A challenge for next A/C Fuselage: New Hybrid Thermoplastic Material, Testing activities definition

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Abstract. A new hybrid thermoplastic concept patented by Leonardo allows to obtain a material that can be processed at temperature lower than usual thermoplastic resin processing temperature without any problem concerning the crystallinity. The high-performing hybrid material based on commercial PEEK-Carbon Fiber prepreg with the addition of amorphous (PEI) films overcomes the disadvantage of high/narrow processing parameters window and allows to take full advantage of prepreg material automated lamination, essential to make thermoplastic parts economically convenient respect to thermoset ones. Thus the new concept answers to the needs to have reduced weight and consequently reduced fuel consumptions and emissions on aircraft, as well as reduced manufacturing and operational costs. The preliminary tests performed on the new hybrid material showed good results, the goal of this work is to define an extensive mechanical test campaign to elaborate on material structural properties and validate static and dynamic behaviour of structural parts for next A/C fuselage.

1 Introduction

Stratview Research has released a new research report, about Trend, Forecast, Competitive Analysis, and Growth Opportunity for Aerospace & Defence Thermoplastic Composites Market by Aircraft Type, by Resin Type, by Application Type, by Fiber Type, by Process Type, and by Region.

This report studies the global aerospace & defence thermoplastic composites market over the trend period 2012 to 2017 and the forecast period of 2018 to 2023. The global aerospace & defence thermoplastic composites market is likely to offer significant opportunities over the next five years to reach an estimated value of US$ 636 million in 2023.

Several factors are bolstering the growth: increasing commercial and regional aircraft deliveries, increasing demand for advanced composites in the structural applications of aircraft, increasing production rates of composites-rich aircraft (B787 and A350 XWB), increasing demand for thermoplastic composites to fabricate structural and interior parts, and superior benefits of thermoplastic composites including recyclability and reduction in parts count. [1]

In fact, there is a sort of roadmap in place for development of thermoplastic composites in Europe that involves almost every major European aero structures supplier. They are working for an impressive percentage of recently completed, large-scale aircraft demonstration projects. Someone pursued a two-step approach that means material hand lamination followed by consolidation face, someone else has favored a one-step process using In Situ Consolidation (ISC) where automated material lamination and its consolidation take place simultaneously.

Thermoplastic composites processing temperatures are much higher than thermosets; closer to 400°C vs. 180°C for primary structures. Instead, their cycle times are much shorter because thermoplastic resins require only cooling rather than crosslinking. Thermoplastics also are inherently tough, and they do not need special formulation to provide the fatigue-resistance necessary for aircraft applications. Further, because thermoplastics can be reheated and reformed, they can be welded, contributing to a cost-saving, fastener-free assembly option.

Finally, considering that multi functionality and sustainability are deemed necessary for next-generation aircraft, thermoplastic composites have to be considered a good choice.

2 Thermoplastics Pros and Cons

There is a wide range of thermoplastic materials now used in advanced components for the aerospace industry. Even if many of these thermoplastic polymers have a tensile strength comparable with common thermosetting resins, they generally exhibit superior impact toughness, fire/smoke/toxicity (FST) performance and, with the exception of PEIs, chemical resistance. Thermoplastics also exhibit a near-infinite shelf life at room temperature that compares favourably to a shelf life of fewer than six months in refrigerated storage for typical pre-preg thermoset materials. Although the raw material costs of aerospace thermoplastics can, in some cases, be higher than competing thermosets, the cost of the finished

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component can be lower due to reduced handling, processing and assembly costs. Thermoplastics offer the option to fuse or weld together already molded subcomponents, which can drastically reduce assembly weight and stress concentrations by eliminating fasteners.

