Recycling Carbon Fibre Reinforced Composites:

A Market and Environmental Assessment

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Abstract

Both environmental and economic factors have driven the development of carbon fibre reinforced polymer (CFRP) waste recycling processes. This paper will present the causes of increased use of carbon fibre composites as well as the consequences of such growth. As well, the advantages and disadvantages of three current recycling technologies available are discussed, focusing on fibre quality, commercial flexibility, and environmental impact. Chemical recycling produces best quality fibre with negative environmental impact while mechanical recycling produces bad quality fibre with good environmental impact. As a result, this paper argues that the best recycling method available today is a thermal process called conventional pyrolysis, because it produces good quality recyclate while being very energy efficient, tolerant to contamination and therefore also the best commercial candidate.

124 words

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Introduction

Carbon fibre reinforced polymers (CFRPs) are extremely advantageous materials in lightweight structural applications due to their high strength-to-weight ratio and resistance to corrosion (Xu, Li, & Ding, 2013). These materials are used in the aerospace, automobile, wind turbine, and sports industries. CFRPs are especially useful in aircraft applications mainly due to the material's weight-saving properties. CFRP use also contributes to large-scale reductions in fuel consumption and greenhouse gas emissions. In fact, new aircrafts such as the Boeing 787 and the Airbus A350 are composed of more than 50% carbon composite materials by weight (Pimenta & Pinho, 2011). The advantageous properties of CFRPs have lead to a large increase in its use. Over the past decade, the global demand for CFRPs has risen between 16,000 and 55,000 tonnes/year every year and is expected to reach 140,000 tonnes/year by 2020 (Witik et al., 2013). As a result of increased CFRP use, there has also been a rise in carbon composite waste.

Manufacturing waste accounts for approximately 40% of all CFRP waste, while the remaining 60% accounts for components at end-of-life (EoL). Notably, by 2025, 8500 commercial aircrafts will be decommissioned, representing more than 20 tonnes of CFRP waste per aircraft (Pimenta et al., 2011). Unfortunately today, most CFRP waste is landfilled due to technical and economical complexities of its recycling processes. Landfilling and waste incineration are extremely detrimental to the environment and promote disposal of non-renewable materials. As it happens, the European Union requires that by 2015, 85% of a vehicle must be reusable or recyclable (Morin, C., Loppinet-Serani, A., Cansell, F., & Aymonier, C., 2012). With increasing environmental regulations, it is important to find reliable CFRP recycling methods in order to preserve its use.

The following will discuss the various advantages and disadvantages of recycling carbon composites, as well as three possible recycling solutions: mechanical, thermal, and chemical recycling. It will be demonstrated that thermal recycling is the best available method today, in terms of environmental and economical impact.

Background

There is a strong need for the development of ways to sustainably reuse or recycle CFRPs. Fortunately, there are good economic incentives for recycling these composites. Carbon fibre is extremely expensive (up to 73$/kg) and consumes much energy to produce (up to 165 kWh/kg). Also, landfill disposal can cost up to 0.36$/kg (Pimenta et al., 2011). If the entire 140,000-ton global annual demand for CFRPs were to be landfilled this would represent a cost of $50.4 million per year and increasing due to scarcity of landfill space. Furthermore, industry suggests that by using pyrolysis to recover CFRPs, only 5-10% of the energy required to produce new or Virgin Carbon Fibre (VCF) is used (Witik et al., 2013). Despite these incentives, there are still important technical and commercial difficulties regarding CFRP recycling.

There are three main technical challenges to recycling carbon fibre composites. First, CFRPs use carbon fibres, woven together and mixed with thermosetting polymers (usually epoxy resin), which hardens to produce a solid part. Thermosetting polymers, unlike thermoplastic polymers, cannot be melted down or remoulded (S. Pickering, 2006). Thus, recovering CFRPs requires physical removal of the polymer. Second, the composite parts are often moulded with metallic inserts, cardboard honeycomb core, or hybrid composites (Pimenta et al., 2011). Removing these parts consists of additional time-consuming steps to the recycling process. Thirdly, there is great variability amongst carbon fibre waste products. Identifying and sorting different compositions together can be done somewhat easily with manufacturing waste, but is extremely difficult for EoL products where different kinds of CFRPs are often mixed together

(Witik et al., 2013). The separation and collection of different waste types makes the recycling process more time-consuming. Moreover, the best method must yield good results with a variety of wast products.

