Disassembly of eco-designed helicopter demonstrators

Reporting

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Disacop

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Final Report Summary - DISACOP (Disassembly of eco-designed helicopter demonstrators)

Executive Summary:
Thermoplastic matrices for fiber reinforced polymers have become very popular. So-called thermoplastic composite materials (TPC) offer great potential regarding weldability, thermoformability and recyclability when compared to thermosets. Consequently, the manufacturing costs of such parts are reduced hence augmenting their economic value. Furthermore, their storage life is not restricted and they are known for their excellent toughness and chemical resistibility.
For mainly these reasons, a rising attention for aerospace applications can be noted. Typical shell constructions, in which many stiffeners and panels are joined to complex structures, can be built in a much more integral and weight efficient way with the help of fusion bonding techniques. The advantage of fiber reinforcement can be fully exploited, as holes and rivets become unnecessary.
This study investigates the possibility of disassembling such integral structures for recycling purposes. By inverting the fusion bonding process, single elements can be detached from the main structure and in the best-case scenario reused in a refurbished component. The focus lies hereby on the assessment of the best suitable heating method. Preliminary tests on coupon level have been conducted to gather the main drivers. Hereby, the resistance heating method in which a conducting material is placed within the interface region of the bond has been identified as most promising technique. Fracture mechanical tests are conducted as well in order evaluate the impact of the separation process on the parts. Finally, the separation process is adapted on demonstrator level, where an omega-stringer-stiffened panel is disassembled.

Project Context and Objectives:
The state of the art manufacturing of high-performance helicopter structures with carbon-fiber reinforced polymers (CFRP) is actually based on the use of thermoset prepregs, which generally cause high manufacturing costs. Furthermore, the molecular structure of thermoset resins is characterized by strong chemical crosslinks which cannot be untied after the final curing cycle. Subsequent manufacturing steps such as fusion bonding, thermoforming or even recycling are consequently not possible.
Thermoplastic matrices for fiber reinforced polymers have become very popular. So-called thermoplastic composite materials (TPC) offer great potential regarding weldability, thermofomability and recyclability when compared to thermosets. Consequently, the

manufacturing costs of such parts are reduced hence augmenting their economic value. Furthermore, their storage life is not restricted and they are known for their excellent toughness and chemical resistibility. TPCs have therefore acquired a rising relevance for aerospace structures in the past years, which is why manufacturers and suppliers have also increased their research activities on the fusion bonding of TPCs.

This project focuses on integral TPC helicopter structures (see Figure 1). The subcomponents for such assemblies consist in most cases of stiffened panels, also called shell constructions (Figure 2). In the case of metal structures, the subcomponents (stiffener and skin) are usually joined with the help of bolts and rivets. These enable the disassembly of the structures in the case of damage or for recycling purposes. Despite the advantage of a possible disassembly, this joining method requires a large amount of additional weight. With the use of TPCs, subcomponents can be directly welded, enabling an aditional weight reduction. However, in the case of aerospace structures, the subcomponents should still be separabe. In the best case scenario, both components stay intact after the separation process and can be reused as subcomponents if these are not damaged.

Different recycling strategies exist, which can be classified according to their environmental benefit (Figure 3). Only the disassembly of the structure in its single components enables a correctly sorted manipulation of the different materials according to their degradation or damage state. The most environmental friendly recycling strategy is given by the “component recycling” method, since already manufactured components can be completely reused in other assemblies. In order to ensure the reusability of the components, these have to be undamaged after the disassembly process, whereas in the best case scenario, both components are intact.

The main objective of this project is the disassembly of fusion bonded thermoplastic aerospace structures. Therefore, the best suitable bonding method for disassembly is identified by benchmark. Then coupon-level tests are conducted before applying the designed method to the demonstrators.

