ADVANCED SYSTEMS FOR THERMOPLASTIC COMPOSITE (TPC) REPAIRS

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The future of aeronautic factories is oriented to manufacture lighter and cost-effective components using greener materials like thermoplastic composites (TPCs). In this sense, given their increasing use, providing with cost-efficient repair methods for their complete integration in production is needed. The main objective of RETPAIR is the development of new high performance, flexible and cost-effective, automated and robotized net-shape technologies to rework and repair TPC parts to be integrated in the manufacturing line. The proposed solutions assure one-side accessibility and are supported by a digital-based methodology to assist the patch design and manufacturing. An induction welding solution for structural damages repair based on pre-manufactured patches will be developed, and two in-situ consolidation solutions for structural and non-structural applications based on automated and robotized layer-by-layer patch in-situ creation: an automated laying (AL) solution based on ATL/AFP technologies (automated tape laying/automated fibre placement) will be investigated for structural and large size repairs, and a 3D printing FFF-based (Fused Filament Fabrication) solution, using both continuous carbon fibre filaments and short fibre filaments will allow to tune patches' strength for different repair requirements (structural and cosmetic) to assure the thermal and mechanical quality of the repair, the critical process parameters (temperature, pressure, times/ rates) will be monitored and controlled.

RETPAIR will contribute to European aeronautical industry competitiveness by developing digital environments in aircraft manufacturing plants, which will allow for higher integration, shorter production cycles, energy efficiency improvement and environmental friendliness. Highly flexible automated and robotized processes will be possible in such digital framework, and such solutions will be extended to in-service MRO operations, contributing to develop the future aircraft smart and customized maintenance solutions for the benefit of European airlines and MROs.

1 INTRODUCTION

The future of aeronautic factories is oriented to manufacture lighter and cost-effective components using greener materials like thermoplastic composites (TPCs). In this sense, given their increasing use, providing with cost-efficient repair methods for their complete integration in production is needed. The main objective of RETPAIR project is the development of new high performance, flexible and cost-effective, automated, and robotized net-shape technologies to rework and repair TPC parts to be integrated in the manufacturing line [1].

The proposed solutions assure one-side accessibility and are supported by a digital-based methodology to assist the patch design and manufacturing. An induction welding solution for structural damages repair based on pre-manufactured patches was developed, and two in-situ consolidation solutions for structural and non-structural applications based on automated and robotized layer-by-layer patch in-situ creation: an automated laying (AL) solution based on ATL/AFP technologies (Automated Tape Laying/Automated Fibre Placement) were investigated for structural and large size repairs, and a

3D printing FFF-based (Fused Filament Fabrication) solution, using both continuous carbon fibre filaments and short fibre filaments allowed to tune patches' strength for different repair requirements (structural and cosmetic) to assure the thermal and mechanical quality of the repair, the critical process parameters (temperature, pressure, times/ rates) were monitored and controlled [2, 3].

RETPAIR will contribute to European aeronautical industry competitiveness by developing digital environments in aircraft manufacturing plants, which will allow for higher integration, shorter production cycles, energy efficiency improvement and environmental friendliness. Highly flexible automated and robotized processes were possible in such digital framework, and such solutions can be extended to in-service MRO operations, contributing to develop the future aircraft smart and customized maintenance solutions for the benefit of European airlines and MROs (in-service repair).

2 MATERIALS AND METHODS

2.1 Thermoplastic Composites Materials

Due to the huge range of repairs to accomplish and their different mechanical requirements, different materials were used. Aiming to study and develop repair technologies for novel carbon-fibre-reinforced thermoplastic material based on a low-melt polyaryl ether ketone polymer matrix (CF/LM-PAEK).

The key properties of this material are listed in Table 1 for prepreg tape, which was also used to manufacture the laminates provided by TORAY Advanced Composites [1].

Table 1: Material properties summary.

