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Carbon fibre reinforced plastic EOL: Protecting Remanufacuring status and Life cycle route analysis

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Abstract

For a remanufacturing industry to take hold within society it is critically important that people understand the term remanufacture. While general public remanufacturing awareness problems of course exist, within academia and industry remanufacturing awareness issues can also exist. It is also true that academia and industry are both directly involved in strategies to reuse carbon fibre reinforced plastic (CFRP) waste obtained from the manufacturing process (cut offs for example), and that obtained from end of life (EOL) CFRP products such as aircraft. Through a lack of awareness, remanufacturing terminology is often used to describe creating a new product from an existing one within these sectors. This of course is a problem for two main reasons. Firstly, remanufacturing is a standalone process, having its own protocols and criteria that must be adhered to and secondly, if the term remanufacture is not used correctly, a lack of awareness of remanufacture will inevitably continue. This paper presents a brief description of the efforts by industry and academia to create new products from waste and EOL CFRP. It goes on to mention why remanufacture terminology although used is not generally applicable to describe these products. Further, to help stop the potential spread of remanufacturing terminology being used wrongly in this growing sector (which only seeks to water down true remanufacturing meaning) and to increase remanufacturing profile in general a product identification flow chart is presented. The flow chart has two main purposes, 1) it informs the user involved in product EOL whether they have remanufactured, recycled, reconditioned, repaired or re-used a product and 2) it allows for a very simple and efficient method to analyse any previously owned (i.e. not brand new) product in terms of the type of EOL treatment performed.

Introduction

An increase of some 300% in CFRP by consumption is predicted from the 2010 levels in 2020; placing the expected global market value at somewhere in the region of $25.2 billion to $36 billion [1]. The key industries driving this market are the aerospace industry, the wind turbine industry, the sports and recreation industry and the automotive industry. Looking at the aviation industry, modern aircraft are increasingly using more and more composite, for example the Boeing 787 Dreamliner is over 50% composite [2] and the new airbus A350 XWB is approximately 50% composite [3]. Coupled with the increased use of composites is the growth of the airline sector; through a combination of increased airline travel and replacements for retired aircraft Boeing expect demand for new aircraft from 2014-2033 to approach 36,770 units, placing the expected market value at around $5.2 trillion [4]. Running parallel to the growing aerospace industry is the global effort to reduce both carbon emissions and waste, evidence of practice within the European union is readily available; municipal and construction waste recycling targets [5], WEEE directive [6], end of live vehicles directive [7], landfill directive [8]. There is also greater responsibility placed on product manufacturers and product importers to adhere to regulations, as such both industry and subsequently academia are investigating ways to use both manufacturing scrap CFRP and EOL CFRP.

To better understand these efforts (with an emphasis on remanufacture); it is appropriate to first investigate the products created by academia and industry. Following this, it will also be shown that the term remanufacturing has effectively lost its meaning in this field and why it is important to protect the terminology. Progressing further, a bespoke flow chart designed to allow the user to determine if a product is remanufactured, recycled, repaired, reconditioned, or reused in a simple and efficient way is presented. Lastly a discussion of the aforementioned flow chart is presented along with conclusions.