Project Results:

1. Material and Manufacturing Processes of GRC Demonstrators

Disacop is based on the demonstrators from GRC 6.1 (DEfcodoor) and GRC 6.2 (ECO-Fairs). The DEfcodoor project is conducted at the TUM with ECD as industrial partner and aims at demonstrating the applicability of the automated fiber placement (AFP) and thermoform process for complex aircraft structural TPC parts.

The industrial partner of ECO-Fairs is AW. The main goal of this project is the design of integral panels and complex shape fairings for helicopters with thermoplastic composites. Therefore, reliable design and manufacturing procedure guidelines are developed. Three demonstrator types are planned: An upper panel, a sponson fairing and a complex curvature demonstrator (e.g. radom).

Both projects are based on the application of “ecological-friendly” materials and processes, which help to reach new targets regarding costs and structural weight. The general approach relies on integrated design, reduced number of manufacturing steps, fully recyclable products and ease to dismantle for recycling. Thermoplastic materials possess a high potential to reach these targets and are therefore considered for these projects.

1.1. DEfcodoor

This section includes the required input from DEfcodoor such as the used material and the description of the demonstrators.

1.1.1. Material

The material used within the DEfcodoor project consists of reinforcing carbon fibers which are impregnated with the amorphous thermoplastic polyethersulfone (PES) and delivered as unidirectional tapes. They are then processed on the AFP machine to subcomponents. The following table (Table 1) summarizes the product data as delivered by the material supplier.

1.1.2. Manufacturing Concept

The manufacturing concept for the DEfcodoor demonstrator is mainly based on the combination of thermoforming and AFP. The latter enables the in-situ consolidation of fiber reinforced polymer parts: The production of a composite part in one single step. Therefore, pre-consolidated fiber tows (see previous section 1.1.1) and the soil are heated up above the melting temperature, the incoming tape is placed, consolidated and simultaneously cooled down (see Figure 1).

A state of the art helicopter structures consist of a multitude of joined parts [13], hence innovative joining techniques are deployed in this project. Thermoplastic materials are predestinated for fusion bonding. When compared to riveted or bolted joints, this technique saves additional weight and can increase the bonding strength when compared to adhesive joints [14]. The complete DEfcodoor process includes the manufacturing of customized blanks in the AFP process, which are formed to stiffeners in a subsequent thermoforming process. Tailored blanks show great potential regarding scrap minimization and the achievement of an ideal fiber orientation.

After the stiffeners have been formed, the cavity of the omega-stringers is filled with a water-soluble core and the skin layers are placed directly on top. This technique enables the in-situ production of the skin and the joining of the stiffener-skin-interface in one step. The

single steps are illustrated in the following diagram (Figure 2).
This so-called in-situ process underlies different requirements than the manufacture of monolithic laminates, which is one main aspect within the DEfcodoor project

1.1.3. Demonstrator

The feasibility article, as named within the DEfcodoor project, represents the last step of the development of the DEfcodoor technology. This demonstrator includes a complex three-dimensional curved stiffener, which is bonded in the in-situ process (described in section 1.1.2) to the skin. The following image (Figure 3) shows the actual conceptual design of the described part. A more detailed overview is given in the drawing EC12920A100, which has been submitted to the EU in the course of the DEfcodoor project.

1.2. ECO-Fairs

No detailed information concerning ECO-Fairs could be obtained so far. The following images show the planed demonstrators within this project, which will be manufactured from PPS (Polyphenylenesulfide) including a thermoplastic induction fusion bonding process.

1.3. Material Overview

The welding and thermal properties of the used thermoplastic materials from DEfcodoor and ECO-Fairs are compared in the following table.