UD CF/LM PAEK	
Prepreg	Cetex TC 1225
Manufacturer	Toray Advanced Composites
Reinforcement	T700
Nominal resin content w_f (%)	34
Tape width (mm)	25.4
Melting temperature, T_m (°C)	305
Glass transition temperature, T_g (°C)	147

Different filaments from VITREX were also provided, with LM PAEK as matrix, without reinforcement and with 10, 15 and 20% of short carbon fibres. These filaments were used for non-structural repair by FFF, while for structural repair applications, the material selected was Suprem™ P 48%/ C10001.

2.2 Repair Technologies Overview

RETPAIR combines different materials and advanced manufacturing technologies in order to rework and repair TPC parts to be integrated in a future TPCs aircraft manufacturing line. The goal is to cover the different scenarios in terms of complexity, accessibility, and mechanical requirements among others. Therefore, different technologies were studied to cover as many scenarios as possible, as the scheme in Figure 1 show.

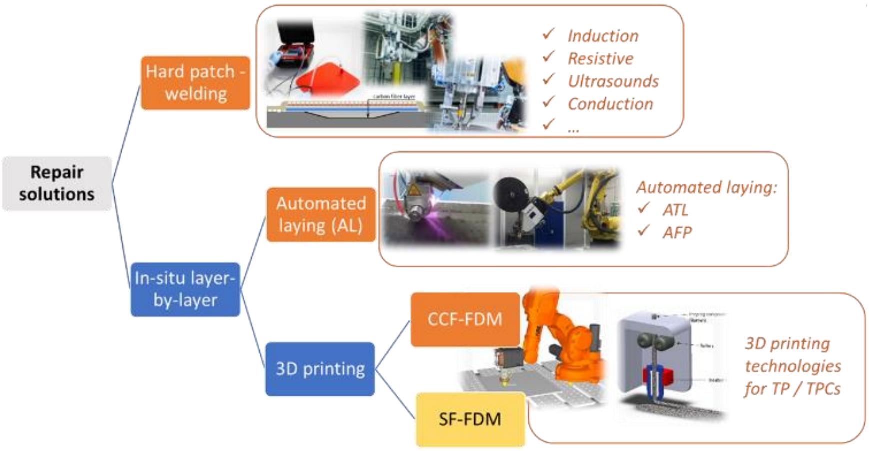

Figure 1: Technologies studied for TPCs repair.

2.3 Induction welding equipment

Induction welding repair was studied for structural applications, based on a flexible vacuum blanket, adaptable to different patch geometry and size, with high-speed induction heating device, and avoiding the use of metallic inserts into the joint. Msquare blanket, that is shown in Figure 2 was used for this concept, which stands out for its high flexibility in dimensions and curvatures. This solution for structural applications is based on create a weld between the part to be repaired and a pre- manufactured patch [1].

Figure 2: Heated blanket for induction welding in hard- patch repair.

2.4 ATL/AFP cell

In-situ consolidation based on AFP/ATL (Automated Fiber Placement/ Automated Tape Laying) were studied for in-situ structural repairs. For AFP/ATL technologies (Figure 3), the lay-up process was designed ad-hoc for each geometry and dimensions to be repaired. The manufacturing of these repair specimens was done in AIMEN, with a Combility AFP head installed in a six degree-of-freedom robot (FANUC IC-2000 Serie), using 25.4 mm (1”) tape as deposition width. As heating source, a diode laser from Laserline LDM with 6000 W maximum output was used to head the substrate and the incoming tape. The nip point temperature was measured by two pyrometers, and the pressure application system consists of a 90 mm diameter roller, covered by 5 mm thick silicone.

Figure 3: AFP cell at AIMEN facilities.

2.5 Fused Filament Fabrication (FFF) cell

REPTAIR implements FFF robotized technology for high-performance TPCs printing, using a non-commercially available, custom-made development as FFF head. Moreover, also a customized laser-based heating system was developed and integrated with the FFF process, to improve the interface and interlayer consolidation, as it is shown in Figure 4. For this purpose, different types of lasers were studied and Laserline LDM 400-150 was finally selected as the best one for this application.