Results

Products created by industry

Currently academia seeks to recycle fibres from existing CFRP by two main methods, method 1 - mechanical recycling and method 2 – fibre reclamation through chemical and thermal treatment [9]. Looking at mechanical recycling, the process involves grinding, crushing and milling existing CFRP to a point where segregation of matrix and fibrous material can take place. These sorts of materials are typically used as filler or reinforcement in new materials. Looking now at the second type of recycling, fibre reclamation, which is essentially the process of extracting the actual carbon fibres from existing CFRP. This process is typically performed using techniques such as pyrolysis, oxidation in a fluidised bed or chemical treatments; the most commonly used technique and generally the only one practiced thus far on a commercial scale is pyrolysis. All three techniques seek to break down the matrix element, (the energy from the thermoset resins is recoverable) while leaving the fibres relatively unaffected. (It should be made clear however that once reclaimed, fibres tend to lose their sizing and revert back to their ‘fluffy’ form.) It should also be pointed out that, particularly for pyrolysis, the processes involved are not an exact science, for example, a too light pyrolysis cycle leaves residual char on the fibres but does not degrade fibre strength whilst a too strong pyrolysis cycle leaves no residue char on the fibres but does degrade the fibres. Either of these cases may be beneficial depending on the applications of the future fibres, so it is a generally accepted premise that recycling could potentially take an application specific form. Once reclaimed, the fibres are commonly referred to as recycled fibres. Once the recycled fibres are procured, they can be re-impregnating with new resin. The impregnation is performed in a number of ways [9] [10] with the resulting product now being classed as a recycled carbon fibre reinforced plastic (rCFRP). Note that it is not necessarily the case that academia and industry perform both fibre reclamation and recycle rCFRP. Companies such as ELG Carbon Fibre Limited tend to perform the fibre reclamation only, leaving the impregnation process for another company or research institution.

Protecting remanufacturing status

The term remanufacture (also quoted as re-manufacture) is often used to describe general manufacturing operations involving recycled carbon fibres and commonly appears as a way of describing the processes of using the recycled fibres to create rCFRP, with many examples found in literature [10] [11] [12] [13] [14]. The use of the term, remanufacture, is completely understandable, it almost makes perfect sense; without having knowledge of remanufacturing (industry/concepts/criteria etc.) then it would appear to be correct word/s to use when describing the process of manufacturing CFRP for a second time. However, the stumbling blocks, especially when it comes to public perception, that stop remanufacture fulfilling its potential as a viable, robust, expandable, sustainable EOL strategy are awareness and perception problems. As such only products which are capable of being disassembled, cleaned, inspected, have their components replaced or repaired to original standard, reassembled and sold with a warranty at least equal to the original should be classed as being remanufactured. Clearly, rCFRP is not created by remanufacturing recycled fibres for the reasons stated above, and also that remanufacture cannot possibly be a subset of recycling.

It can be said at this stage, the term remanufacture is generally used to describe the creation of recycled product (rCFRP), which is of course clearly a nonsensical concept. Nonsensical to remanufacturing researchers, but to other researchers and scientists (not currently aware of remanufacturing) the concept could make perfect sense. Hence, it is important that remanufacture is not used casually, as if used casually, lack of awareness and confusion will inevitably continue. If protected and used correctly, remanufacturing awareness and public perception should increase.

Development of product identification matrix

When developing a decision matrix to determine if a product is remanufactured, recycled, reconditioned, repaired or reused, the definition of these terms must of course in some way be included. This poses an interesting question:

> ‘How to design a flow chart to include the definitions of EOL treatments while at the same time reduce the complexity of the definitions so as to allow for a clear differentiation of EOL treatments?’

The answer to this is to ask a number (as small as possible) of leading questions with these questions having only yes or no answers. It should also be the case that the flow chart allows for any previously EOL product (excluding brand new products of course) to be quickly identified as being, recycled, re-used, repaired, reconditioned or remanufactured.

When deciding on the types of leading questions to ask, the first instinct is to determine the differences in criteria between the EOL treatments. For example, reconditioned is typically more labour consuming than repair, and remanufacture is more labour consuming that recondition. Following this methodology, one could develop a very efficient diagram to distinguish between the EOL treatments, see [15]. However, this approach moves away from actually allowing the user to determine if there part is recycled, re-used, repaired, reconditioned or remanufactured and is more focused on informing the user of the subtle differences in EOL treatments, leaving the user to make their own decision. The flow chart presented here does not require the user to evaluate the EOL treatments and then decide; this flow chart directly informs the user if the product is recycled, re-used, repaired, reconditioned or remanufactured. The definitions for remanufacture, recycle, repair, recondition and reuse can be found in literature [16], from this point on it is assumed they are known and understood.