2. State of the Art Heating Methods for Fusion Bonding of TP Materials

Many established heating methods for the fusion welding of TP constructions exist, which are well described in literature. These are most commonly classified based on their introduction mode at the bondline (see Figure Figure 5).
External heating methods rely on convection and/or conduction to heat the weld surface. Internal heating methods can additionally be divided into mechanical and electromagnetic heating. Internal mechanical heating is based on the conversion of surface and intermolecular friction into heat. Internal electromagnetic heating techniques absorb and convert electromagnetic radiation and convert it into heat.
Above mentioned techniques can further be sub-divided in one and two-stage heating respectively welding methods. Two stage processes require a heating and forging stage, as the heating device must be removed from the bondline prior to the forging stage, in which the parts are brought together.
In order to disassemble fusion bonded joints, the heat which is necessary to melt the polymer should ideally only warm-up the interface region. Otherwise, the integrity of the parts cannot remain during and after the disassembly process. Additionally, the heat introduction must be independent of any pressure application, as the bonded parts must be separated during heat application.

3. Benchmark of Separation Scenarios

In this chapter, the different separation scenarios mentioned in chapter 2 are benchmarked regarding their suitability for the disassembly of thermoplastic fusion bonded structures. The benchmark is based on the literature review conducted in the previous chapter. The following scale is used:
An overview of the benchmark is given in Table 3 whereas a more detailed explanation is given in the further course of this section.
The category of bulk heating techniques includes co-consolidation and hot-melt thermoplastic adhesives, which are not particularly suitable for the disassembly of fusion bonded structures. By heating the complete part, complex tooling must be provided in order to reduce the delamination of the structural reinforcement layers. Dual-resin bonding on the other hand can possibly reveal good potential for the disassembly of structures as the temperature applied to the part is below the melting temperature of the matrix. However, this method is only applicable to semi-crystalline thermoplastics. Due to the fact that this technique is not adaptable to any TP material, it is not further regarded in this project.
The group of frictional heating techniques includes spin, vibration and ultrasonic welding. All three are not suitable for Disacop. Spin and vibration welding cannot be applicable, as the components must be separated from each other in order to produce heat at the interface. In the case of ultrasonic vibration, pressure must be applied to the components, in order to transmit the vibration which generates the heat. After releasing the pressure, the temperature declines and the matrix solidifies consequently prohibiting the disassembly of both components.
The group of thermal heating consist of hot-tool, hot-gas, infrared and laser heating. These methods are all not suitable for the disassembly of thermoplastic structures, for the same reasons as the bulk-heating techniques. Except the laser welding technique can be applied, if one component is manufactured from laser-translucent material.
Electromagnetic heating methods show the highest potential for the disassembly of thermoplastic structures. Despite the complications when using dielectric heating methods, the application of a so-called dielectric layer can enable the heating of the components below the melting temperature of their matrix (similar to the dual-resin bonding technique). Microwave heating shows the

same difficulties as the dielectric heating method, due to the shielding effect of TPCs. The inclusion of strongly electromagnetically absorbent material in the interface area could enable the disassembly process. The most promising techniques are the induction heating method and the resistance welding technique. These two methods enable the heating of solely the interface region. Tests with induction and resistance heating are conducted on coupon level and described in the following course of this report.

4. Disassembly Tests with Induction Heating

Tests on coupon level have been conducted in order to judge the feasibility and if applicable identify the main processing parameters for the disassembly process. Simple nonstandard coupons have been designed (see Figure 6) and processed on an induction welding apparatus provided by Airbus Helicopters Germany.

The samples (ca. 130 x 100 mm) consist of two quasi-isotropic ([+45, -45, 0, 90, 0, 90]s) carbon fiber reinforced polyethersulfone (PES) plates which are welded by co-consolidation. The induction apparatus consists of a coil, an aspiration and an infrared temperature measuring device. The coil is movable in two directions (height and length). The induction parameters are controlled via the IR-measured temperature, which regulate the surface temperature. The disassembly force is introduced by weights, which are attached to the patch. The force was varied between 0 and 5 N whereas the set temperature between 280 °C and 320 °C. The average surface temperature is checked on the output monitor of the induction setup, which is measured by the already mentioned infrared thermometer. The given values can only be used as rough estimation of the surface temperature, as various fumes bug the infrared temperature measurement unit. Therefore, only a qualitative investigation of the preliminary trials is conducted.