The advantages of thermoplastics over conventional thermoset resins (eg: an epoxy) are summarised below [2].
Since thermoplastic resins do not cure via a chemical reaction, they have an unlimited shelf life and do not have to be stored in freezers. The thermoplastic is already “cured” and it is formed into the final net shape as required using heat and pressure. This effectively infinite shelf life is a big advantage and avoids problems with material age and storage.
Many types of manufacturing methods are available for thermoplastics. These include compression moulding, pultrusion, filament winding and thermoforming. Prepreg material made from reinforcing fibres pre-impregnated with thermoplastic resin can also be used to build parts using a two-step or one-step approach for consolidation. The majority of processing time is consumed in melting the resin and compacting the part, so the overall cycle is considerably shorter compared to thermoset; recurring costs can be also reduced considering that joining thermoplastic parts can be a simple process since they can be welded together using local heating. In addition automated procedures may be used for the manufacture of thermoplastics and this can reduce part costs substantially, offsetting the high raw-material costs.
In some processes the only limiting factors in production are how quickly the material can be cooled to allow the correct level of crystallinity.
Thermoplastic composites have been shown to have impact resistance values similar to common aerospace toughened thermosets . However, damage is easier to detect on a thermoplastic composite since the surface permanently deforms to form a visible physical depression.
At temperatures above the melting point the resin flows and can be re-formed into another shape. This attractive aspect of thermoplastics allows scrap materials to be easily recycled and parts to be potentially repaired.
The water absorption level for many thermoplastic resins is very low. PEEK and PPS resins take up moisture to about the 0.1-0.2% level under hot and humid conditions. This compares with about 3% or more for many epoxy resins. Moisture uptake results in a decrease in mechanical properties such as stiffness. Moisture uptake is also negative in bonded repair procedures since moisture is a source of voids in the repair bondline. Thus thermoplastic matrix composites exhibit excellent mechanical performance in hot/wet environments.
Both PEEK and PPS resins exhibit excellent chemical resistance to both jet fuel and hydraulic fluids and this makes thermoplastic materials ideal for many aviation operating environments. In general, crystalline morphologies have a greater resistance to chemical attack.

The disadvantages of thermoplastics over conventional thermoset resins (eg: an epoxy) are summarised below [2].
The temperatures required to form thermoplastics are far greater than for thermosets. Typical processing temperatures for PEEK are 380°C and higher.
Conventional manufacturing equipment such as autoclaves may not be able to reach these temperatures and in any case there is the need of expensive inert gas and different lay-up consumable materials (such as bagging films and sealant tapes.
Depending on the manufacturing process, high pressures can be required to form thermoplastics. Thermoplastics melt at high temperature but still remain fairly viscous which can make it difficult for the resin to flow and the composite part to consolidate.
The cost of thermoplastic resins is currently high but is expected to decrease over time. The cost of thermoplastic resin prepregs can be up to four times that of comparable epoxy prepregs. Overall cost reductions can be made since shorter processing times are required and the fact that many parts can be produced using automated equipments. Repair procedures for thermoplastic composites have not yet fully matured and have not yet become a certified process during aircraft service.

3 Relevant Research work on new hybrid thermoplastic composite material

Among thermoplastic materials, the PEEK-Carbon Fiber prepreg is widely used for commercial applications with more then 10-years history in aircraft industries and very well-defined process parameters. In fact, properties of the structures realized with this material are similar to the ones of the best class of thermosets, with some specific properties (e.g. toughness and impact resistance) even better (see fig.1).

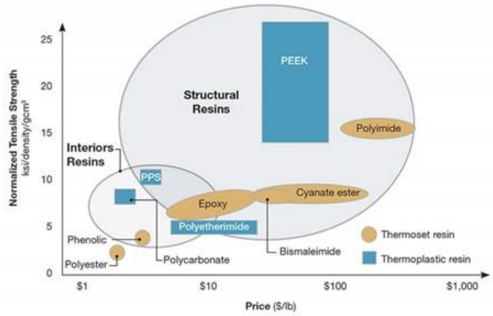

Fig. 1. Normalized Tensile Strength vs. Raw Material Price for Aerospace Thermoset and Thermoplastic polymers [5]

In order to be used for aircraft structures, PEEK-Carbon Fiber prepregs need to be processed above the melting temperature of the crystalline phase of PEEK (at least 380°C). Furthermore, the cooling rate must be kept

inside a fixed processing window because a too fast cooling induces a decrease of crystallinity content compared with the standard one [3]. In particular for PEEK the process window (385-390°C) is narrower than the other members of the polyaryletherketone (PAEK) family (often referred to as polyketones), so the one-step consolidation process is quite hard to be achieved.
To overcome the disadvantage of high/narrow processing temperature and take full advantage of prepreg material automated lamination, essential to make thermoplastic parts economically convenient respect to thermoset ones, Leonardo Aircraft patented [4] a new tape concept based on the addition of amorphous PEI films to carbon fiber PEEK prepreg tape, in order to have an hybrid composite thermoplastic material composed by PEEK having the desired crystallinity level sandwiched between amorphous films (see fig. 2). The adhesion between PEEK and PEI in the hybrid material is very good thanks to PEEK and PEI deep compatibility and their attitude to produce blends when mixed.

