Carbon Fibre Recycling

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Abstract

Carbon fibre strengthened plastics (CFRP) are composite materials that comprise of carbon strands installed in a polymer grid, a blend that yields materials with properties surpassing the individual properties of every part. CFRP has a few favourable circumstances over metals: they offer better quality than weight proportions and better opposition than consumption and substance assault. These key attributes, alongside ongoing enhancement in assembling methods, have brought about fast development in the quantity of CFRP items and applications particularly in the aviation/flying, wind vitality, automotive, and donning products ventures. As the use of this material increases, so has waste. This has created a huge need for recycling both from obsolete products and from production waste. In spite of existing restrictions to recycling, the industry is growing. Current carbon fibre recycling processes incorporate mechanical, chemical, and thermal methods. The major limitation of CFRP reusing is the capacity to recuperate materials of high-value and maintain their unique properties. To this end, the most appropriate process based on the examination of the pros and cons of each approach is chemical processing, where the polymer bonds can be separated and expelled from the material, with minimal harm to the fibres. This can be accomplished utilizing high fixation acids, even though such a procedure is not the safety because of the toxic levels of such chemicals. However, there is hope for better recycling processes as technology and research advances.

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Introduction

Carbon Fiber is a composite material made from either natural or a synthetic polymer that is also commonly called graphite fibre or Carbon Fibre Reinforced Polymers (CFRPs) that simply comprises of fibre reinforced plastic. It is widely used in various manufacturing processes for its unique attributes: strong and very light. These factors make the material a desirable replacement for most metals where strength and weight need to be balanced. To put this into perspective, CFRP is five-times stronger than steel and twice as stiff. These are just a few reasons why carbon fibre is favoured by engineers and designers for manufacturing. Given its properties, carbon fibre has become one of the most widely used materials in the auto-manufacturing industry and even in industrial processes including the manufacture of bike frames, aircraft wings, shipping containers, propeller blades and various automobile parts. With increased use comes increased waste after use and remnants of the manufacturing process. As millions of cars from the around the world are shipped into demolition yards, so are tons of carbon fibre that may end up in landfills complicating an already choked environment. This paper looks at the necessity carbon fibre recycling, the available methods and the pros and cons of each method by drawing support from relevant literature.