The separation of the patch from the main plate was proven to work. Figure 7 shows a selection of different separated coupons with varied parameters.

It was shown that a minimum disassembly force is required in order to detach the patch from the plate. With increasing temperature and force, the quality of the detached parts increases as less fiber tow pull-outs are observed. In all cases, the fibers of the upper layer (+45°) of both components have been partially pulled out. This is mainly due to the lack of fixation at the edge of the component (Figure 8).

In order to prevent this damage mode, a fiber orientation of 90° of the outer layers should be considered, as these remain fixed to the plate when temperature is applied to the heating zone. The use of 0° orientation is not practicable, due to the same reason.

Due to the temperature increase occurring as a result of the so-called “edge effect” (Figure 9a), the edge of the upper component overheats and the matrix burns (Figure 9b). This occurs as the currents cannot follow the shape of the coil. In order to create the closed-loop paths, the eddy currents are forced to travel along the edge resulting in higher current densities and subsequently higher temperatures. Different possible approaches exist to suppress this effect. A simple way could be the programming of a variable power output along the path, enabling a reduction of the inputted power in edge regions.

A further challenge when using the induction heating technique is the exact adjustment of a temperature in the interface region. If the complete laminate is heated, by consequence the delamination of the reinforcement layers is inevitable (Figure 10). However, this effect could be minimized by either cooling the upper surface of the laminate or adapting the lay-up (increasing the number fiber crossings in the interface region). A further possibility can be to include a metallic mesh in the interface region, which is the most susceptible material for magnetic fields.

5. Disassembly Tests with Separation Layer

5.1. Concept

Similar tests to the ones conducted with the help of induction have been performed with resistance heating. The idea is to introduce a conductor material within the interface region of the welding zone. The heat generation follows Joule’s Law. As a result, the joining and separation process can by performed with the help of one implant. For this purpose, a “separation layer” has been designed and included between two CF-PES plates. The same layup as previously described was used to build the plates.

Different options as conductor element have been considered, e.g. metallic sheets, conductive particles which are introduced in a matrix or conductive fibers. After the consultation of experts from the consortium partner Qpoint, a rough baseline concept was designed (Figure 11).

Preliminary tests (see D2) showed that the production of a “stand-alone” version of the separation layer facilitates the handling and manufacturing and reflects a realistic production cycle as the layer can also be used for bonding. In contrast, the “in-situ” version is produced by placing all required components such as stitched wires, insulation and thermoplastic matrix foil between the consolidated composite plates and co-consolidated under pressure and temperature. This variant does not reflect a realistic production cycle and has therefore been rejected (see D2).

Stitched Pattern

The metal wires are stitched onto a glass fiber woven fabric with a fiber area weight of 108gsm using a stitching machine (Qpoint). The pattern (Figure 12) can be defined for any geometry, allowing an adaptation of the separation layer to any kind of weld geometry. In this case, the geometry is adapted to the manufactured coupons for disassembly trials and fracture mechanics testing. Different metals and wire diameters have been benchmarked regarding manufacturability and power output. Copper wires of 0.12mm diameter yield the best results. The contact of the wires to the power source is achieved in this project with the help of copper foil, which is wrapped around the wires (see D2) in order to reduce the resistance between the contacts of the power source and the heating element.

Electrical Insulation

Due to the property of carbon fibers to conduct electrical currents, an insulation of metal wires must be included in the separation layer. Therefore, glass fabric web, which is already used as stitching support, is also placed on top of the wires and impregnated together with the rest of the stack. Different amounts and types of glass fiber fabric are applied within preliminary tests (see D2), in order to find the optimum between supplement weight and sufficient electrical insulation.

Process Monitoring

In order to measure the temperature in the bond line and therefore monitor the process of debonding, a thermocouple is applied onto the upper glass fiber fabric. The wires are stitched in the same manner as the conducting wires to a glass fiber web support. The latter also acts as insulation layer and is directly integrated in the impregnated stack.