EOL identification matrix

By responding yes or no to these questions, it is possible (if the questions are asked in the correct order) to determine whether a product is recycled, re-used, repaired, reconditioned or remanufactured. The underlying principle of the flow chart and questions is to systematically eliminate EOL treatments depending on the answers to the questions, this principal is detailed in the four points below.

1- Recycling destroys emergy – this clearly separates recycle from re-use, repair, recondition and remanufacture. The first question is designed to eliminate recycle or select recycle.
2- To differentiate between re-used, repaired, reconditioned and remanufactured ask a series of questions (first six questions) for which the answers must be yes for a remanufactured product.
3- If no is answered for questions 2,3,4,5 or 6 then remanufacture is eliminated.
4- If remanufacture eliminated, a minimum of one and a maximum two questions are asked to determine if product is re-used, repaired, reconditioned.

The questions and the order in which the questions should be asked is as presented in table 1 and the corresponding flow chart is presented as figure 1.

Table 1 - Questions asked to determine if a product is recycled, re-used, repaired, reconditioned or remanufactured

Question number	Question
1	Is emergy (energy expired to create product from raw materials)

	retained from original EOL product?
2	Does the product have a core?
3	Is core capable of being disassembled?
4	Has the core been disassembled?
5	Is warranty of product equal to or better than the original?
6	Have all core components been cleaned, inspected, replaced / repaired to original standard and had its core reassembled such that the product is in like new condition?
7	Have all major broken components and components on the verge of failure been replaced or repaired?
8	Has the product been restored to an acceptable level in any significant way (and core reassembled if applicable)?

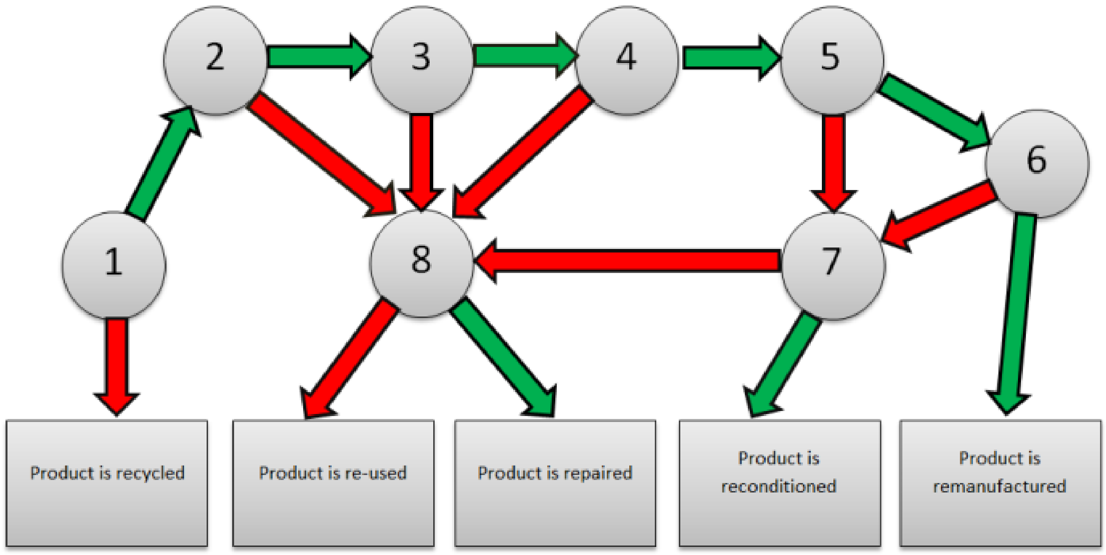

Figure 1 - Product identification flow chart. Noting that red arrow corresponds to a no and a green arrow corresponds to a yes

Discussion

While multiple texts exist that clearly define the differences of recycling, re-using, repairing, reconditioning, and remanufacture [15] [16] [17] [18] the general concept in literature is to present the differences normally in a table. This system encourages the reader to learn new knowledge which is obviously desirable, but the possibility of confusion between EOL terms still exists (for example, one could misinterpret or misunderstand texts, or get fixated on concepts such as the labour content). The system devised in this paper, seeks to eliminate any confusion and allows one to quickly and efficiently determine if a product is recycled, re-used, repaired, reconditioned, or remanufactured. Also, owing to remanufacturing ambiguity, a clear definition of a remanufactured product is presented in the same flow chart.