Figure 4: FFF head to print continuous CF- filament.

The process was studied for continuous carbon fibre filament (CCF-filament) and short fibre filament (SF-filament) allowing tuned strength of the patches for different repair requirements, that can be structural or non-structural.

2.5 Digital-based patch repair design methodology

Damage digitising by robotized 3D scanning to obtain an accurate CAD that will be the basis for the repair design (PbP model and solid models). CT Engineering Group has developed a set of automatizations that allows the recognition of the type of damaged and the generation of the 3D models and Ply-by-Ply models of the repair patch. This 3D models and Ply-by-Ply models are the input needed to automatically generate AFP and FFF machine trajectories. This 3D models were used as an input to automatically generate robotic trajectories (path planning) to perform the repairs with the selected robotized repair solutions (FFF or AFP).

As it is shown in Figure 5, the scanning used was a Coordinate Measuring Machines, Handheld 3D scanners, Stationary 3D scanners and Automation in metrology with robotic arms. To obtain the scanned surface, a cloud of points is generated. In a 3D Cartesian coordinates system, a point is identified by three coordinates that, taken together, correlate to a precise point in space relative to a point of origin. X, Y and Z axes extend in two directions and the coordinates identify the distance of the point from the intersection of the axes (0) and the direction of divergence, expressed as + or -. Point clouds are generally produced by 3D scanners or by photogrammetry software, which measure many points on the external surfaces of objects around them.

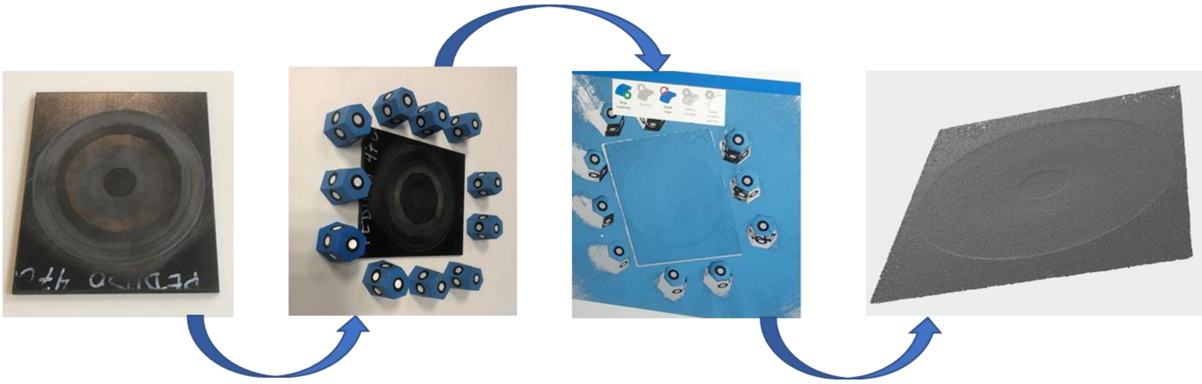

Figure 5: RETPAIR scanning process of machined damaged areas of composite plates.

In order to create the 3D model of the patch, it was developed a tool that generates a solid patch that matches the scanned surface. Intersections between scanned surface and selected planes lead to obtain several points with the highest z components which are used as support of a plane from what a cylinder is generated and then carved with the scanned surface (Boolean operation), obtaining a 3d model of the desired patch. After this a ply-by-ply 3D model is create, and later create the robotized trajectories, that will be used for repair defect with the automated manufacturing solutions proposed (AFP and FFF).

3 RESULTS ON COUPON AND ELEMENT LEVEL

3.1 Patch repair by induction welding

For the induction welding for patch repair, the first point of study was the heating element selection, and for that different solutions were studied, but the one that gave the best results was a graphite foils Sigraflex by SGL Carbon. This foil heats up way faster and reaches the highest temperatures compared to the other materials, which is the reason why it has been selected as the most feasible material for the welding process.

