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IMPROVING DESIGN FOR RECYCLING - APPLICATION TO COMPOSITES

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Abstract: The use of composite material increases. End of life regulations, material consumption reductions or restrictions, ask engineers about their potential use. Innovative recycling solutions arise that recover efficiently carbon fibres. This paper explores the design for composites recycling issue. Recycler becomes a new knowledge expert for the designer. It is necessary to analyze their information shares and exchanges. The recycler is an end of life facilitator. He is also the second life material user and can ask for material evolutions. The collaboration must be improved using knowledge performance indicators. These discussions will be enlightened by examples from carbon recycling experiments.
Keywords: Design method, Recycling, Composite

1. Introduction to composite design and recycling interaction

Today sustainable development has become a necessity for design and manufacturing. Less material-energy consumption resulting in controlling and reducing pollution is the key objective. Composites provide good opportunities, combining high modulus materials with free definition of geometry. Carbon fiber reinforced composites (CFRCs) [1] and more especially thermoset matrix based composites are currently used by the aerospace, aeronautics and automotive industries. They are also used in the leisure and sports fields. High-tech industries have high quality requirements for the materials, but few integrate end of life aspects. On the contrary, industries for large public applications have now started taking this perspective into account and are including recycled materials in their products. Regulations (focusing on the recycling rate to be achieved by products) are increasing this trend. It is now necessary to take into account the end-of-life (EoL) of carbon fibre/thermoset composites by (i) avoiding landfill or energy recovery (i.e. incineration), and (ii) exploring the carbon fibre recovery via new stakeholders in the areas of transport, leisure and sports .
Composite design is driven by mechanical characteristics improvements, searching for light mechanical structures, and ensuring to know the behaviour during the product life stages. The design phase integrates complex decision algorithms. Product optimisation (shape, mass and costs) depends on the material characteristics (glass, carbon, aramide, natural, etc ...), the type of reinforcement (uni directional or multi directional layers, 2D or 3D orientations, woven or non crimp fibres). The reinforcement can be made of a mix of different natural fibres depending on the objective mechanical properties, density and costs. Manufacturing processes (TRM, filament winding, pultrusion, contact moulding, etc.) limit the use of some kinds of reinforcements [2]. These processes are mostly chosen due to their geometry possibilities and the final use of the product. Aerospace and aircraft applications have strong requirements that limit and reduce the possible manufacturing process (either for fibre placement and matrix curing) [3]. In addition, some reinforcements do not adapt to some geometrical shapes such as corners, angle shapes or spherical areas. The fibre orientation (woven) slide and the expected reinforcements are lost. Many constraints interact in the composite part design process. They go one step further with the need of part assembly. Gluing is efficient, but many applications require connections using rivets or bolts (metallic) for security. The result is hybrid assemblies and non perfectly mastered behaviour of the structures. Thus, the optimisation gains are limited. To solve this multi entrance decision systems, the designer often imposes the manufacturing process or the material and reinforcements. The design optimisation consists in minimising the thickness, i.e. the number of plies depending on the symmetrical orientation requirements to balance internal residual stress and distortion. This optimisation should resist to all the loading cases of the product or assembly. No evident composite design methodology has been found to give a real alternative to product/material/process multi choice selection [4]. However, comparative criteria already exist (specific resistance, delamination criteria and cycling limits, total mass and costs) and a new criterion, the manufacturing time, has become a key issue for large audience applications such as in the automotive industry.
In this perspective, recycling during the design phase can be done by proposing simple guidelines in order to ease i) dismantling (e.g. a mechanical assembly should be preferred to a mix of mechanical and glue), ii) matrix-fibre separation (e.g. no metallic inserts or limits the massive area thickness), iii) material recognition before and after recycling (e.g. use one single type of fibre in a structure). But today, these considerations are far from designers' interests. The only way to force them to take recycling aspects into consideration is to provide cheap recycled reinforcement fibres with good mechanical properties. We first developed a re-manufacturing process of recycled carbon fibres [5]. We have to give the materials and mechanical information to the designers for design product use and to inform them of the real recycled fibre history.
In this paper, we will first focus on the recycling of CFRCs, with particular attention to the current and future limitations and legislation. We will see that, to date, the recycling of CFRCs especially concerns the fibre itself. In the second part, we will study the possibilities of recovery and the improvement expected for the recycling of CFRCs.