Fig. 2. A sketch of the Leonardo patented hybrid thermoplastic concept

This new material have several advantages. It can be processed at a temperature lower than the usual PEEK processing temperature, just above the Tg of PEI (about 210°C) without any problem concerning the PEEK crystallinity, which isn't affected by the process, because melting temperature of PEEK is much higher.
For this reason, the new functionalized PEEK can be easily and cheaply processed via ISC without requiring any other additional consolidation step in autoclave because during layup only PEI films need to be melted and consolidated together. This will avoid the use of autoclave and will allow to manufacture complex and big aerostructures by AFP (Automated Fiber Placement) process.
In order to verify the feasibility of Leonardo concept, a sandwich with a PEEK matrix carbon prepreg between two amorphous PEI films has been realized. The coupling process has been performed at controlled temperature and cooling rate, in order to obtain the right PEEK crystallinity (in terms of both amount and morphology). A picture of the hybrid material is shown in fig 3. The good integration of the two materials (PEEK and PEI) is obtained through a transition zone with different percentages of the two materials, progressively ranging from 100-0% to 0-100%, which is possible due to the capability of the two resins to make blends.
In particular, the materials used to realize this hybrid stack-up are:

- 1 layer of AS-4 carbon/PEEK tape
- 2 layers of PEI films

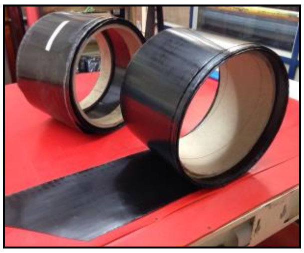

Fig. 3. Manufactured hybrid thermoplastic material

Once the hybrid material has been available, lamination tests have been performed and the following prototype panels have been manufactured:

- 2 panels, 600x250mm, [45,-45,0,-45,45]
- 2 panels, 600x250mm, [0,45,90,-45,-45,90,45,0]

The panels have been laminated per hand lay up with no remarkable manufacturing issues and consolidated in autoclave according to the consolidation cycle reported in figure 4. Overall cycle time was shorter if compared to cure cycle of thermosetting materials and temperature was almost 50% lower than the usual PEEK process temperature.

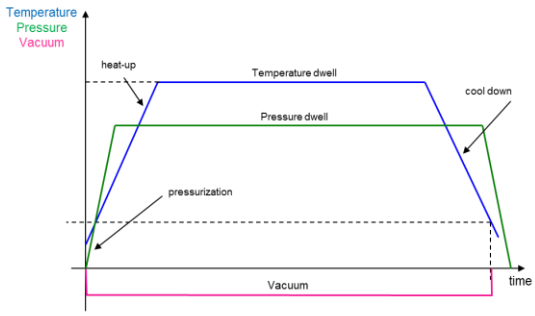

Fig. 4. Autoclave consolidation cycle

The panels have been visually inspected without any visual defect detectable and then trimmed to acquire specimens for micrographic analysis.
Optical microscopies of prototype panels have been performed (fig. 5) and no voids have been localized, confirming that a good consolidation has been achieved.

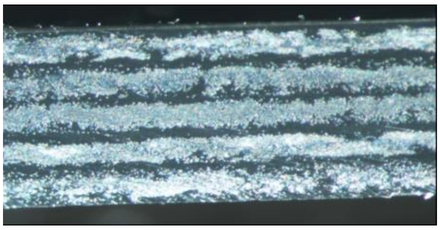

Fig. 5. Microscopy picture of the laminate section manufactured with the new thermoplastic material

Finally mechanical tests have been performed on the panels in order to verify their hail impact resistance /see fig.6). The scope of this activity was to confirm the potential application of the new hybrid thermoplastic material for the realization of regional fuselage panels. In particular the minimum gauge for a crown panel was investigated in comparison with the actual 2024 Al same panel.

Fig. 6. Hail impact test

The objective of the test was to evaluate the potential thermoplastic damages at 50J (98% of cumulative probability) with an hail weight of 108 g and hail diameter of 2,4”. The results were acceptable considering that no damages have been detected through visual and ultrasonic inspections.

