ECO-CLIP: circular economy from factory waste material towards aircraft structural components

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Abstract. This paper discusses the development of short fibre frame clips and system brackets made from recycling CF/LMPAEK factory waste composites employing two technologies (injection molding and 3D-printing). The project will develop and validate fused deposition modeling (FDM) as cost-efficient process to manufacture system brackets using the novel formulation of recycled composite as raw material. Energy directors development for ultrasonic welding is presented for successful joining of the clips to the fuselage, avoiding fasteners. The manufactured parts will be assembled into the lower half of the multifunctional fuselage demonstrator. The results were developed within ECO-CLIP project, which aims to: (1) assess technical aspects of material recyclability and (2) assess the economic and environmental validity of the technology.

1. Background and context of the project

The future of aeronautical factories is oriented to manufacture lighter and cost-effective structures and components using greener materials and technologies, allowing cost, weight and fuel consumption reduction with shorter manufacturing cycles and increasing energy efficiency in aircraft fabrication. Thus, the aim to recycle materials is also a great objective in all EU aeronautic industry since the footprint of air travel also extends across the entire lifecycle of the aircraft (from manufacturing, maintenance throughout operational service to end of life), hence airliner’s components must be preferably recyclable.

An approach to reduce weight in the construction of aircrafts is the replacement of metal parts for composite structures. Thermoplastic composites (TPCs) are considered the next generation of composite materials with some advantages over thermoset composites (TSCs), such as high ductility and toughness, and efficient, reliable, and easy-to-implement manufacturing routes. Moreover, TPCs have a great recycling potential, which can be translated in reducing cost because their ability to be re-used.

In fact, reinforced fibre TPCs are on the rise, and it can be anticipated that the use of these materials will increase 200 to 300 percent in the coming decade, encroaching on market share now owned by metals and thermoset composites. Airbus has pioneered the use of TPCs, nowadays represented by A350 XWB with carbon fibre reinforced thermoplastic (CFRTP) in primary structure parts.
CS2 with the ambition of creating greener and more effective technologies has started to develop projects focused on solutions for the recycling of TPCs aircraft. In this context, ECO-CLIP addresses the development of short fibre reinforced thermoplastic composites using recycled CF/LMPAEK from factory waste for the manufacturing of structural parts such as frame clips and system brackets. Both of them will be installed in the next generation of fuselage demonstrator, which is undertaken as part of the Clean Sky 2, Large Passenger Aircraft – Platform 2 [1]. The lower half of the MFFD, frame clips and system brackets are depicted in Figure 1. A technical assessment will be performed to justify a significant reduction of the environmental and economic impact.

In this respect, ECO-CLIP project contributes to the CS2 objectives with an in-depth study of the behaviour of new CF/LMPAEK recycled composites, the definition of a manufacturing process with reduced energy consumption and the validation of the proposed methodology from an environmental and economical point of view. ECO-CLIP will demonstrate the feasibility for the industrial implementation of the proposed materials and the associated recycling and manufacturing technologies.

In ECO-CLIP, frame clips and system brackets are being manufactured with short carbon fiber recycled LMPAEK by injection molding, a “ready-to-assemble” process, and new technologies and approaches for primary tooling production (3D printed customised and modular plastic and metallic moulds) is being used. Thus, 3D printing (Fused Deposition Modelling, FDM) is also being explored as a worthwhile manufacturing strategy that has been used to produce non-critical interior aircraft components (light-load cabin parts) for almost a decade. This technology will be used for manufacturing one of the system brackets to establish a comparison with the same bracket manufactured by injection molding. Moreover, instead of riveting and the use of fasteners, in ECO-CLIP ultrasonic welding will be employed as joining process to join the clips to the rest of the structure avoiding the use of fasteners and rivets.

As a result, it is expected almost 100% re-use of the scrap (considering a few non-hand particles), about 50% of parts weight reduction, 20% CO₂ emission and 50% energy reduction during the manufacturing, and about 30% cost reduction is estimated within the whole technology approach (use of injection molding, redesign of the parts, welding technique, and recyclability of the material).

In summary, thanks to ECO-CLIP an environmentally friendly and feasible technology will be demonstrated. ECO-CLIP will actively contribute to one of the great objectives of CS2 Large Passenger Aircraft (LPA) Platform using advanced materials such as recycled CF/LMPAEK thermoplastic composites for the lower half of a multi-functional fuselage demonstrator (MFFD), within the reduction in weight of the fuselage.