2. The recycling of CFRCS

2.1 Legislation in force for composites

Composites are not differentiated within legislation. Their EoL is indirectly involved in the Waste Electrical and Electronic Equipment Directive (WEEE) [2] and in the legislation for landfill [6]. Composites are also mentioned in the Reach legislation (Registration, evaluation, authorization and restriction of chemicals) if they contain toxic or harmful substances such as flame-retardants, currently used in aeronautics. Only the legislation on end-of-life vehicles (ELVs) mention composite recycling. In fact, the rate of reuse and recovery should reach 95% in 2015, and 85% for reuse and recycling, according to the European directive "VHU 2000/53" [7].
The European directive, WEEE, and other end-of-life directives thus force industries to seek new methods of recovery for composite parts. In this context, the quantity of composite recycling will increase due to the creation of dismantling platforms. As an example, in the southwest of France, the

TARMAC Aerosave[1] platform specializes in civil aircraft applications together with EADS-Airbus and EADS-Sogerma. They mainly focus on the reuse and certification of replacement parts in aircraft maintenance. In addition, the P2P platform (clean platform for the dismantling and testing of solid propellant from defence and embedded system products) deals with the disassembly of ballistic weapons.

2.2 Assessment of CFRC recycling

Waste landfill or energetic valorisation are the oldest option for EoL composites. Knowing that CFRCs are made with non-renewable materials and that they are quite expensive (e.g. carbon pre-preg: approx. 180 €/kg), giving them a new life by recycling is a better option both economically and environmentally. Recycling a composite means: i) having recycling technology available, ii) finding a dismantling solution and an access a market for the product, and finally iii) material identification and selection. Thus, carbon fibre recovery would help design engineers to balance energy efficiency and cost, and would also open up new opportunities for developing second-life composites, for the manufacture of medium or low mechanically loaded parts (non-structural in many cases).

Several techniques exist to recycle CFRCs [8]. Mechanical recycling consists in grinding fibre and matrix. It is cheap but very aggressive and destructive for the carbon fibres [9][5]. The ground material is reincorporated as filler (powder) or used in a chopped strand mat (short fibres). A last option consists in using CFRCs as a mineral phase in concrete. It results merely in a low material .Thermal recycling can be by oxidation in a fluidized bed, by pyrolysis, or by treatment in a molten salt bath [10]. Pyrolysis is the technique that is the most common at the present time. The oxy-thermal effect on the carbon fibre reduces its initial mechanical properties. Chemical recycling (based on solvolysis: supercritical conditions for fluid) includes all methods of cold recycling (temperature lower than 450°C, and pressure around 250 bar, depending on the matrix polymerization degree), with the use of chemicals [10].

Pimenta presents the advantages and drawbacks of each technique. But the main limitation for the use of recycled CFRCs (rCFRCs) is the fibre length. Consequently they are mainly used in ground material forms in cement for civil engineering or integrated in non-structural parts (e.g. as a filler) in the automotive industry.

Pyrolysis or Solvolysis methods are able to recover quite long carbon fibres and to preserve mechanical properties. The fibre length, therefore, directly depends on both the size of the to-recycled part (pre-preg off-cut or end-of-life part) and the size of the chemical reactor. The resulting recyclate retains up to 90 percent of the fibre's mechanical properties. In some cases, the method enhances the electrical properties of the carbon recyclate because the latter can deliver a performance close or superior to the initial material [11]. Nevertheless, the economic viability of the chemical recycling solution including chemical processes has yet to be demonstrated and validated on an industrial scale.

In such cases, the second use of composite fibres will be for the manufacture of medium or low-loaded parts (non-structural in many cases). Their use will also depend on the consolidation possibility: alignment ratio, woven possibility, thickness performance, and use in the existing composite process. Pimenta presents an overview of the possible application depending on the recycling process (id.es. the mechanical properties) and the composite manufacturing process. The following markets could be interested in this product: the automotive (in semi-structural parts) and leisure and sports industries [10].