5.2. Final Design

Different disassembly trials are performed with the baseline design of the “separation layer”, as named in the further course of the project. The layup, the isolation material as well as the wire type is varied. During the disassembly trials (Figure 13), thermography images are generated in order to assess the temperature homogeneity.

The main results are summarized hereafter:

- A separation layer should be produced separately (stand-alone version).
- The wires of the heating element should not be too thick. Monofilament wires are better to process despite the higher risk of failure as no redundant wire is available. However, fiber bundles are flattened during the press process and a high risk of contacting with adjacent wires occurs.
- The heating material should have a low resistance. Copper metals showed the best results. Nonetheless, it should be investigated, if the use of different materials e.g. metallized carbon fibers is possible.
- Sufficient material for electrical insulation must be included when using carbon fiber reinforced parts, to minimize the risk of hot spot and malfunction of the implant.

The final design of the separation layer consists of 6 layers of isolating glass fibers, 4 layers of PES matrix and 0.12mm copper wires.

5.3. Trials

Prior to the actual disassembly trial, a series of functional tests is conducted. First, the resistance of the heating implant is measured and compared to the value recorded before the co-consolidation. Then, the isolation between the carbon fiber reinforced part and separation layer is tested. Therefore, the electrical conductivity between the copper wires and a cable attached to the carbon fibers is measured. At last, the thermocouple is tested. In the case of short-circuit between the carbon fiber reinforced part and the resistive implant or a too high resistance of the implant itself, the sample is not used. In the case of a malfunctioning thermocouple, the sample is used by solely monitoring the surface temperature of the sample.

For the disassembly trials, the wires are connected to the low-voltage power source (Figure 16). The heating is done stepwise. Therefore, the voltage is sequentially arisen after the temperature stagnates at one level. At every level, the temperature is noted together with the electrical power input values. Furthermore, a thermography image (Figure 17c) is generated using an infrared camera. The power input can then be determined using Joules Law (Eq. 1) or using the temperature dependent resistance (Eq. 2) which is determined by a reference temperature (Rref) and its correspondent empirical coefficient (ɑref). With the thermography image, the homogeneity of the temperature distribution can be determined on the one hand and on the other the value measured in the interface region by the thermocouple can be verified.

Initially a voltage of 3.5V (I=0,6A) was applied. Test specimen 1 was heated up to 80°C at a rate of 0.5K/s. Afterwards the voltage was set to 8.8V (I=1.1A) which raised the temperature to 180°C at a heat rate of 0.8K/s. To gain higher temperatures, the voltage had to be raised to 12.7V (I=1.3A). At 280°C the test piece bloated up in its mid-section (see Figure 17a). A complete separation was not possible as the edge areas where still bonded together. Based on this result test specimen 2 is heated up at lower rates and thermally isolated to guarantee a more homogeneous heating. The initial voltage was 3.6 V (I=0.6 A) and test specimen 3 was heated up to 115°C. Then the voltage was raised to 8.0 V (I=1.1 A). The heat up rate was 0.5 K/s. At a temperature of 240°C the test piece bloated up again (Figure 17b).

These tests on the one hand showed that in principle, it is possible to transfer heat to the interface region of a fusion bonded part with homogeneous heat distribution. On the other hand, the final disassembly was not possible due to the missing heat in the edge region of the patch. In theory, this can be avoided when using the implant for the welding process, as only the regions covered by the implant are heated and therefore melted. For subsequent tests and especially for the planned demonstration activities, two measures are taken to prevent the above mentioned observation: The separation layer is manufactured slightly bigger than the CFRP patch and additionally, the region around the implant is masked with high temperature tape.