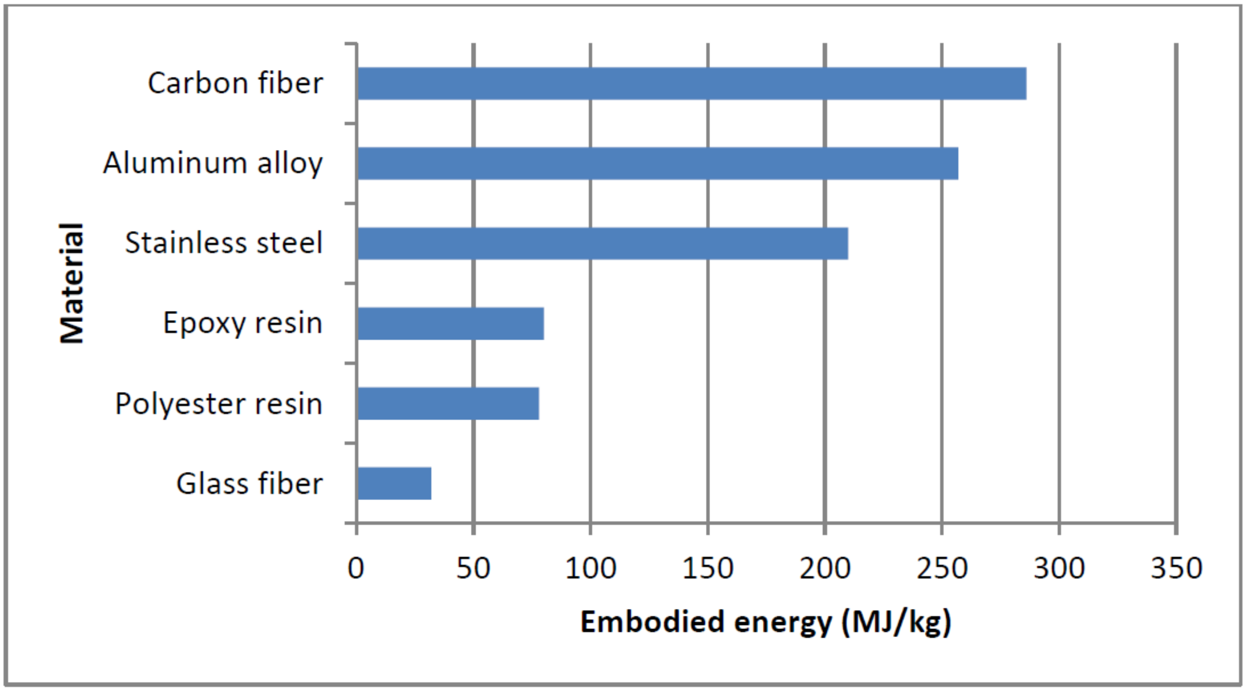
The Necessity of Carbon Fibre Recycling

Increased use of CFRPs in various industries has created a huge amount of waste that needs to be managed well. As a matter of fact, new aircrafts such as the Boeing 787 and the Airbus A350 are composed of more than 50% CFRPs materials by weight, which translates to a bigger percentage by volume given that the material is very light (Pimenta & Pinho, 2011). Over the past decade, the demand for carbon fibre in the global market has increased by about 16,000-55,000 tonnes/year and is expected to hit 140,000 tonnes/year by 2020 (Witik et al., 2013). Contingent upon the source material, the fibres contain distinctive levels of carbon determined by the desired strength/tensile and electrical properties. Initially, CFRPs were made from cellulose and created by means of pyrolysis. Today, distinctive carbon sources such as pitch or customized polymers are common depending on the desired properties of the material. Nonetheless, the majority of CFRPs manufactured today and open to recycling are based on polyacrylonitrile (PAN).

With increased usage, there is bound to be more waste generated. The majority of the waste comes from the CFRP manufacturing processes and from the disposal of materials made from CFRP. Witik et al., (2013) estimate that manufacturing operations generate about 24,000 tonnes of waste carbon fibre annually. With the industry expanding exponentially, the waste levels will likely hit 32,000 tonnes by 2021. Such estimates are not far-fetched. Carbon fibre has a dirty secret that many players in the industry are not willing to reveal: the hi-tech material is profligate to manufacture and challenging to recycle. For it to become the tough, light composite material loved by automobile and aero manufacturing plants, carbon fibre is made from covering the fibre with either synthetic or natural polymer resin. Normally, the material is produced in large sheets similar to flat iron sheet panels but it is hard to mould once manufactured. Again, the sheets of composite material handled manually making the process wasteful in terms of the material and even energy consumed. Such a situation makes it necessary to consider recycling the material.

Again, there are good financial incentives for recycling CFRPs. The compound 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 the 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). In spite of such worrying figures, governments and industry players have failed to improve recycling patterns. A US Senate committee report on energy and natural resources says that the Washington state alone has 96 composite companies producing two million pounds of production waste carbon fibre annually that ends up in landfills. Such waste has a potential market value of $50 million if it can be reused and recycled (S. 1432, the Carbon Fiber Recycling Act of 2015 By Sen. Maria Cantwell (D-Wash.).

Ideally, to comprehend monetary and natural advantages, the typified energy demand for common materials during their production life cycle must be thought about. The investigation of needed energy levels gives the aggregate energy inputs devoured by the material from the start to other life cycle stages. Fig 1 demonstrates the epitomized energy requirements of common materials used in industrial and manufacturing processes. The virgin carbon fibre has the most elevated epitomized vitality in light of the fact that the assembling procedure for carbon fibre requires high temperature amid carbonization. What's more, two other real handling stages for carbon that requires huge utilization are oxidization and adjustment.