CFRP recycling also faces a few commercial issues. In order for CFRP recycling to become widely used, it is necessary to develop a "closed loop" (figure 1), a product life cycle that reuses an EoL product in a new product (Morin et al., 2012). For example, if the carbon fibre used in an airplane frame is to be reused in another airplane, the mechanical and physical properties of the recycled carbon fibre reinforced polymer (rCFRP) must be almost identical to VCF. If the recycled carbon fibre (RCF) does not meet the customer's needs (cheaper than VCF and good mechanical properties), then this loop will never be closed (Meyer, L. O., Schulte, K., & Grove-Nielsen, E., 2009). The available technologies today can yield mechanical properties very close to those of the virgin fibres. However, this is usually measured on a single-fibre basis (Witik et al., 2013). There is limited length and alignment of the fibres that can be obtained via recycling, reducing overall mechanical properties since length and alignment of carbon fibre are proportional to overall strength of CFRPs. Because of fibre length and alignment reduction, rCFRP from an airframe cannot be reused for construction of another airframe (Pimenta et al., 2011). Nevertheless, by "down cycling" the reuse of CFRP to non-critical applications, possible markets can be developed. For instance, a few structural car components as well as interior components for aircrafts such as arm rests have already been manufactured (Pimenta et al., 2011). Yet, before commercial recycling can become widespread, a few technicalities must be addressed. According to Pimenta and Pinho (2011), there is a need for stricter regulations and standards in recycling CFRPs, government incentives given to industries using RCF, and logistics must be well-organized between waste producers, recyclers, and RCF purchasers.

Figure 1 – Closed life-cycle for CFRPs from Pimenta & Pinho (2011)

It is now clear what obstacles exist both technically and economically for recycling CFRPs. However, it is also essential to evaluate the environmental impact of each recycling technique; the amount of energy and the possibly to toxic solvents used in producing RCF must be accounted for.

As previously mentioned, there are three main methods available today for recycling CFRPs: mechanical recycling, thermal processing through pyrolysis, and chemical recycling. Each technology has advantages and disadvantages with regards to quality of the recycled product and environmental impact of the process. Naturally, a method producing greater quality RCF will have a greater opportunity to develop markets using RCF. This thorough analysis will confirm that the current best solution for recycling CFRPs is conventional pyrolysis (a thermal process) due to the quality of the RCF produced, its minimal environmental impact, and since newer and better technologies lack repeatable proof.

Discussion

Mechanical Recycling

Mechanical recycling of CFRP waste, although a very simple solution, only produces recycled material that can be used in very specific and limited non-structural applications. The process involves crushing or cutting CFRPs down to sizes between 50μm and 10mm. The small fibres and powders produced can then be used as filler reinforcements in new composites or in the construction industry (artificial woods, asphalt or mineral sources in cement) (Pimenta et al., 2011). Recycled CFRP fillers can also be used in electromagnetic shielding or electrical conducting surfaces (S. Pickering, 2009). Environmentally speaking, the many steps needed to decrease the size of the fibres to a powder are extremely energy intensive (Morin et al., 2012). However, mechanical recycling does not use any corrosive chemical solvents. Quality wise, this process creates recycled fibres that are extremely short so that their architecture is very unstructured, coarse, and non-consistent. As a consequence, the mechanical properties are significantly reduced compared to VCF (Morin et al., 2012). Furthermore, the recyclate is coated in polymer residues, making it difficult to incorporate in new composites and achieve full reinforcement benefits (S. Pickering, 2009). Overall, mechanical recycling greatly reduces fibre quality and has very limited applications, making it a non-reliable process to implement for wide-scale reuse of carbon composites. It is therefore necessary to evaluate technologies that separate the polymer from the fibres, in order to preserve length, orientation, and strength.

