The abstract has been selected for the conference. The corresponding author, Veronika Radlmaier (TUM) , will give the oral presentation about the paper which will be handed in by February 2014.

List of Websites:

Beneficiary 1: TUM (www.lcc.mw.tum.de)
Beneficiary 2: DTC (www.composites.nl)
Beneficiary 3: AFPT (www.afpt.nl)

Contact details:

TUM: Ms. Elisabeth Ladstätter (ladstaetter@lcc.mw.tum.de) Ms. Veronika Radlmaier (radlmaier@lcc.mw.tum.de)
DTC: Mr. David Manten (d.manten@composites.nl) Mr. Sjoerd Hooning (s.hooning@composites.nl)
AFPT: Mr. Patrick Kölzer (patrick.koelzer@afpt.de)

Related documents

final1-publishable-summary.pdf

This project is featured in...

RESEARCH*EU MAGAZINE

Can Hydrogen revolutionise our lifestyles?

Issue 38, December 2014

Share this page

Last update: 8 July 2014

Record number: 141817

Permalink: https://cordis.europa.eu/project/id/287103/reporting/en