An optimized coil design is also very important to be able to heat the interface zone efficiently. If a coil is not adapted to the application, the target temperature may not be reached, or the temperature distribution may be uneven. Four different inductors were tested, having each one different coil geometry. It was observed that as higher the number of individual coils, the better the homogeneity of the temperature profile. Smaller spacing between the wires, also create smaller self-heating and a more homogeneous temperature distribution in the susceptor. Finally, it was also noted that higher capacitance in the oscillator results in higher heating because it automatically increases the oscillating circuit current. However, this is associated with higher losses in the form of self-heating.

For the induction welding test, the set-up created is shown in Figure 6, where two CF/LM PAEK Toray laminates where used, with one thermocouple just above the susceptor and other on the laminate without susceptor, as a reference.

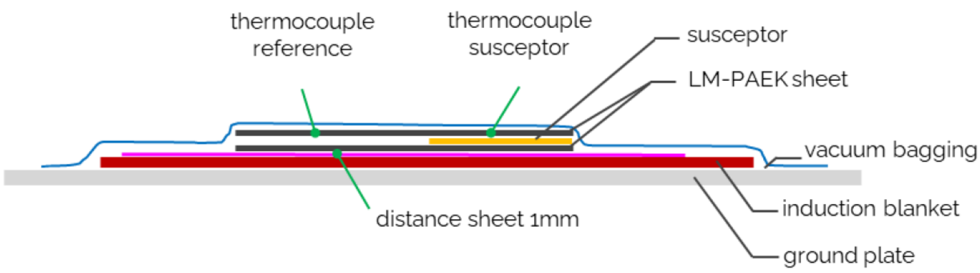

Figure 6: Induction welding trials set up.

On this trials, different heating element thickness were used and 0.0017 mm was the one with better results, since allow to achieve the required temperature for the welding, which is between 350- 380°C, as it is shown in Figure 7.

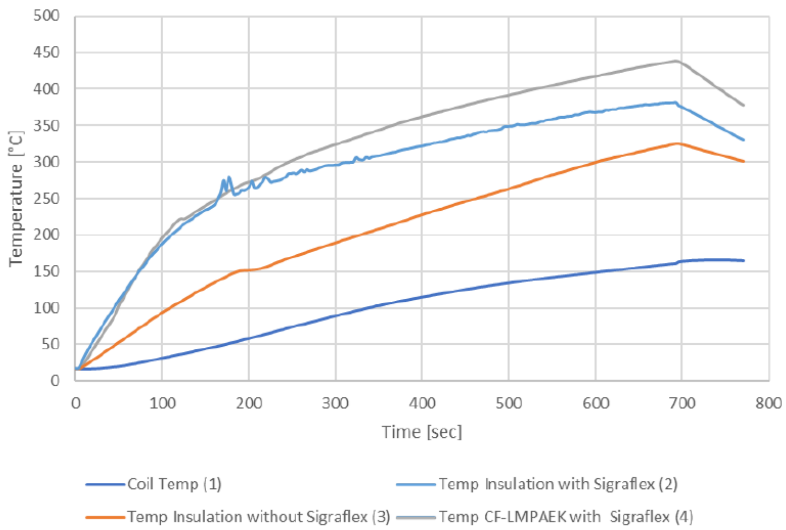

Figure 7: Welding test with 0.017mm graphite foil.

3.2 In -situ repair by AFP

This solution has been developed for structural repairs, in which a process window has been created as a crucial point, which allows not only to know what combination of parameters allows to achieve it, but also the relation between the change of these variables and the material mechanical performance.

Since this approach requires testing a large number of combinations of variables, it was decided to use a simplified mechanical test that allows the determination of the Single Lap Shear Strength (SLSS) with only 4 layers, and whose specimen configuration and details have been reported in other published studies on this subject. This method that allows to determine the interlaminar bonding strength was developed at the DLR Institute of Structures and Design in Stuttgart [3].