Put simply, this system allows for clear identification of what type of EOL treatment a product has received without having intimate knowledge of the subtle differences between EOL treatments. For example, to determine if a product is recycled, the system presented here only requires one question to be asked, namely, ‘Is the emergy retained from original product?’ The emergy question quickly determines if the EOL treatment performed on the EOL product results in the treated product being classed as recycled without getting needlessly bogged down in the recycling processes. Further, the concept of a core is also used to determine quickly if a product can be reconditioned or remanufactured, for example, question 2 ask ‘Does the product have a core?’ If the answer is no, then immediately reconditioned and remanufactured are eliminated and product must be at this point, re-used or repaired. However, there is still significant cross over between EOL treatments which can still cause confusion, for example while it is true that a reconditioned or remanufactured product require a product core, it is not true that a product with a core is always required to be reconditioned or remanufactured. Products with cores can still be repaired or just re-used. This cross over, leads to the realisation that singling out individual characteristics that a product must have to be called recycled, re-used, repaired, reconditioned or remanufactured is fraught with difficulty. However, the system presented here manages to do so. It does so based on asking questions and using the definition of remanufacture to eliminate EOL treatments leaving the only probable answer remaining as the EOL treatment performed

What this flow chart is not

It is important to point out that the system devised in this paper does not present a deep understanding of recycle, repair, re-use, recondition or remanufacture – this analysis previously conducted [16]. For example the system presented here omits the fact that in order to successfully remanufacture, a company/organization would require a steady supply of cores and that the product should fail from a functionality standpoint and not from a dissipative standpoint. This level of detail is not anticipated to be required by potential user of the flow chart presented in this text – the flow chart is designed to be used to determine what type of EOL treatment has been given, not which type should be given. For a deeper knowledge on recycle, re-use, repair, recondition and remanufacture, there exist multiple texts presented in the references which one can avail them self of.

Advantages of the flow chart

The flow chart developed has two clear benefits 1) the amount of people using remanufacturing terminology incorrectly should decrease, ergo increasing the profile and raising awareness of remanufacturing and 2) allow for general EOL terminology to be applied correctly by researchers across many different disciplines, thus reducing confusion. More specifically, the user of the flow chart is able to determine what particular type of EOL treatment that a) they have given to a product or b) what type a product has received. Looking at the product discussed in this paper, rCFRP, the fibre re-impregnation process described in literature as remanufacture or re-manufacture. It is presumably the case that the terms remanufacture or re-manufacture are used without an awareness of remanufacture, hence the strange use of the term in this instance. In this case, the user having prior knowledge of the re-impregnation process could simply go through the flow chart and it would be readily apparent that no remanufacture has taken place. It is also true that the flow chart presents a useful tool for people new to the field or members of the public at large; initially it can be difficult to determine if a product is repaired, reconditioned, remanufactured or able to be. For example using the flow chart presented here it is readily apparent that if no core exists, then product is not able to be remanufactured or reconditioned and that remanufactured products must have warranty at least equal to the original. Focusing on remanufacturing characteristics, another benefit from the flow chart developed in this paper is that only the essential characteristics of a remanufactured product are presented. To exemplify this attention can be drawn to literature. Andreu [19] a presents a list of essential characteristics of remanufacturable product,

1. The product has a core that can be the basis of the restored product. A core is the used equipment to be remanufactured.
2. The product is one which fails functionally rather than by dissolution or dissipation.
3. The core is capable of being disassembled and of being restored to original specification.
4. The recoverable value added in the core is high relative to both its market value and its original cost.
5. The product is one that is factory built rather than field assembled.
6. A continuous supply of cores is available.
7. The product technology is stable.
8. The process technology is stable.