Chemical Recycling

Chemical recycling yields the greatest results in terms of quality, but can have some market and environmental downsides. The most conventional process for chemical recycling is low-temperature solvolysis. This process uses reactive solvents to break down the chemical bonds of the polymer matrix in order to separate it from the CF (Morin et al., 2012). As shown in figure 2, useful chemicals can be extracted from the polymer matrix while the RCF retrieved has very high mechanical properties and fibre length (Morin et al., 2012). Because conventional chemical recycling is the most efficient method for obtaining good quality recycled fibres, it can be commercially promising. However, chemical recycling has very little tolerance for contamination. In fact, the only two existing plants in the U.S.A. and Japan both need to use pyrolysis processes before and after the chemical process in order to deal with impurities (Xu et al., 2013).

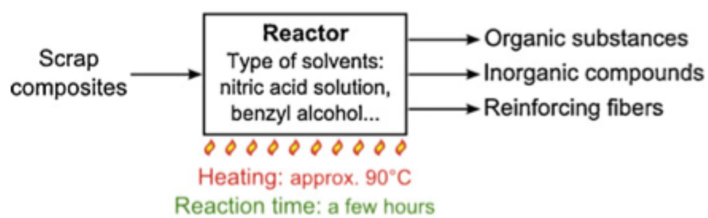

Figure 2 – Chemical Recycling: Solvolysis at Low temperature process from Morin et al. (2012)

Environmentally speaking, some of the chemical solvents used in low-temperature solvolysis can be toxic to the environment (Pimenta et al., 2011). Thus, chemical recycling is the least eco-friendly method compared to mechanical and thermal recycling. Fortunately, a more recent type of chemical process called sub- or supercritical fluid solvolysis has been recognized for producing RCFs with virtually no mechanical degradation while using non-toxic and inexpensive solvents (Morin et al., 2012). However, studies for this new technology have only been conducted in lab settings.

Ultimately, chemical recycling has the potential to produce great quality RCF but only under certain conditions and using toxic chemicals; there must exist other recycling technologies that sustain great fibre quality and that appeal to a variety of composites, all while being environmentally friendly.

Thermal Recycling through Pyrolysis

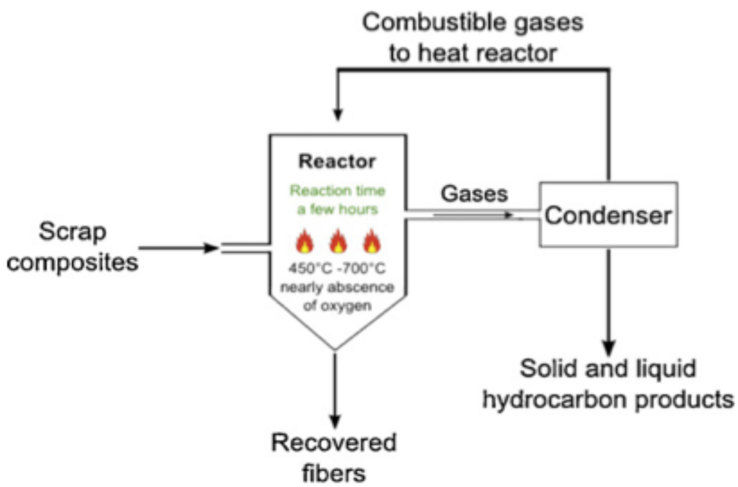

Figure 3 – Thermal Processing: Pyrolysis of CFRP waste from Morin et al. (2012)

The third type of recycling method for CFRPs is thermal recycling. The most common and efficient technology using a thermal process is called pyrolysis, which is superior to mechanical and chemical recycling both for economic and environmental reasons.

The pyrolysis process (figure 3) consists of heating CFRP waste between 450°C and 700°C in the near absence of oxygen, which decomposes the polymer matrix into gaseous form (Pimenta et al., 2011). At the end of the process, the carbon fibres are recovered with good mechanical properties and tensile strength between 4 and 20% less than VCF (Morin et al., 2012). These recycled fibres, as in chemical recycling, can be re-manufactured into new structural composites.