For AFP the efforts where focused on temperature and speed study, as key variables to be optimized and which values are crucial, since their combination compromise the temperature that material reaches and the time it is subjected to the heat source. As it is shown in Figure 8, the maximum SLSS is achieved at 400°C and around 250 mm/s, values that will be considered as the optimal.

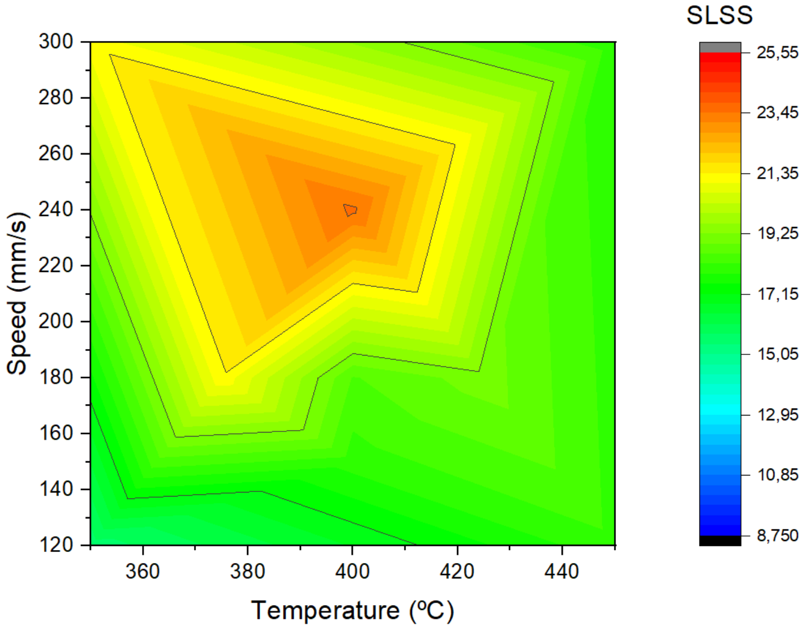

Figure 8: AFP process window for CF/LM PAEK tape from TORAY.

Regarding the relation between these variables, at low speeds, performance throughout the entire temperature range studied. Above180 mm/s, and between 360 and 420ºC, where the best values are achieved, having a drastic increase once the nip point temperature increase, while above 400ºC the properties decrease again. These results will be taken as a starting point for the scaling of the technology to a representative part, where geometry will become one of the biggest challenges.

3.3 In -situ repair by FFF

In the case of non-structural repair, this is done with low-loaded filament with short carbon fibres, or without reinforcements, both of then provided by VITREX. In this case, the laser is used exclusively to generate the bond between the cosmetic repair and the material or part to be repaired, not being necessary between the layers printed by FFF. This solution does not require high mechanical performance, as it is a cosmetic repair, focusing again on SLSS values. However, SLSS tests were carried out to determine the final performance that could be achieved with this solution.

These tests were carried out according to the AITM 0019 standard, with a thickness correction to have the same stiffness, since one part was a CF/LM PAEK laminate, and the other was manufactured by FFF, to create the joint between that will be the weakness point, as it is shown in Figure 9.

Figure 9: Single Lap Shear specimen manufactured by FFF.

The results shown that for LM PAEK filaments with 15 % short CF, SLSS achieve values of 14.97±1.62 MPa, whereas for the LM PAEK without reinforcement the average is 17.76±1.12 MPa. Although the polymer exhibits greater adhesion, both materials would be valid to achieve cosmetic repair performances using this technology.

As for the structural repair, as mentioned above, this is carried out with continuous CF/ PEKK filament supplied by Suprem™ . In this case the critical weak point was found to be the bond between layers and not only with the material to be repaired. Working on its improvement both scenarios through the implementation of a laser heating. As can be seen in the micrographs in Figure 10 without laser heating the void content is above the 7%, but once the laser heating is used to promote interlayer adhesion, the void content drops to 1%.