4 Testing activities definition

On the base of good results of the preliminary tests performed on the new hybrid material patented by Leonardo, an European research program has been activated to fabricate and validate new hybrid thermoplastic primary structures.
This research project is named NHYTE (New HYbrid ThErmoplastic composite aerostructures manufactured by out of autoclave continuous automated technologies) has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 723309 and has the following targets:
- Development of a pre-industrial continuous automated process for the fabrication of the innovative multifunctional thermoplastic prepreg material, based on Leonardo patent, already described;
- Manufacturing of hybrid PEI/PEEK aero-structures by means of low temperature in-situ consolidation process through Automated Fiber Placement technology;
- Application of advanced out of autoclave joining method (welding) for reducing fasteners number and decreasing assembling operations;
- Performing extensive mechanical test campaign to investigate material structural properties and validate static and dynamic behaviour of the designed structures;
- Optimization of products and processes to be developed with regards to their quality and cost, as well as environmental and Life Cycle Assessment, according to ECO-quotation procedures and weight and cost savings.

The materials selected in Nhyte project are:
(1) PEEK-Carbon AS4 Fiber Prepreg.
(2) PEI film (1 mil and 2 mils) Ultem 1000-1000.

The component selected to represent the demonstrator is the fuselage crown panel of an ATR type aircraft (see fig.6). The omega shaped stringers will be welded per induction to the skin.

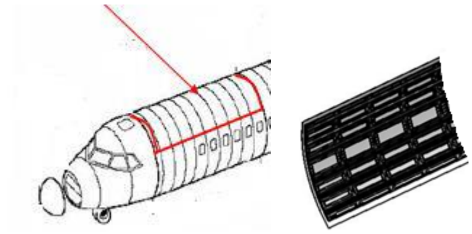

Fig. 6. Selected demonstrator panel

In Nhyte project preliminary tests during the development activities of the new material will be conducted, in order to determine optimized material production process parameters.
Later, evaluation of properties of the Nhyte hybrid thermoplastic composite laminate will be performed according to a building block approach, starting from evaluation of mechanical properties of material on coupons, passing through the evaluation of performances of small structural elements up to tests on subcomponents (see fig.7).
In particular the following typologies of tests will be performed:
- Single lamina test
- Coupons test
- Elements test
- Subcomponent static and fatigue test

Tests on lamina and coupons will be conducted at cold temperature (-60°C), as received condition; at room temperature (23°C) and as received condition; at hot temperature (85°C) and wet condition.
Where “as received” indicates not conditioned coupons and “wet” indicates humidity saturated coupons (stay at 70°C and 85% relative humidity up to equilibrium, per EN2823).
All tests on elements and subcomponents will be conducted at room temperature.

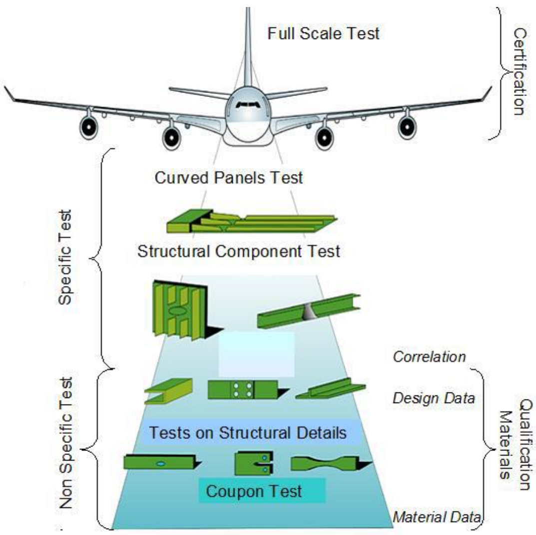

Fig. 7. Building block approach

4.1 Single lamina and coupons test description

For each PEI thickness, microscopy analysis and Differential Scanning Calorimetry (DSC) tests will be performed to verify the consolidation between PEI and PEEK and the crystallinity percentage of the PEEK resin.
Moreover several panels will be laminated per AFP and ISC, in order to determine the chemical, physical and mechanical performances of the hybrid material.
In particular the resistance of the laminates to conventional aeronautical fluids will be investigated. Typical physical characteristics as thickness, areal weigth, fiber content will be also measured.
Finally mechanical performances of the material will be investigated in terms of notched and unnotched tension and compression properties, in plane and interlaminar shear strength.
The results will be compared with the ones coming from a similar test campaign on coupons manufactured per hand layup followed by autoclave consolidation.
The obtained material properties will be used to size the elements and the subcomponents to be tested according to the following sections.

4.2 Elements test description

Hail impact and tool drop resistance have been identified as dimensional criteria of the designated final demonstrator so hail impact test and tool drop test will be performed on flat elements.
For Hail Impact (see fig.8), a hail dia from 1.75” to 2.75” and an impact energy between 14J and 120J will be used. The use of an appropriate gun have to be foreseen to correctly address the test. NDI shall be performed before and after impacts.