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Other than cost, strict regulations on environmental conservation call for increased recycling of materials where applicable. As it happens, the European Union requires that by 2015, 85% of a vehicle must be reusable or recyclable (Morin, Loppinet-Serani, Cansell, & Aymonier, 2012). The US has yet to create laws that mandate firms to invest in carbon fibre recycling. With increasing environmental regulations, it is important to find reliable CFRP recycling methods in order to preserve its use. Rush (2007) attributes the low uptake of carbon fibre recycling to stigma associated with products made from recycled materials noting that individuals usually associate recycled materials with soda cans but not aircraft or automobile parts despite the fact that recycled carbon fibre strands retain 90 to 95 per cent of their unique properties and are viewed as of higher quality than some VCF used in auto-manufacturing.

Common Challenges to Recycling Crfp

Despite the necessity for recycling the compound, there are some key hindrances. Recycling CFRP is problematic in that it cannot simply be recycled through melting and transformed like aluminium or steel, as the key manufacturing materials the composite has replaced. Carbon fibre composites get their strength from long, precisely aligned carbon fibres, fixed within a glue-like polymer that is cured at high temperatures and pressures. Once cured, most of these tough polymers will not melt and have to be burned off or chemically dissolved to reclaim the valuable fibres. Such recycling options could be expensive and sometimes defeat the purpose of reprocessing with manufacturers opting to use fresh materials.

Thus, there are three key methodical difficulties to reusing carbon fibre composites. To begin with, CFRPs use carbon filaments, intertwined together and blended with thermosetting polymers (e.g. epoxy resin), which solidifies to make the end material strong and tough. Unlike thermoplastics, thermosetting polymers become irreversibly hardened once cured meaning that they cannot be remoulded to other desired shapes (Pickering, 2006). Consequently, recouping or reusing CFRPs requires the physical abstraction of the polymer from the final material.

Secondly, the composite parts are usually reinforced with metallic components, cardboard honeycomb centre, or crossover composites (Pimenta et al., 2011). Thus, the recycling process requires the evacuation of these additional materials thereby making the recycling process extra tedious and time-consuming. These types of CRFPs have increased their desirability in the infrastructure industry given that when they are reinforced with unidirectional high strength twisted steel wires, the strength increases to about seven times that of regular steel reinforcing bars. As such, the material is widely used in the construction of bridges and may soon find its way in the construction of high-rise buildings. The situation means that the recycling of CRFP might not just involve small components such as automobile parts but monster constructions which capture the other core challenge in the recycling process.

Thus, the third core challenge is the fluctuation in the nature, size, and composition of CRFP for recycling purposes. Identifying and sorting distinctive CRFP compositions is challenging and time-consuming. This is mainly because the ability to customize carbon fibre by incorporating other materials implies that oftentimes, materials targeted for recycling often comprises more than five materials. This further complicates the recycling process as more than one recycling process is required.

The other key challenge to the recycling of CRFP pertains to the availability of a market for recycled materials. There is restricted length and arrangement of the filaments that can be acquired by means of reusing, diminishing generally mechanical properties since length and arrangement of carbon fibre are corresponding to the general quality of CFRPs. Due to fibre length and arrangement decrease, CFRP from an airframe can't be reused for development of another airframe (Pimenta et al., 2011). All things considered, by "downcycling" the reuse of CFRP to non-basic applications, conceivable markets can be created. For example, a couple of auxiliary vehicle segments and also inside segments for flying machines, for example, armrests have just been produced (Pimenta et al., 2011). However, before business reusing can wind up boundless, a couple of details must be tended to. As indicated by Pimenta and Pinho (2011), there is a requirement for stricter directions and gauges in reusing CFRPs, government incentives to private firms utilizing RCF, and coordination must be efficient between waste makers, recyclers, and RCF buyers.

