TOD – Thermoplastics on Doors: Development of full scale innovative composites doors, surrounds and sub-structure for Regional Aircraft Fuselage barrel on-ground demonstrators. Innovative overall manufacturing and assembly approach and preliminary results obtained at the early stage of the project.

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Abstract. Thermoplastic composites can reduce cost and save weight in airplane structures. Currently on the market there is no thermoplastic door available for commercial aircraft. The overall goal of TOD project is to demonstrate and validate the manufacturing process of thermoplastic door components, induction welding assembly process, additive manufacturing and metallic parts of door mechanism, metallic and thermoset parts of surrounding structure of the passenger and service door of an aircraft. The activities of TOD project have received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement number 821192.

1. Introduction

The use of composite materials in aeronautics has progressively increased over the last decade bringing a step change to the way aircrafts are designed and built, mainly with a drive for light weighting. The use of composites has brought the possibility to integrate components and functionalities within the aircraft architecture. However, the use of thermoplastic composites, up to now have come at a price in terms of manufacturing recurring and non-recurring costs, as well as long lead times and relatively modest production output. An emerging tendency, already confirmed in other industrial sectors is to move from thermoset composites, which have required long curing cycles often in large and expensive autoclaves, to thermoplastics with improved mechanical properties and fast production cycles. Furthermore, thermoplastics can be heated and reheated locally thus opening the door to a multitude of opportunities for the industrial uptake of leaner and more automated manufacturing processes. Thermoplastics also has an added advantage of plastics recyclability for other applications at the end of life, reducing carbon emissions and its environmental footprint.

It is in this context that the Clean Sky 2 programme seeks to develop a full scale representative aero structure demonstrator which will unite many advantages of this move towards thermoplastics for future
aircraft programmes. The Thermoplastics on Doors (TOD) project contributes to the global objectives of Clean Sky 2 (CS2). More precisely, the impact of the activities performed in the project is related with the following:

- Use of thermoplastic materials and the development of out-of-autoclave manufacturing processes, which are drivers of manufacturing cost reduction and of manufacturing rate increase. These technologies are projected to save 75% energy usage over standard autoclave processing.
- Minimum 15% weight reduction on structural components such as doors. Recent thermoplastic composite studies already demonstrated the substantial weight reduction that can be obtained by combining automated production processes and thermoplastic materials.
- Reduction of recurrent cost considering the conception of an adaptive and smart manufacturing equipment to increase production flexibility and decrease full line tools cost.
- Reduction of waste and scrap by 10% by working directly at the defect root cause with a multidisciplinary approach through the sensors for in-line monitoring directly connected to the manufacturing equipment.
- Significant eco-impact reduction through the component’s and aircraft’s life-cycle: the reduction of energy usage during manufacturing of thermoplastics, combined with the light-weighted parts will contribute to the reduction of CO2 emissions during both product manufacture and operation.
- TOD addresses a key issue of extensive use of out-of-autoclave composite with aerospace relevance. The R&D work will generate new scientific knowledge as well as new technologies, and thus strengthen the European positions in this field.

2. Process Setup

The selection of the material and of the manufacturing process suitable for the door, were based on information received by the end user of the project: Leonardo S.p.A. The definition of the materials and of the manufacturing process has taken place for each component of the door namely:

- Carbon Fibre Reinforced Thermoplastic (CFRTP) sheet thermoforming
- Thermosetting autoclave curing
- Mechanical milling
- Additive manufacturing of metallic part

The assembly strategy of the individual parts has also been identified which is:

- Joining metallic and composite (thermosetting and thermoforming) parts with rivets
- Use of induction welding for the joining of the thermoplastic beam and skin

The thermoforming process will be used to manufacture the outer skin and inner skin as well as the horizontal and vertical beam which are parts of the Forward (FWD) Door Plug show in figure 1.

Figure 1. Outer skin and inner skin (grey colour) and horizontal and vertical beam (yellow colour).
The door pan (door edge shown in figure 2a) is the most critical part in terms of the fabrication process. The door pan will be manufactured in thermoset carbon fibre reinforced polymer (CFRP) (IMS977-2) using an autoclave process. Moreover, door surround intercostals shown in figure 2b, will be manufactured with the same process.

![Figure 2. (a) Door edge and (b) door surround intercostals.](image)

Metallic components for the door handles, lock mechanism as well as the door surrounding structural fittings, presented in figure 3, will be manufactured by machining milling or additive manufacturing depending on the design and material.