It is the authors' opinion that only points 1), 2) and 3) are truly indicative of a remanufactured product. Point 4) is not needed as economics change from country to country and potential exists for a product to be remanufactured in one country and not in another, point 5) is not needed owing to evolving technology and processes and from the knowledge that generally most products assembled in the field are done so with a view of customization and point 6), 7) and 8) are not needed when deciding if a given product has been remanufactured or not. It can be said that points 4-8) are best described in the authors' opinion as criteria that one would expect from a product that has been remanufactured from an economical/industrial view point. The system presented in this paper states a remanufactured product characteristics in isolation of whether it should or should not be remanufactured and from the characteristics that one would generally expect from an economically driven remanufactured product, a quality that the list by [19] fails to do - these fundamental characteristics being 1) emergy is retained 2) Product has a core 3) core capable of being disassembled and reassembled 4) the product has a warranty equal or better than original and 5) all core components have been inspected, replaced or repaired to original standard. A final benefit of the flow chart is that it allows a quick comparison between EOL treatments which may or may not be remanufacture and remanufacture. For example, it is often the case that organizations perform remanufacture but call it something different, i.e. it has been previously stated that that the term 'overhaul' in the aerospace industry is equivalent to remanufacture [20]. The system developed here requires a maximum of 6 questions to be answered to determine if this is indeed the case

Further work

By seeking to simplify the determination of EOL manufacturing process and force them to group into one category, i.e. recycle, re-use, repair, recondition or remanufacture, some unexpected results can arise. It should first be said, that while strictly possible (i.e. the flow chart does not violate any definitions) it is very unlikely that the forth coming scenario will materialize. So, the flow chart allows for repaired / reconditioned / re-used products to be given a better warranty than the original. This in general is never the case in reality. In many definitions of repair and recondition it is stated that the warranties are generally of lesser quality than the original warranty, which is indeed the case. However, owing to the fact that the flow chart is designed to provide a definition of a remanufactured product, which means warranty must be included, and the unlikelihood of a repaired / reconditioned product being given a warranty better than the original, this 'anomaly' was not deemed as a concern. However, it may in the future be appropriate to design a more rigorous and robust flow chart to eliminate any potential source of confusion. This has many challenges however, not least of which is how to maintain simplicity when increasing complexity and robustness. Further work related to this paper includes validation of the flow chart against a number of different products.

Conclusions

This paper has shown that the aerospace industry is highly invested in using CFRP materials for modern aircraft. It has also been shown that the aerospace industry is expected to grow significantly and that regulations and directives effectively force the industry into reusing materials from existing and future aircraft. This has driven research and investment from academia and industry towards the pursuit of discovering ways to use existing EOL CFRP and manufacturing waste CFRP in new products. Literature has also shown that the terminology remanufacturing or re-manufacture is used in a generally sense to describe the process of re-impregnating reclaimed fibres with new resin, creating rCFRP. In the authors' opinion, it is important to preserve the legitimacy of remanufacturing if a remanufacturing industry is ever to make the step change in society at large. A tool designed to help in this regard has been developed and presented in this paper. Using the flow chart documented, researchers from many different areas can quickly determine whether a set of EOL manufacturing process performed on EOL products result in the product being classed as recycled, re-used, repaired, reconditioned or remanufactured. The flow chart documented in this paper and the approach taken to inform the user about the state of a product is to the authors' knowledge unique. Currently, a researcher involved in EOL treatment for CFRP, or any product for that matter, if not already aware of recycle, re-use, repair, reconditioned and remanufacture would have to read literature and evaluate the practices performed on a product to determine if the product was recycled, re-used, repaired, reconditioned or remanufactured. Using the system presented here, the user would only need to answer a series of short questions with yes/no answers to arrive at the same conclusion. This system should help researchers involved in EOL CFRP avoid incorrect use of remanufacture terminology and be more accurate in their description of the manufacturing processes performed. Further benefits include, protecting remanufacturing status, raising remanufacturing awareness and providing new comers to the field and the general public with a quick and simply way of stating whether an EOL product has been recycled, re-used, repaired, reconditioned or remanufactured.

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