Types of the recycling process

There are two main technology families available today for recycling CFRPs:

- Mechanical recycling and
- Fibre reclamation

Mechanical

Mechanical reusing includes breaking– down the composite by destroying, smashing, processing, or other comparable mechanical processes; the subsequent piece would then be able to be isolated by sieving into powdered or pellet forms (wealthy in pitch) and fluffy or fibrous items (rich in strands). Typical applications for mechanically–recycled composites include their re-incorporation in new composites (as filler or reinforcement, Pickering 2006) and use in the construction industry (e.g. as fillers for artificial woods or asphalt, or as mineral–sources for cement, (Conroy et al. 2006). However, these products represent low–value applications hence the technologies are not suited to high-value products. The two major processes in this family are pyrolysis and chemical processes.

Chemical recycling

Compound reusing yields the best outcomes as far as quality, yet can have a few showcase and natural drawbacks. The most ordinary process for substance reusing is low-temperature solvolysis. This procedure utilizes responsive solvents to separate the substance obligations of the polymer network so as to isolate it from the CF (Morin et al., 2012). As appeared in figure 2, valuable synthetic concoctions can be separated from the polymer network while the RCF recovered has high mechanical properties and fibre length (Morin et al., 2012).

Since ordinary compound reusing is the most effective technique for getting great quality reused filaments, it can be monetarily encouraging. Nonetheless, substance reusing has next to no resilience for defilement. Indeed, the main two existing plants in the U.S.A. furthermore, Japan both need to utilize pyrolysis forms when the synthetic procedure so as to manage debasements (Xu et al., 2013).

Naturally, a portion of the synthetic solvents utilized in low-temperature solvolysis can be poisonous to nature (Pimenta et al., 2011). Along these lines, substance reusing is the slightest eco-accommodating technique contrasted with mechanical and heat reusing. Luckily, a more late kind of compound process called sub-or supercritical liquid solvolysis has been perceived for creating RCFs with no structural damages while utilizing non-harmful and reasonable solvents (Morin et al., 2012). In any case, examines for this new innovation has as it was been led in lab settings. At last, compound reusing can possibly deliver extraordinary quality RCF however as it were under specific conditions and utilizing dangerous synthetics; there must exist other reusing innovations.

Advantages of chemical recycling

- High maintenance of mechanical properties and fibre length
- High potential for material-recuperation from resin

Disadvantages

- Regularly reduces adhesion to polymeric resins affecting structural stability and strength
- High likelihood of contamination

- Lessened adaptability of most strategies in most recycling plants
- Conceivable ecological effect if toxic solvents are utilized

Thermal recycling (pyrolysis)

The pyrolysis process involves heating CFRP waste between 450°C and 700°C in oxygen-deprived space (inert environment), which decomposes the polymer matrix into gaseous form (Pimenta et al., 2011). Thermal treatment in oxygen-controlled environments partially burns the fibres reducing the quality of the CRFP. A relatively higher amount of oxygen in the chamber will lead to slight burning of the carbon fibres thereby reducing their strength. Alternatively, too little oxygen in the chamber leads to excessive char being formed thus reduced polymer bonding strength with the RCF. 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). A new pyrolysis process involving microwave heating has been developed, producing similar mechanical results and eliminating char residue. These recycled fibres can be re-manufactured into new structural composites.

The point of pyrolysis is the heat deterioration of the framework in a sans oxygen condition, consequently uncovering and saving the strands. Amid pyrolysis, the macromolecular framework is changed over into pyrolysis gases, for the most part, carbon monoxide, hydrogen, methane and other, generally short affixed alkanes. The pyrolysis gases can along these lines be burned and used to fuel the pyrolysis procedure.

While diverse fibre types by and large carry on contrastingly when exposed to high temperatures, thermogravimetric estimations demonstrate no weight reduction of unadulterated strands amid pyrolysis notwithstanding for delayed stay times. Fibre damage due to the high temperatures involved in the pyrolysis process can be considered to be insignificant. This further relates to the strands being produced under pyrolytic conditions in any case, with generally fibre types having recently persisted temperatures up to 3,000 °C.