![Figure 3. Metallic components for the door handles, lock mechanisms and door surrounding structural fittings.](image)

2.1. Setup of TOD individual process and validation
At a preliminary stage, a compliance matrix defined in this task including relative pass/fail criteria has been produced and shared with the Topic Manager (TM). This matrix allowed setup of the induction welding process by the project partner CETMA based on some mechanical test results of the welded parts, to validate the process parameters.

Project partner DEMA developed numerical simulations with the MSC Software suite to finalize and optimize the thermoforming process and tool design. The numerical simulation assisted to define the behaviour and geometric details of the silicone pad to be used in the tool to grant the right compression during the thermoforming process. The silicone material was selected to be high temperature resistant (up to 320°C intermittent, max operating temperature 300°C). The usual operating temperature is 180°C to be reached on the heated mould as per the thermoforming cycle for polyphenylene sulfide (PPS) preconsolidated sheets shown in figure 4.

![Figure 4. Thermoforming cycle for PPS preconsolidated sheets.](image)

Moreover, a thermostructural analysis of the mould during the hot phase of the process has been carried out to validate the heating system power management and the tool behaviour as it is shown in figure 5.
Figure 5. Thermostructural analysis of the mould.

Some preliminary tests have been made on a simplified geometry to validate the process parameters. The simplified geometry is shown in figure 6.

Figure 6. Simplified geometry of samples where preliminary tests were performed to validate process parameters.

2.2. Assembly jig design, manufacturing and manufacturing of welding tool

Project partner CETMA has defined the assembly plan document in order to establish the correct welding sequence avoiding interference. In addition, the door configuration on the tool has also been defined; in fact, the door model provided by the TM has been analysed to establish the best strategy for the welding of the beams to skin. It was decided to weld the door with the outer skin placed on the tool. This orientation allows good support under the welding interface to oppose the applied force.

The first phase is to join the horizontal beams to the outer skin as shown in figure 7.

Figure 7. Orientation of the door for the welding of the beams to the outer skin.

After the horizontal beams are attached, it is possible to weld the other beams to the skin as shown in figure 8. The detailed welding sequence for the beams will be defined after the design of the tool.

Figure 8. Orientation of the door for the welding of the beams to the outer skin.

The welding between the inner skin and the beam will be the last step (phase 3) as it is shown in figure 9. Each beam will be welded with the inner skin from the opening near the beam. The lateral access is necessary to apply pressure during the process with a couple of rollers.
Figure 9. Orientation of the door for the welding of the beams to the inner skin.

Pressure will be applied with a cantilever roller. As shown in figure 10, the outer skin is placed on the tool and the roller can apply pressure without deforming the beam. The width of the upper face of the beam should be less than 50 mm.

Figure 10. External door skin welding strategy.

Figure 11 illustrates a concept design of the head configuration adopted for the welding of the beams to the outer skin.

Figure 11. Phase 1-2 Welding strategy (outer skin).

The welding of the inner skin requires a different strategy because the pressure applied by the roller should be balanced. The stiffness of the beams is not enough to support the material during the heating. The heated part of the beam should be supported to have a good result in terms of deformation of the structure. The support will be realized with a second roller, which applies a local pressure to stabilize the welding area as it is shown in figure 12.

Figure 12. Phase three Welding strategy (inner skin).
Moreover, preliminary tests of induction welding process on polyphenylene sulphide (PPS) /carbon laminates with an upper layer of glass fabric have been performed in order to evaluate the mechanical properties of the joints manufactured, in terms of single lap shear strength (SLSS) and evaluate the strategy to optimize mechanical properties of welded joints.

2.3. Laser Powder Bed and Linear Friction Welding for additive manufacturing of complex parts

Laser Powder Bed Fusion (BPF-LB) and Linear Friction Welding (LFW) are both emerging technologies for the manufacturing of titanium and aluminium alloy aerospace components. Never before have the two technologies been combined to produce optimised components. LPB alone produces optimised components with a rate seldom adequate for commercial aero throughput. Large components require expensive LPB investments. LFW produces welded components of very high integrity within seconds, yet output material is often not as close to shape as LPB.

To improve process efficiency, PBF-LB will leverage linear friction welding (LFW) technology to join multiple PBF-LB parts. The hybrid PBF-LB – LFW manufacturing process is expected to improve production lead time by at least 30%, reduce 50% of waste material, and promote environmental sustainability as less powder feedstock is exposed to the laser melting process enabling efficient powder recycling. Three components will be manufactured using LPB only, three using LFW only, and two will combine LPB and LFW processes together and showcase the benefits of this combination, see Figure 13.

![Figure 13](image_url)

Figure 13. List of components selected for additive manufacturing by L-PBF and LFW or combined L-PBF and LFW.