Figure 1. Overview of lower half of multifunctional fuselage demonstrator with system bracket and frame clip.
2. Recycling material development

Factory waste materials from different sources (raw tape, cut-off and out of autoclave laminates) from different providers, and commercially available unreinforced LMPAEK and their PEEK analogues were purchased. DSC and TGA characterization were performed to study the chemical properties of the starting materials (factory waste and LMPAEK) and their PEEK analogues for comparison. Factory waste material was shredded and sieved leading to three different fractions (Figure 2): F1 (particles size between 0-2 mm, ~5% weight for 3D printing applications), F2 (particles size ranging from 0-18 mm, ~82% weight for injection molding applications) and F3 with particles sizes >20 mm and ~10% weight to be shredded again (Figure 1). When reprocessing F3, F1 and F2 increased in 56% and 6% weight, respectively, while F3 decreased by 89% weight. Thus, the total recycled material used for 3D printing and injection applications was 96.45%, with only 3.55% lost of material that could be still optimized at the industrial scale. This study will be extended in more detail during environmental life cycle performance assessment and a life cycle cost analysis.

Fraction F2 with 100% factory waste material was fed in the mixer to evaluate the optimal processing temperature. Afterwards, the mixture was fed in the extruder (twin-screw fully-intermeshing), where different parameters were varied such as temperature, extrusion speed and nozzle diameter, finding an optimal combination. This study was performed for mixtures with different percentage of carbon content (30%, 40%, 50%, 60 and 66%), obtaining filament and pellets of the newly developed material (Figure 3). Fiber Length Distribution (FLD) studies were performed for the different recycled mixtures (rPAEKCF) to elucidate the fiber length distribution on the material obtain after one and two extrusion
cycles and chemical and mechanical characterization were performed during these studies (acid digestion, CTE, rheology, TGA, DSC, SEM, SLS).

Figure 3. ECO-CLIP material (40%CF, rLMPAEK40CF) obtained after extrusion: filament (left), pellets (right).

Simulation of the injection process for each of the mixtures were carried out using commercially available materials: (PEEK (90G), LMPAEK (AE250P), PEEK 150 CF 30, PEEK 40%CF (90HMF40) y PEEK 30%CF (AV-651 CF30) (Figure 4). This study was based on rheology studies of rPAEKC and commercially available LMPAEK, PEEK and PEEKCF and the fiber size and the specific heat for the different mixtures.

Figure 4. Clip and brackets Cad Mold simulations for injection molding.

Due to the difficulties encountered for the longest bracket during the injection process when material contains more than 40% CF, it was decided to go ahead with the design and manufacturing of the mold for the manufacturing of the clips and brackets with the mixture of rPAEK40CF (recycled material containing 40% CF). Injection trials at laboratory scale were carried out to optimize injection parameters to manufacture flat specimens for tensile and compression tests. A study of scale-up of the process was done by shredding the factory waste material at UNTHA’s facilities. This material containing also 40% CF was also fully characterized including rheology studies showing identical viscosity as its analogue rPAEK40CF.

With this optimized extruded material preliminary injection trials were carried out by modifying several parameters to reach the optimal conditions such as injection temperature, mold temperature, pressure, volume, and post pressure (cooling time) among others. Once the optimal parameters were found for flat rectangular specimens with dimensions of 150.0 x 40.0 x 4.0 mm, injection coupons have been manufactured to elucidate the mechanical properties of the material.

CAD Mold simulations depicted in Figure 4 were performed with the consecutive re-designs to validate the expected clip and bracket performance, avoiding fibre degradation and other undesirable phenomena, and improving fibre density and orientation. Using this means, it was easy to identify where the injection point should be placed and which carbon fibre percentage in the developed recycled mixtures (vide supra) was optimal for this process. For accurate simulations, rheological characterization of the different mixtures developed were elucidated. One of the brackets (Figure 5 right) was also designed accordingly for additive manufacturing technology (FDM) as an alternative process to injection molding. Analysis will allow to define the cost-efficiency of the 3D-printing technology for manufacturing a specific batch of brackets versus injection molding.
3. Brackets manufacturing

Before manufacturing the different bracket systems, the original CAD had to be adapted for each of them in order to achieve a design that was easily process through injection moulding. Some modifications were done in order to manufacture them all in one single cavity (one mould) with different exchangeable inserts. The idea of incorporating the three brackets into one single mould with different inserts allow a cost reduction of the brackets and optimize the resources (Figure 5, brackets on the left center).

For the small bracket shown in Figure 5 (top left and right) is important to differentiate between the two different technologies that are going to be used for the manufacturing, injection moulding and 3D printing. In this case, the thickness of the bracket walls was reduced to be able to be processed by injection moulding and some holes will be incorporated by drilling after injection moulding. While in the case of the bracket manufactured via 3D printing, all the holes will be incorporated during the manufacturing process due to the versatility of the technique (Figure 5, right). In this way, both brackets will have the same geometry allowing the comparison between both technologies.