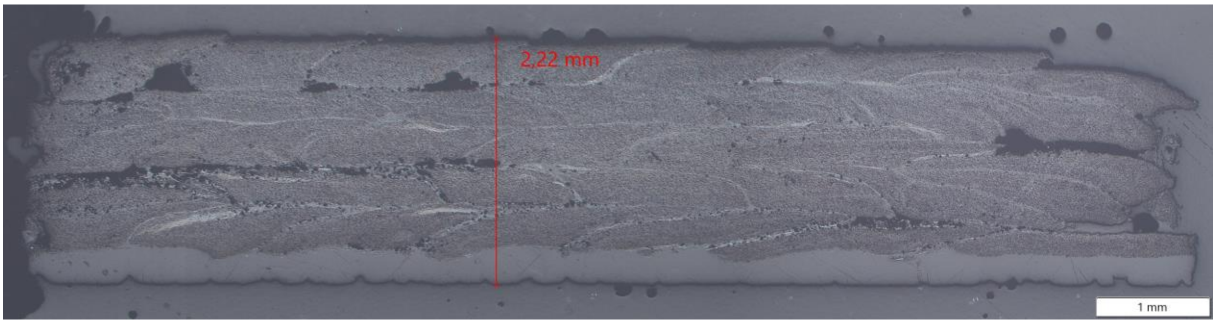

Figure 10. Continuous CF/PEKK coupon manufactured by FFF without laser.

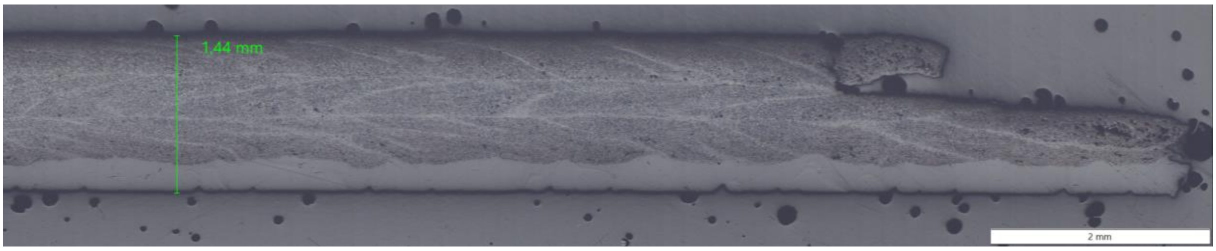

Figure 11. Continuous CF/PEKK coupon manufactured by FFF with laser.

These change in the use of this system means a doble the value achieved in Interlaminar Shear Strength from 40 MPa to 72 MPa according to ASTM D2344. These promising results will be complemented by further test campaigns to see what this technology can deliver on thermoplastic composites repairs.

5 CONCLUSIONS

The suitability of the thermoplastic composite's repairs, especially for CF/LM-PAEK was investigated in RETPAIR project. For this purpose, a range of technologies were studied, and its process parameters and process windows were studied and adjusted to maximize the material an repair performance.

Patch weld repair by induction proved to be a viable solution, although it needs to be further studied to meet the requirements of the aeronautic industry. However, its flexibility in terms of geometry and size makes it a very promising solution. In the study of this technology, an in all RETPAIR technologies, it has been observed that it is not only important to optimise and study parameters, but the efforts also have to be on optimising and improving heads and set -up to meet the requirements.

As for in-situ remediation solutions, in the case of the AFP the results are promising, and the rest focus on scalability and the ability to cope with the variability of situations and re-occurrences. In terms of FFF, the remainder meet the specified requirements, with the key point being the laser heating of the joints, generating the bond between the new material and the part to be repaired.

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DISCLAIMER

The results, opinions, conclusions, etc. presented in this work are those of the autor(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

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