The quality of the recovered fibres is however lower than in chemical recycling, explained by the deposition of pyrolitic char on the fibre surface during the process. Pyrolitic char is the residue from the polymer that cannot be evaporated during the pyrolysis process. Having excess char results in reduced quality of bonding between the fibres and the new polymer, while too little char residue can cause damage to the fibres during heating which can reduce mechanical properties (S. Pickering, 2009). Thankfully, contamination with pyrolitic char can be avoided if the atmosphere during the process is controlled to allow oxidisation of the char (S. Pickering, 2009). However, the quality of the RCF is still very sensitive to the processing parameters (Pimenta et al., 2011). An excess of oxygen in the chamber will lead to slight burning of the carbon fibres and reducing fibre strength. Alternatively, too little oxygen in the chamber leads to excessive char formation thus reduced polymer bonding strength with the RCF. Nevertheless, pyrolysis is still the most commercially used method for recycling carbon composites due to the fact that it is much more tolerant of contaminated scrap materials than chemical recycling (S. Pickering, 2006). As such, there are pyrolysis plants in the U.S.A, the U.K., Germany, Italy, and Japan that recycle both EoL products and manufacturing waste (Pimenta et al., 2011). Recently, a less conventional type of pyrolysis using microwave heating has been developed, producing similar mechanical results and eliminating char residue. Similarly to new chemical recycling methods however, these results have yet to be seen and studied in industry. Another advantage of pyrolysis is that the gases produced can be burned in order to directly heat the chamber or to produce electrical energy (S. Pickering, 2009). Because of this attribute, pyrolysis is more energy efficient than chemical recycling, in addition to the fact that is does not use any toxic solvents (Morin et al., 2012) . Reports from industry suggest using pyrolysis consumes 5-10% of the energy required to produce VCF (Witik et al., 2013). Overall, pyrolysis produces good quality recyclate, and is energy efficient and environmentally friendly, making it the best candidate for recycling carbon fibre composites.

Conclusion

Use of carbon fibre reinforced composites continues to increase in industries such as the aerospace and automobile industries, where weight reductions lead to reduction of fuel consumption and emissions. In order for the world to continue benefitting from this material, increasingly more strict environmental regulation must be met, thus requiring proper disposal of carbon fibre at end-of-life. This study has demonstrated that, the current and most optimal technology for meeting commercial and environmental constraints is a thermal process called pyrolysis. The process of pyrolysis surpasses any other recycling methods in terms of ecological and economical impact. Pyrolysis yields slightly more toxic waste than mechanical methods yet is less energy intensive than both alternatives. This thermal process also produces much greater fibre quality than mechanical recycling and similar quality to chemical recycling. Unlike chemical recycling, pyrolysis can retrieve great quality RCF for a wide range of CFRP waste products. Industries worldwide seeking to recycle CFRPs should therefore use pyrolysis processes over chemical or mechanical methods, since it is clearly the best solution available today.

2,455 words

References

Meyer, L. O., Schulte, K., & Grove-Nielsen, E. (2009). *CFRP-recycling following a pyrolysis route: Process optimization and potentials*, 55 City Road, London, EC1Y 1SP, United Kingdom.

Morin, C., Loppinet-Serani, A., Cansell, F., & Aymonier, C. (2012). Near- and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: State of the art. *The Journal of Supercritical Fluids, 66*(0), 232-240. doi: http://dx.doi.org/10.1016/j.supflu.2012.02.001

Pickering, S. (2009). Recycling carbon fibre composites. *Materials World, 17*(12), 19-21.

Pickering, S. J. (2006). Recycling technologies for thermoset composite materials-current status. *Composites Part A: Applied Science and Manufacturing, 37*(8), 1206-1215. doi: 10.1016/j.compositesa.2005.05.030

Pimenta, S., & Pinho, S. T. (2011). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *Waste Management, 31*(2), 378-392. doi: http://dx.doi.org/10.1016/j.wasman.2010.09.019

Witik, R. A., Teuscher, R., Michaud, V., Ludwig, C., & Manson, J.-A. E. (2013). Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. *Composites Part A: Applied Science and Manufacturing, 49*, 89-99. doi: 10.1016/j.compositesa.2013.02.009

Xu, P., Li, J., & Ding, J. (2013). Chemical recycling of carbon fibre/epoxy composites in a mixed solution of peroxide hydrogen and N,N-dimethylformamide. *Composites Science and Technology, 82*, 54-59. doi: 10.1016/j.compscitech.2013.04.002