For all these reasons, it is necessary to improve the carbon fibre recycling processes and to integrate these possibilities (recycled material and recycling processes) into the composite product design phase. Cheaper materials with good properties could find wider applications than composites today and with a more environmentally-friendly impact.

3. DESIGN FOR "X" APPROACHES

The Design for "X" (DFX) refers to integrated design approaches or concurrent engineering as proposed by Sohlenius [12]. It points out issues that occur in the different phases of the product life cycle. This integration is supported by design guidelines or design rules. From a knowledge-based point of view, these elements represent an explicit form of knowledge that contains information about "knowing-how-to". This knowledge of how to formalize and integrate is related to element issues that are caused (or affected) by the characteristics of a product. The Design for "X" proposes methods and engineering environments that help to generate and apply technical knowledge in order to control, improve, or even invent particular characteristics of a product**.** This approach proposes for each phase of the real product life cycle some knowledge integration as formalized by Pahl which gives a classification of the design for "X" relative to the product phase. [13]. Shu proposed the Axiomatic Design in order to structure and understand design problems and the links between the different areas of expertise [14].

The development phase leads to design rules for innovation [15] mass customization [16][17] or design for standards. Eco-design concerns adress the Design for Environment approaches [18][19]. The production phase points out the design for manufacturing and manufacturability [20] with many specific proposals for each process. Lenau highlights the needs for exchanges between material science experts and designers in order to reconsider the material choice method in parallel with the manufacturing process and the initiation of the product-process-material method [21]. Many in-depth studies were carried out on assembly design, by the automation and the subdivision of products into functional modules [22]. Disassembly was also started to be integrated [23]. The use phase integrates user focuses (ergonomic or aesthetics) or after sales interests (maintainability or serviceability). Finally the end of life phase promotes the design for disassembly [24] for further valorisation such as reuse, re-manufacturing [25] or recycling [26]. The separation plays a major role in recycling efficiency [27][28].

The design to cost has a specific position because the cost is affected by all the phases of the product. Through engineering design: i) physical interfaces between parts or components or assemblies of the product and, ii) the manufacturing equipment as well as the logistical material flow systems can be changed, and thus cost reduction in operating the latter may be achieved [29].

This brief overview confirms that interest in environmental concerns is present in all phases of the product life cycle. This aspect is studied specifically or in addition to another approach. However, recycling (or end of life solution for products) is not often the subject of specific research. Nevertheless, Ardente developed the ENDLESS software in order to compare end-of-life alternatives [30][31]. Our proposal is more deeply linked to the recycling processes. We integrate information at the material and process level. This information helps designer decisions related to: i) the future use of recycled materials and, ii) the anticipation of end-of-life products. We built a material history follower as a starting architecture for the integrated design tool supporting end of life concerns. The key point is to identify (before integration) the information that has been exchanged between recycling engineer designers and material science experts.