The network polymers anyway don't completely break down into just vaporous parts, yet rather leave strong buildups, for example, roast, residue and other carbonates. Due to these carbon buildups, unadulterated pyrolysis items are solid, fragile and difficult to isolate without harming them. A great reuse of strands appears to be in this way inconceivable. So as to free the strands from their carbon coverings, the pyrolysis items would then be able to be oppressed to a brief timeframe introduction of oxygen at higher temperatures. The oxygen oxidizes the carbon buildup and uncovered the fibre. Then again, a specific low level of oxygen can be straightforwardly brought into the pyrolysis procedure. While the two techniques are powerful at decreasing the carbon outside layers, both additionally harm the carbon filaments. The subsequent filaments have elastic qualities of around thirty to eighty per cent contrasted with virgin carbon fibre.

Advantages

- Pyrolyis can be more efficient in that the gases produced can be burned in order to directly heat the chamber or to produce electrical energy making the process self-sustaining (Pickering, 2009). This attribute makes pyrolysis more energy efficient than chemical recycling and does not use of release any toxic compounds (Morin et al., 2012).

In fact, Witik et al., (2013) suggests that using pyrolysis consumes 5-10% of the energy required to produce Virgin Carbon Fibre (VCF).

- It allows the recycling of waste mixed plastics that cannot be efficiently recycled by alternative means such as chemical recycling
- Pyrolyis is suited to the recycling soiled and already contaminated plastics including plastics used for mulching, greenhouse and drip irrigation.
- Recycling of plastic covers, coextrusions and multilayer bundling films, especially those with aluminium layers that are hard to reprocess using alternative recycling methods.

Disadvantages

- Huge corruption of mechanical properties
- Unstructured, coarse and non-predictable fibre structure.
- Limited potential for reuse in major industries

Oxidation in fluidised bed

Oxidation is another warm procedure for CFRP reusing; it comprises in combusting the polymeric composite in a hot and oxygen-rich stream (e.g. air at 450 ◦C to 550 ◦C). This strategy has been utilized by researchers and there are well-documented records of its applicability (Pickering 2006). In testing the method, Pickering used CFRP scrap (chopped into roughly 25 mm pieces) fed the compound into a bed of silica on a metallic mesh made of high heat tolerance metal. As the hot air ruses through the bed and breaks down the tar, both the oxidized atoms and the fibre are conveyed up by the air stream, while heavier metallic segments soak in the bed; this normal isolation makes the FBP especially appropriate for dirty and contaminated EoL parts. The filaments are isolated from the air stream in a strong air current, and the resin is fully– oxidized in an afterburner. The energy– recuperation process makes the procedure attainable and energy efficient (Pickering 2006).

Advantages

- High resilience to degradation
- Does not retain residual tar on the fibre surface
- Entrenched process

Disadvantages

- Reduced quality somewhere in the range of 25% and 50%
- Decreases fibre length
- Unstructured ("cushy") fibre structure
- Does not permit recovery of components of the resin

Fiber Reclamation

Fiber reclamation comprises on recuperating the filaments from the CFRP, by utilizing intense heat or chemicals to break– down the composite. The fibre strands are discharged and gathered, and either energy or molecules can be recouped from the process. Fibre recovery is usually carried out after primer tasks such as cleaning and mechanical sizing to reduce waste. These methods are appropriate to CFRPs: carbon filaments have high warm and substance security (Pickering 2006), so, for the most part, their magnificent mechanical properties are not fundamentally corrupted (particularly with respect to firmness). The rCFs have a perfect surface and mechanical properties practically identical to VCF.