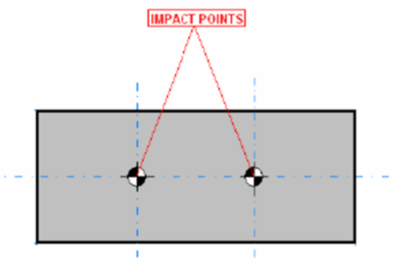

Fig. 8. Hail impact test element

For tool drop energy (see fig.9), the specimen will be rigidly clamped all around on a metallic frame in order to avoid excessive vibration during the impact and an improper energy dissipation. Impactor drop with 1” dia will be used with impact energy between 10J and 25J.

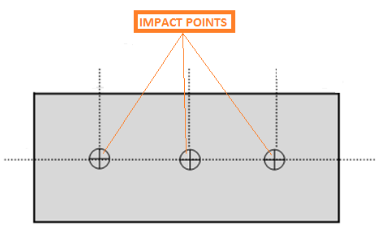

Fig. 9. Tool drop test element

After the optimization of the induction welding process for the integration of omega stiffening elements on the external skin, additional elements test will be performed to investigate the welding mechanical performances trough the following testing: single lap shear, double cantilever beam and pull-out test.

4.3 Subcomponent static and fatigue test description

The numerical results obtained on the above element tests, allow to study and to define the best solution to scale a dedicated fuselage panel to test in static and fatigue condition, that is the final focus of this research activity.
A skin (see fig. 10) of overall dimensions of 900 mm x 1500 mm with 4 omega shape stringers (pitch about 200 mm) will be submitted to impact to obtain a barely visible damage (BVID). After the damage, the panel will be loaded in tension up to the designated limit Load.
Finally, the test article will be tested by a tension load up to the panel failure to verify the structural capability to sustain the ultimate Loads.
Standard ultrasonic NDI are planned after impacts and limit load to monitor the damage and the defect growth.

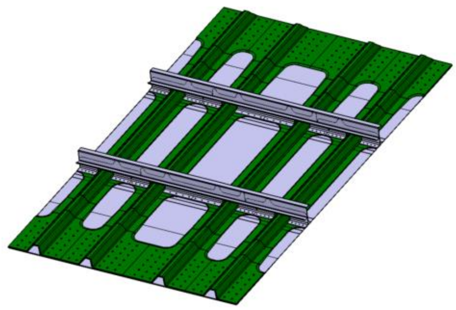

Fig. 10. Static test element

A panel with overall dimensions of 1600 mm x 1000 mm and five welded stringers will be submitted to fatigue test.
Test Article will be submitted to BVID.
Standard ultrasonic NDI is required on the Test Article after impact damage to evaluate the delaminated areas. The article will be tested by a tension - tension fatigue test composed by 90000 cycles and then statically up to the panel failure (see. fig.11).
ND ultrasonic Inspections are required at different cycles nearest the damages zones.

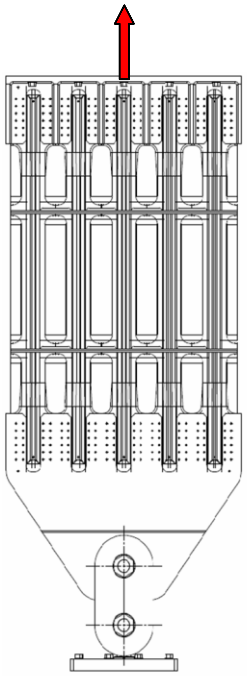

Fig. 11. Skin-stringers fatigue test set-up

4.5 Curved subcomponent demonstrator

A curved stiffened demonstrator representative of a fuselage crown panel of an ATR type aircraft will be manufactured. It will be realized to validate on a representative scale the identified process technology for the new hybrid thermoplastic material. In particular, the demonstrator (1.5 m x 1.5 m) will be composed by a quasi isotropic layup skin made per AFP and ISC techniques and 6 omega shape stringers integrated through induction welding process.

5 Conclusion

The new hybrid thermoplastic concept object of this paper is a strong candidate material for next generation regional aircraft fuselage. The promising preliminary results obtained on representative panels, in terms of technological feasibility and structural properties have allowed to define a more detailed test campaign in accordance with the standard building block approach to develop a deep material characterization and a preliminary set of design allowables.

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