1 http://www.tarmacaerosave.aero/

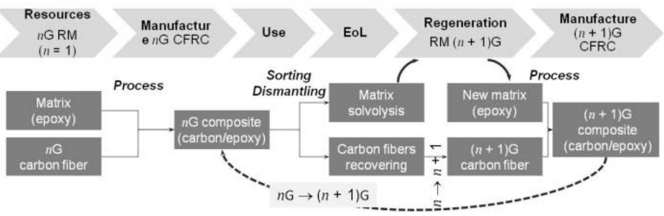

Figure 1. Lifecycle of a CFRC, from resources to the carbon fibre regeneration

4. COMPOSITE RECYCLING

We developed a recycling process based on solvolysis technology (supercritical fluid) which separates thermoset matrix and carbon fibres. Due to this process, the lifecycle of the carbon fibres (CF) is extended by the CF regeneration that allows the cycle to be closed as illustrated in Figure1. We propose to follow the "generation" evolution (1st generation 1G, 2nd generation 2G, etc.) of the fibres in order to predict its future integration in a product design inspite of the small loss of mechanical properties after recycling. It is also necessary to master the use of the nG-CF (n Generation of Carbon Fibre) in order to meet the mechanical needs and the material possibilities. Thus, the composite based on this reinforcement will be called nG composite. In reality today, product lifecycles from different industries are not connected and the carbon reinforcement is only valorised as energetic coal (dotted line on Figure 2). Considering the aeronautics, automotive and leisure and sports industries, products lifecycles work in a closed system (i.e. there are no interactions between them), but not necessarily in closed lifecycles (except, perhaps, for the automotive industry that allows the use of ground composites).

We propose to link these three industries by improving CFRCs' end-of-life. As soon as one industry accepts rCFRCs from another one, they are linked together. Specialists of the End of Life have opportunities to improve a material usually non upgradable in a new potential source of raw material. Taking into account the limitations previously listed (length of the recovered fibre, designer reluctance, etc.), the complete CF lifecycle can be drawn as in Figure 2 diagram. It is a cylindrical representation of the successive integrations of the (recycled) CF in different product lifecycles. Only the main steps of each lifecycle are displayed: i) integration of the raw materials (in particular carbon reinforcement); ii) design, process and production of the composite; iii) logistic, product distribution and transport; iv) use and maintenance; v) product end-of-life.

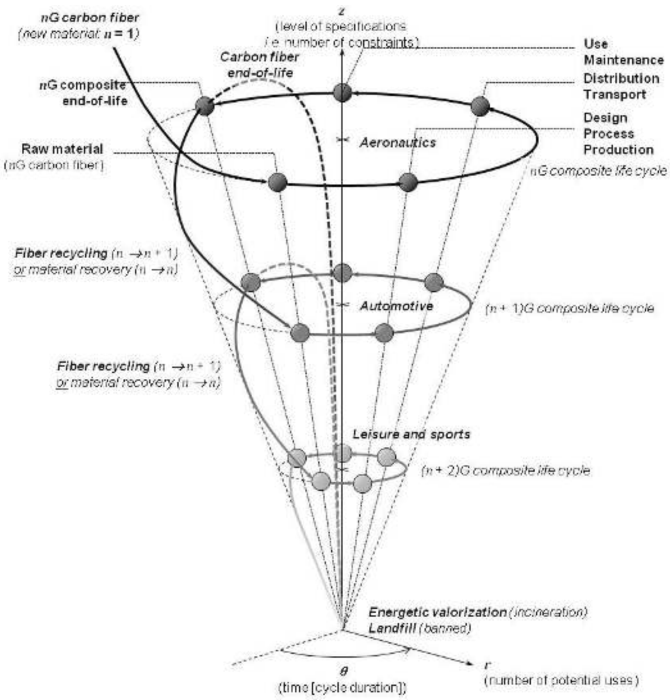

Figure 2. Multi-circular representation of the CF lifecycle. Integration of the (r)CF in successive product lifecycles, depending on their level of specifications (i.e. number of constraints). The radius r of each lifecycle depends on the number of potential uses for the (r)CF.

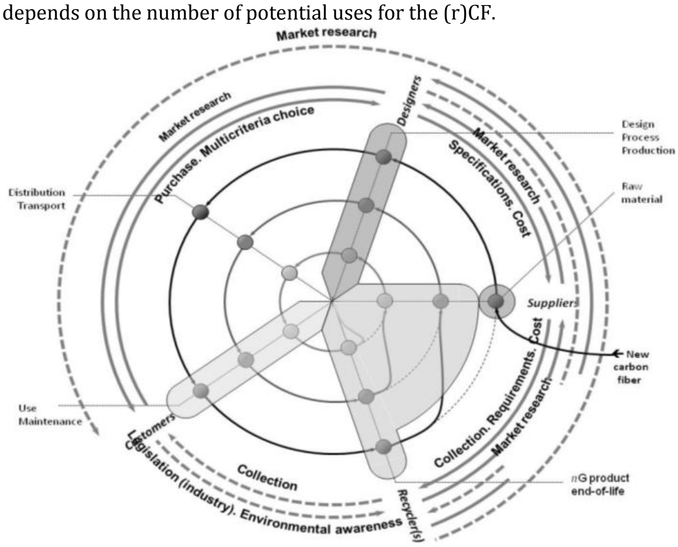

Figure 3: Figure 2 seen from above - stakeholders (grey area: suppliers, designers, customers and recyclers) and their interactions.