3. Tool design and fabrication for process validation

A deep and continuous analysis of the CAD models provided by the TM was made to highlight the potential improvements of the design in order to improve the manufacturing. The number of tools reduced as much as possible, by categorizing parts based on the type of tool that is needed to manufacture them and by applying appropriate modifications. Based on numerical simulation, tools were designed with appropriate silicone pad thickness and spring stiffness to avoid wrinkles on the heated material blank. This is shown in figure 14.
Figure 14. Tools design with appropriate silicone pad thickness and spring stiffness to avoid wrinkles.

Regarding the metallic parts and thermoset composite parts, project partner DEMA used the common and deeply acquired skills about manufacturing and managing of supply chain, highly qualified on serial production.

4. Non-destructive inspection

The different components which are going to be manufactured in the TOD project were chosen to be inspected in terms of their quality through two non-destructive inspection techniques namely:

- Computed Tomography (CT)
- Ultrasonic Inspection

4.1. Computed Tomography

Computed Tomography (CT) is a widely established technique, referring to the cross-sectional imaging of an object from either transmission or reflection data collected by illuminating the object from many different directions. X-ray CT is also widely used for volumetric inspection in industrial sectors. It provides the user with high-resolution cross-sectional density data on the internal volume of the object, and has become a workhorse in the field of industrial Non-Destructive Testing (NDT). CT is used across different sectors and numerous component materials and it is currently used in multi-material composites in the civil [1] and aerospace [2] industries, additive manufacturing [3] and plastics [4], amongst others.

The NSI X5000 that TWI has, will be used to carry out the inspection of the clips and its main characteristics are the following:

- A micro-focus X-ray source based on cone beam geometry. Minimum focal spot size of 5μm, a maximum tube potential of 240kV, and maximum tube current of 3mA
- A 7-axis rotating manipulator capable of handling up to 25kg load and geometric magnification up to 160x
- A Varek XPD 1611 AP 3 X-ray flat panel detector. The detector has a field of view of approximately 409.6mm x 409.6mm. It has a 16 bit analogue-to-digital converter (ADC) with 4096x4096 active pixels and 100μm pixel size

For repeatable inspection of the components, different 3D printed fixtures will be designed and manufactured. The fixtures are primarily created in order to stack multiple components and scan them in a single CT scan. A low density material will be used to manufacture the 3D printed fixtures in order to avoid interference to the radiographs.

4.2. Ultrasonic Inspection

Ultrasonic Testing (UT) of metals and alloys is a common practice within industry. Ultrasonic waves employed in NDT have frequencies between 100kHz and 10MHz. Higher frequencies provide a better spatial resolution, but are also more attenuated due to microstructure interactions in materials. Ultrasonic testing of composite materials is more difficult due to the higher attenuation of sound caused by resin/laminate boundaries and scattering due to the reinforcing fibres. Furthermore the anisotropic nature of composites means that the speed of sound varies with fibre orientation. For this reason, zero-degree longitudinal beam setups are preferred for composite inspection.
Thermoplastic components in TOD will be inspected ultrasonically to check for defects such as delaminations (in composites), porosity and inclusions. Smaller components will be inspected manually using state-of-the-art equipment while larger components will be automatically inspected using a robotic inspection facility at TWI Wales.

5. Industrial cost evaluation
With the use of the industrial cost evaluation, the economic performance of a thermoplastic door compared to the equivalent conventional aluminium door using life cycle costing (LCC) analysis will be performed. The overall cost estimating process can commence as shown in figure 15.

The system boundary that is defined is cradle to grave. The life cycle is processed in three major phases: production phase, Operating & Maintenance (O&M) phase and End of Life (EoL) phase. The bottom-up method has been selected for developing the cost estimation model. This method needs to develop a Cost Breakdown Structure (CBS). The CBS established should comply with the Mutually Exclusive and Collectively Exhaustive (MECE) principle [5], which means elements in the CBS should have ‘no overlaps’ and ‘no gaps’. Three cost elements are identified in the first level which are: production cost, O&M cost and EoL cost.

6. Conclusion
The innovative approach in manufacturing aerostructures using composite materials with out-of-autoclave process in order to reduce CO$_2$ and production costs is promising and feasible, even if some details in the process are still to be fully automated and controlled. The welding capability of thermoplastic material, the additive manufacturing process for complex mechanism parts and the high rate production of thermoforming processes are the stronger potential features that can help to reduce weight and time to manufacture a complex aeronautical assembly, such as a passenger door. The project will demonstrate the high potentiality as well as the feature to be improved to make the selected process and technologies ready and competitive for industrial production.

7. References
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