The remaining bracket has been the most challenging among all the brackets due to its geometry and dimensions (Figure 5 bottom left). The thickness of the bracket had to be reduced in order to make possible the injection process, nerves were placed in the plate to maintain the mechanical properties in the same range. Another problem observed in the geometry of the bracket was the length of the demonstrator and therefore the time that takes to the material to fill all the geometry. To solve this problem, it was proposed to separate the bracket into two different parts to speed up the process and ensure a better quality of the final part.

For 3D printing applications, the filament with the final composition selected as ECO-CLIP material is the same than for injection moulding with the same carbon fiber content (40% CF, rPAEK40CF). Bracket is under development, but preliminary studies were carried out to de-risk these studies and to evaluate the 3D printing application with the final geometry of bracket 2b with commercially available short carbon fiber filament (Figure 5). For this study was employed PA-CARBON+, which contains 82% Polyamide and 18% chopped carbon fiber (Figure 5).
4. Energy directors development for clip manufacturing

Before clips manufacturing, ECO-CLIP consortium is developing several geometries of energy directors by laser texturing and further evaluation of their welding efficiency by ultrasonic welding. These energy directors can be easily produced during the injection stage by the presence of an insert in the mold with the desired negative microstructure. AIMEN has developed two textures by different laser techniques, cones and ridges, with several dimensions that will affect the welding and final thickness of the molten material, and therefore to the quality of the weld (Figure 6). Flat specimens were manufactured at coupon level with the energy directors developed. When cones were used as energy directors, saturation of the cones inserts took place after several injection cycles, and therefore, this geometry was discarded, and ridges were chosen for further studies.

Full characterization of injected coupons at laboratory scale with and without energy directors (DSC, acid digestion, microscopy, fiber length distribution studies, SLS) allowed to verify the quality of the injected coupons and the homogenous fiber content through all the specimen. Preliminary welding trials are being carried out with and without optimized ED and mechanical characterization is being performed. Final validation of new materials and manufactured parts will include structural performance on the frame clips manufactured with the optimized injection (rPAEK40CF) material and energy directors. Welding optimization and interfaces validation studies will include studies at coupon level and in the clip to the UD CF/LMPAEK (simulating skin and frame couplings).

Figure 6. Ultrasonic welding equipment at AIMEN facilities (left), clips to be welded to skin and frame coupling (center) and conical energy director (ED) in injected flat specimen with ECO-CLIP material (right).

5. Life Cycle Assessment (LCA) and Life Cycle Cost (LCC)

Finally, in order to evaluate environmental benefits of using recycled materials for injected parts, a life cycle assessment (LCA) and a life cycle cost (LCC) will be carried out. Life cycle inventory will include the information during shredding, compounding, and injection/3D-printing processes aforementioned. Therefore, evaluation of the environmental impact of using recycled CF/LMPAEK to produce aeronautical components will be studied together with the economic viability of using this recycled material in aeronautical circular economy context.
6. Conclusions

A methodology to recycle CF/LMPAEK scrap material from different sources and the definition of the best recycling route for each technology (injection molding and 3D printing) has been developed. In this sense, ECO-CLIP has optimized the shredding, sieving and extrusion parameters to obtain pellets of the recycled material with different carbon content (short fibre CF/LMPAEK). Injection trials with the new developed material were performed and the resulting coupons were fully characterized. Material for 3D printing has been developed and manufacturing of the bracket is still under development. As a result, it is expected almost 100% re-use of the scrap. This will be the first time using recycled CF/LMPAEK in the development of new composites for injection molding and FDM.

![Figure 7. Scheme summarizing ECO-CLIP results (material development and brackets and clips manufacturing).](image)

The clips will be assembled into the skin and frame couplings of the lower half of the multifunctional fuselage demonstrator by ultrasonic welding technique to avoid fasteners. Thus, energy directors are under development at this point, focusing on the development of different geometries and dimensions and their position on the clip. Preliminary welding tests on coupons have been carried out to elucidate the best performance energy director and their position in the clip. After this, the mold of the clip will be design taking in the account the inserts for the energy development.

LCA and LCC will be performed to establish the environmental and economic impact of recycled CF/LMPAEK in comparison with starting materials. That will be the reference studies to further scale-up of the technology.

Address (URL) of the project’s public website:
http://www.ecoclip-project.eu/the-project/

References
[1] Veldman et. al. 2020 Aerospace Europe Conference Bordeaux “Development of a Multifunctional fuselage demonstrator”

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