Based on this lifecycle and on our expertise, each recycling step can be detailed and a recycling line for carbon fibre can be designed. The *n*G product is first sorted. Specific coatings such as metallic cladding for electric behaviour are not compatible with some recycling processes. Then the product is dismantled (all metallic insert have to be extracted) and cut (*i.e.* adapted to the recycling process reactor). After the solvolysis process, the carbon fabric is recovered as flat layers. The re-manufacturing starts with the reprocessing of these fibres so that they can act as possible reinforcements. The fibres are hackled, possibly mixed (depending on available CFs, or on the quality of the chosen reinforcement for the (n + 1)G material), and reinforced to be integrated more easily in the next recycling stage (*e.g.* pre-preg). Depending on the (n + 1)G composite elaboration process (RTM, infusion, etc.), fibres can be spun, then rewoven or knit, or made available as pre-preg strips, to finally process the composite.

5. Actors interactions identification

Figure 3 corresponds to Figure 2 seen from above. The lifecycles of each of the three industries are linked by exchanges of carbon fibres at the end-of-life stage. The stakeholders and their interactions are identified as follows: i) Suppliers adapt their offer from the designer's needs (market research). They should also be related to recyclers who have to take into account the specifications and cost of the raw materials. ii) Designers obtain information from customers by doing market research; they choose suppliers according to raw material specifications and cost. iii) Customers decide to buy the product or not, according to multi-criteria decisions; they are linked to recycling engineers by legislation or environmental awareness (for individuals). iv) Recycling engineers are those collecting used CFRCs, whose deposit must be taken into account, as the supply source becomes more reliable. They are then the new suppliers in the carbon fibre lifecycle, as they re-use the waste rather than burning them. They choose the appropriate recycling process in order to propose a material adapted to (n+1) designer needs.

We encourage discussion between designers and recycling engineers in order to innovate in the design of new recycled composite products (as presented in Figure 4). This means that information and skills from both sectors will be shared. However, it also implies that materials and mechanical knowledge have to be developed for both designers and recyclers. Therefore, it is necessary to include a third party in the discussion: experts in material and mechanical characterization. Moreover, in the carbon fibre recycling line, discussions between stakeholders must be improved by defining semi-product specifications and formalizing those interactions by quality criteria. The latter are based on process efficiency.

Figure 4. Natec pedal crank made with rCFRCs (desired characteristics: specific stiffness and equivalent mass to the classic one 185 g)

6. Conclusions and perspectives

Carbon fiber reinforced composites recycling is quite a recent problem issue, due to the increase in their use. As a consequence, the legislation in force barely cites composite materials; they are simply mentioned in the WEEE and ELVs directives. As a consequence, both industrialists and individuals have yet to become aware of the usefulness of CFRCs recycling. However, a recycling network, capable of processing the carbon composite recycling (and not only re-using energy) is developing.

We have highlighted that the improvement of local or regional sorting and dismantling platforms is necessary. Based on the solvolysis process, recycling is thus achievable. But a sorting and collection network must be developed to feed the recycling line on an industrial scale. All the stakeholders who will be involved in this line already exist; we now aim to link them. Promoting discussion between designers and recycling engineers in order to propose innovative definition of new recycled composite products will induce the creation of exchange platforms, allowing information from both sectors to be shared. However, it also implies that materials and mechanical knowledge have to be developed for both designers and recyclers. Therefore, it is necessary to include a third party in the discussion: experts in material and mechanical characterization. Lastly, promoting end-of-life carbon fibre would reinforce the link between the aeronautics, automotive, and leisure and sports industries; but one can create demand for recycled reinforcement, by packaging it in useful and attractive forms for those end-users.

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