Publishable summary

1. Objectives

The main goal of PUL-AERO is the development of a material state based controlled pultrusion process for the manufacturing of curved and partially cured stringers that comply with the stringent specifications of the aerospace industry and offer significant savings in production costs. PUL-AERO will design and build a pultrusion line for the production of linear and curved composite stringers for the aerospace industry.
The main disadvantages of the pultrusion process is the difficulty in producing curved parts and the difficulty in handling aerospace grade epoxy resins, mainly due to the relevant stringent requirements regarding exposure to elevated temperatures and their slow cure (which results in slow pultrusion line speed).
PUL-AERO aims to resolve the technical problems of pultrusion when it comes to production of curved aerospace composites parts and take advantage of the benefits of the process. The main benefits of the pultrusion process are the possibility for continuous production, the repeatability of the process and the low production costs (calculated as cost per meter of composite produced).
PUL-AERO will create production processes and technologies with a focus on improved cost efficiency while taking into account the environmental related aspects. The pultrusion line will be split in two stages, adding flexibility to the manufacturing of stringers with different curvatures and improving the cost effectiveness of the production. The whole process will be driven and monitored by a process monitoring and QA system that will provide real time information and control of the line.

The main objectives of the PUL-AERO project are:

- The accurate modelling of the thermoset resin properties in order to design the pultrusion process based on the values of material properties.
- The Prescription of the temperature profiles in the resin bath, stage 1 dies and stage 2 tools (die or LCM tool) based on modelling and simulation of the line. Calculation of the fibres undulation in the curved stringer and provide technical solutions for minimising the effect on the stringer properties
- The correlation of the thermoset resin viscosity to dielectric measurements in order to monitor the resin condition in the resin injection system.
- The development of special dies and pulling mechanisms with curved contours in order to curve the pultruded profiles according to specifications.
- The development or adaptation of methods for in situ Quality Assessment in the pultrusion line
- The design and implementation of a pultrusion process that allows resin injection with a benefit of approximately 60% in resin wastage
- The development and implementation of a pultrusion process that allows the continuous production of curved stringers of aerospace quality with a cost benefit of 20% in comparison to current routes for the incorporation of stiffeners
- The quantification of the keying opportunities offered by the integration of semi-cured stringers in a liquid moulding assembly and the associated mechanical performance of the interface with a cost benefit of 30% associated with the elimination of the necessity for bonding

2. Expected final results / potential impact

The scope of the PUL-AERO project is the development of an advanced pultrusion line with capability to produce curved aerospace composites while taking full advantage of the benefits of the process. The main benefits of the pultrusion process are the possibility for continuous production, the repeatability of the process and the low production costs (calculated as cost per meter of composite produced). The proposed developments will then lead to the optimal, cost-effective and reliable processing of curved CFRPs with aerospace quality standards. The project addresses all variable manufacturing parameters (materials, process conditions, equipment, simulation models, sensors, control strategies and quality/inspection issues) for pultrusion processing of composite materials before integrating the components to a functional and qualified production line. More specifically the project output consists of:

• A novel configuration of the pultrusion processing of composites through the separation of process in two stages: one with linear heated dies for curing and one with curved post forming dies for shaping;
• An alternative pultrusion process route involving production of a semi-solid intermediate product where the semi-cured stringers will be integrated with the dry reinforcement of the skin;
• The resin recirculation system for pultrusion processing with full design, construction and operation guidelines including sensors and actuators for the supply of standard quality liquid resin towards full wetting of the fibres before they enter in the heated die,
• A functional and integrated process monitoring and QA system based on sensors positioned in the resin bath and die exit and on-line inspection system for the detection of structural faults in the processed materials;
• A complete signature of the process accompanying the produced part from the supervisory control system comprising of temperature controllers output, sensor signals from liquid and polymerised resin, on-line inspection data and pultrusion line operation data (line speed and pull force) giving rise to reliable and eco-efficient processing of composite structures;
• The manufacturing of curved aerospace grade components in a continuous process with improved cost efficiency and known quality.
To achieve the objective of increasing the competitiveness in aerospace manufacturing industry, the developments within the PUL-AERO project aim to develop a novel composite materials processing practice in order to produce lighter, lower cost and higher quality (thus more safe) structural parts. This improvement will help satisfy the potential of composite manufacturing methods, which is currently limited because of a lack of automation, the use of very high capital cost equipment and the requirement for highly skilled workers. As a consequence, the development of new and cost reducing processes and practices is of great importance for the increase of competitiveness in the market. Thus the activities of the PUL-AERO research project are very much in line with the EU's air transport policy and its objectives.

3. Work performed

The first activities of the project focused on the definition of key specifications of the technology development and in particular the design of stringer, the selection of resin and fabric for the stringer, the modelling and simulation requirements, the design of the pultrusion line and the relevant processing windows and finally the requirements on the resin injection system and the monitoring and Quality Assessment (QA) systems.

In the modelling and simulation section, the pre-former (linear profile - Stage 1) modelling of the pultrusion process was developed. The model solution was carried in a commercial simulation platform where all relevant sub-models were coded. The energy balance at Stage 1 and Stage 2 (curved profile) of the pultrusion line has been performed. This model has been coupled with the pre-former model to account for the effects of advection and heat transfer. Material models were incorporated through subroutines. Execution of both models demonstrates the effectiveness of the strategy and verified their operation.
The modelling of the distortion in the pultrusion process is crucial for the design of process for curved stringers. The steady state version of this problem, which is relevant for both stages in the pultrusion dies, required only weak coupling with the solution of the heat transfer/cure model.
The material characterisation campaign in the project started after the selection of the resin system for the pultrusion process. It included cure kinetics characterisation, viscosity measurements for chemorheological model, thermal conductivity and CTE measurements, T_g and c_p mapping of the material system, mechanical properties characterisation, mechanical properties measurement at the interface of the co-cured parts and permeability measurements.

During the pultrsuion line implementation work, the manufacturing of the various parts (die, manifold, post-former) for the construction of the line was made.
The resin injection system was constructed. The system comprises of control box, tanks for resin and hardener, pumps, mixing head, mixing tank and connecting tubes. It has been designed to serve two injection strategies: direct injection to the manifold at very low flow rate or use of an intermediate mixing tank for larger quantities of mixed resin. The control box incorporates a touch screen with the PLC software. Two dielectric sensors were incorporated in the manifold and the mixing tank for on-line measurement of resin viscosity. The dielectric sensors and the respective measurement system were integrated to the resin injection system.
The on-line QA system was constructed. The system comprises of: ultrasound sensors, water bath, X- and Y-axis motors, signal generation and response digitisation unit, motion control unit, profile length measurement unit, computing system and commanding software. This software includes formulation of A-scans per axis, gates configuration for determination of thresholds and peaks and organisation of processed data to C-scan representation.
The pultrusion line, as a set-up for the installation of systems, was prepared through fabric feeding system, manifold, pultrusion die, postformer for straight profile and line pullers.
The resin injection system was delivered to the pultrusion line for assembly and connections. Selected resin and hardener were loaded to the tanks and the injection line was connected to the manifold on the die. A trial injection was performed with controlled flow rate (pressure was monitored), whereas the viscosity was measured. The die heating system was set to a selected temperature to produce undercured profiles. The system functionality was verified and the tests showed the achievement of the desired degree of cure.
The QA system was delivered to the pultrusion line for assembly and connections. It was positioned at a specifically designed frame on wheels and was aligned to the pultrusion line right after the line pullers. The line was set to operation and a series of profile lengths were scanned. The system functionality during the trial was assessed and the first indications were satisfactory.