6. Impact of Separation Layer on Mechanical Properties

Within the scope of the research project Defcodoor a comprehensive basic material characterization of the proposed thermoplastic composite material under different loading conditions was done on coupon level. One main focus of Disacop is to characterize “thermal bonded” adherents in terms of bond strength and fracture toughness. Therefore a series of preliminary single lap shear (SLS) and fracture mechanic tests are conducted without separation layer and different layups. These can then be compared to the samples with separation layer. The samples are “welded” by co-consolidation on a heated press. The main geometry and layup is sketched in Figure 18.

All prepared SLS specimens show a significant tape undulation primarily at the beginning of the overlap area (see Figure 19). This is due to the sample preparation method, which includes metal inserts. By substituting these by a CFRP, the undulation disappears (see D2). A substantial effect of this defect on the specimen failure and the shear strength values can be expected.

To identify the impact of the metal type of the wires on the mechanical properties, different samples with the different metal types are also conducted. No impact of the metal type could be identified.

At last, a test plan consisting of fracture mechanics and SLS without and with separation layer (in its final design) is conducted. Single lap shear specimens without separation layer exhibit higher values compared to single lap shear specimens with separation layer (Figure 20). However, for specimens with separation layer the final failure occurs more frequently at the end of the overlap area. With regard to the fracture mechanics tests without separation layer fiber bridging was observed which can be attributed to the fiber orientation in the delamination area. Specimens with separation layer did not fail under pure Mode I loading. A combination of Mode I and Mode II would be more accurate (Figure 21).

7. Demonstration Activity

The tested separation process on coupon level is transferred to demonstrator level. Therefore, a standard aerospace stiffened part is chosen, consisting of an omega stiffener and a flat panel (see Figure 23). Separation layers are placed between both stringer flanges. The bonding of both components is conducted with the co-consolidation process in a press with heated plates. The same production steps and parameters as developed for the coupon level samples are chosen.

Before conducting the actual disassembly trials, the same pretests as for the coupon level experiments are conducted. Then, the power input is connected to both implants as shunt circuit. The total resistance of the implants must therefore be added using equation 3. Again, the voltage is elevated stepwise after the temperature stagnates at a certain value. The levels and associated computed values are listed Table 4. An insulation layer (glass fabric web) is placed above the stringer flanges at approx. 175°C to propagate a homogenous temperature distribution on the one hand and reduce heat loss to the atmosphere on the other. The heating ramp is graphed in Figure 22.

The same effects as on coupon level was observed during the heating process on demonstrator level. The higher temperatures are reached in the center of the heated separation layer. This leads to a central delamination zone that propagates towards the edges region. The disassembly of the stringer is conducted approximately at 330°C, which also reflects the temperature at which the stringer is bonded. It is simply pulled off the skin (Figure 24).

Potential Impact:

The advantages of the use of thermoplastic materials for the production of lightweight aerospace structures has formerly fully been proven. Employing such matrix materials, storage with climate control as used for thermosets becomes needless and hence lowers the environmental impact. Also, 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. The scrap is reduced, which in addition can also be recycled and reprocessed in subsequent processes. Furthermore, consumables and auxiliary materials as needed for vacuum bagging of thermoset prepregs for autoclaving is not required leading to a considerable reduction of environmental and economic impact. The recyclability and reusability of manufactured parts by disassembly was investigated in the Disacop approach. Disacop not only showed that recycling single CFRP parts of an integral assembly is possible but also proved the practicability of a “new” assembly method. Current aerospace structures are mainly assembled using rivets, due to the major requirement for differential constructions (use of different materials, reparability, size limitations of single parts). By implementing new design rules within the development stage of novel composite structures, a high gain in economic value through production and service is expected; Single parts can be designed in a much more fiber fair way hence reducing their weight. The total mass of assemblies can also be reduced due to the missing rivets and bolts. An additional weight penalty caused by a separation layer or additional conductor material can therefore easily be cleared. The possibility of fusion welding TS and TP or even TS and TS structures by integrating a TP foil on the surface of the parts to be welded opens the way to an unlimited amount of possibilities and may substitute on a long term fiber damaging rivets and bolts.

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