Application of rCFRP and rCF

Given that the recycling process applied may affect the quality of recycled products, there is a need to examine the potential use and application of rCF to make the process relevant and self-sustaining. The rCFs are usually fragmented into short lengths mainly due to the reduced size of sheets before the reclamation process, fibre breakage during recycling and intentional chopping of the fibres after recycling. Additionally, the recyclate is in a filamented, random, low–density–packing (fluffy) after the removal of the fibres making unusable in that state. There are four main methods or reuse namely: direct moulding, compressed moulding of non-woven products, compressed moulding of aligned mats, and impregnation of woven.

Direct moulding

This method involves moulding materials in a semisolid state to fit pre-made moulds. The moulds can be injected directly where a mixture of resin and sCF and additives in form of pellets are injected into a mould and pressed. The other method is the bulk moulding compound process that involves mixing resin, fillers and curing agents into bulky charges. These processes are advantageous in:

- There are already tried and tested procedures
- Execution fits well with low or medium appliances targeted for recycling

Disadvantages

- The end product has very low fibre contents ($V f < 20\%$)

- Reduced fibre length affecting structural properties
- The method is complicated and difficult due to rCFs' filamentised form

Compressed moulding of non-woven products

The production and subsequent re-impregnation of 2D or 3D rCF non-woven dry products is one of the most popular reuse methods of rCF and follows the same procedure similar to paper production.

Advantages

- Procedure requires minimal adjustments from one plant to another hence easily replicable
- Processes generally utilized for CFRP and very researched and documented for referral purposes
- Mechanically recycled CFRP identical to VCF
- Potential application in car and aeronautical engineering

Disadvantages

- Commonly experiences fibre damage during compression moulding
- A highly competitive market dominated by relatively cheap materials

Compressed moulding of aligned mats

The method is a key point to improve the mechanical performance of rCFs (Pickering 2009). It not only improves the material's mechanical properties but also improves preferential fibre direction and alignment as manufacturing requires lower moulding pressures and smoother fibre–to–fibre interactions (Turner et al. 2009).

Advantages

- Enhanced uniaxial mechanical properties
- The possibility of fitting the lay-up of rCFRP covers
- Useful for protecting fibre length and accomplishing higher strength

Disadvantages

- The process demands near-perfect arrangement to fundamentally enhance packability
- Technology is at initial stages and calls for considerable advancement of procedures

Impregnation of woven rCFRP

Through this method, it is conceivable to recoup the organized weave from substantial woven things, e.g. pre-preg moves, and airship fuselage. Re-impregnating the recycled interlaced fibre textures at that point produces woven rCFRPs.

Advantages

- Organized engineering with ceaseless strands and high support content
- The simplicity of assembling forms
- Applicable demonstrators effectively produced

Disadvantages

- Suitability only limited to pre-preg EoL rolls
- Scant knowledge on the ability of the process to retain mechanical properties of CF

Conclusion

The research paper has provided an extensive overview of the technology and market standpoint for CFRP recycling operations. The paper has covered the necessity of recycling and re-fabricating forms and the commercialisation difficulties and potential markets for the recyclates. A basic examination between reusing forms demonstrated every one of them to have explicit advantages and drawbacks recommending complementarity instead of rivalry. The vast majority of carbon fibre recycling processes yield products with high mechanical properties that has motivated the advancement of the industry with the emergence of numerous plants globally. Reclaiming composites with rCFs was observed to be challenging in the current market, technological, and cultural environment, particularly with respect to high mechanical properties associated with VCF and demanded of rCF. Nonetheless, the attributes of rCF from some processes have been able to overcome some of the major challenges in terms of quality that have discouraged recycling of CF and even made the venture uneconomical. The future of the industry can only get brighter with governments and scholars interested more in addressing the environmental challenge that has dominated global political and economic affairs. The author, therefore, recommends that players in the industry especially aeronautical engineering and auto-manufacturing be given enough incentives to motivate carbon fibre recycling. This is even more important in the age of electric vehicles and unmanned aerial vehicles that demand lighter and sturdier materials for increased efficiency. As an academic assignment, the exercise was not only enlightening but also fulfilling for a person who holds environmental and technological matters dearly.

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