IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.53
Volume 4, Issue 4, April 2024

Recycling of Carbon Fiber-Reinforced Composites-A Review

Charitidis J. Panagiotis
Environmental Engineering
Democritus University of Thrace, Xanthi, Greece

Abstract: *An important aspect of composite materials concerns the technologies of recycling carbon fibre-reinforced composites. Composite materials present an exciting combination of properties depending on the nature of the matrix and fibre. Such materials as carbon fibre-reinforced composites can replace a variety of materials, providing lighter constructions. The global recycled carbon fibre market is projected to reach 222 million $ by 2026, at a compound annual growth rate (cagr) of 12%. However, the environmental impacts of composite materials at the components' end-service-life make the key challenge of increasing resource efficiency by turning waste into reusable materials. Conventional technologies for recycling carbon fibre-reinforced composites are quite complex and require expensive facilities.*

Keywords: composite materials; carbon fiber-reinforced composites; recycling techniques; chemical recycling; subcritical fluids; supercritical fluids; supercritical alcohols

I. INTRODUCTION

Many materials are effectively composites. This is particularly true of natural biological materials, which are often made up of at least two constituents. Nowadays, a wide range of reinforcements, mostly in the form of fibres (glass, carbon or aramid) are available. A prime concern is the mechanical properties needed in the automotive, aerospace, transportation, and energy sectors [**1-11**]. Consequently, composites are fast becoming the material of choice [**12**], depending on the required strength, stiffness, corrosion resistance, and budget. Another important issue is fibre cost, where carbon fibre is more costly than glass. Carbon fibres are almost ten times more expensive than carbon fibres, while carbon fibers present better mechanical properties (e.g., tensile strength). Prices range from around $7/lb for 48K or heavy tow to around $15/lb for 12K or aerospace-grade tow and into the $100/lb range for very high-performance grades [**13**]. However, recycling carbon fibre composite materials is complex due to their hardness and chemical stability [**14**]. The first aircraft with structural CFRP components will soon be decommissioned [**15**], as well as, 8,500 commercial planes' service life will end by 2025 [**16, 17**], with each aircraft representing more than 20 tons of CFRP waste [**18**]. Recycling is better than waste materials being disposed of in landfill and fulfilling legislative targets. Turning carbon fibre-reinforced composites waste into a valuable resource is vital for the continued use of the material in some applications [1**9,20**]. The conventional ways of disposing of waste such as landfilling, and incineration cause a negative environmental impact and are no longer preferred under the European Union's Waste Framework Directive (Directive 2008/98/EC) [**21**].

Moreover, environmental legislation in some countries has demanded companies recycle up to 85% of all weight of end-of-life products and recover 10% of them as energy starting from 2015 [**22**]. Recycling remains a relatively new area, and the recycling rate is quite low [**23-28**]. In literature, different thermal (pyrolysis), chemical (solvolysis), and mechanical (crushing and grinding) methods have been discussed to recycle composite materials [**29- 35**].The main question that arises is how good the performance of the recycled carbon fibre and its composite is. To answer this question must be considered the composition of the material, the type of the resin as well as the combinations with other materials for metal fixing, honeycomb, hybrid composites and others. This paper is concerned with the understanding of recycling methods of carbon fibre reinforced polymer (CFRP) composite materials.

DOI: 10.48175/IJARSCT-17474

II. COMPOSITE RECYCLING METHODS

Composite materials have simplified modern life (aerospace, transportation, wind energy, pipe and tank, etc.).According to projections, the composite materials market is anticipated to achieve a valuation of approximately $126.3 billion by 2026, exhibiting a compound annual growth rate (CAGR) of 7.5% during the period from 2021 to 2026.

An important aspect of composite materials concerns the technology by which they are produced (filament winding, pultrusion, and resin transfer moulding). A large amount of waste is produced during manufacturing cut-offs, out-of-date prepregs, production tools, as well as testing materials. Researchers concentrate on looking for new composite materials and developing better, optimized fabrication processes to lower fabrication costs and upgrade the material properties [**36, 37**].

The disposal process evolves toxic substances which may affect the living organism as well as the environment. It is immediately noticeable that parameters such as environmental and economic are the crucial aspects of recycling directions today [**38**]. Depending on the nature of the matrix and fibre, recycling at a reasonable cost can be a challenging problem. Concern for the environment, limiting the utilization of finite resources, and the need to manage waste disposal, have led to increasing pressure to recycle materials at the end of their useful lives [**39**]. Recycling of composite waste is economically favourable, however, legislation must be stricter [**12**]. It is crucial to modify composite waste into a valuable resource and close the loop within the composite life cycle [**19, 40, 41**]. Some of the most useful recycling procedures are described as follows.

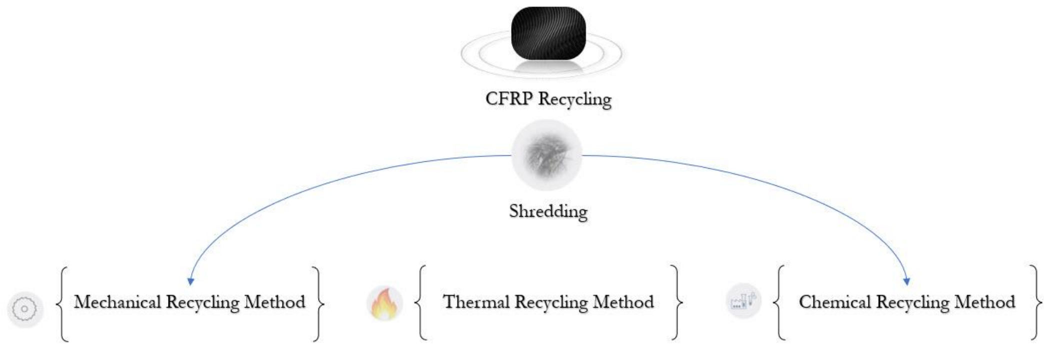

Fig. 1 CFRP recycling methods.

A. Mechanical Recycling

In the basic processing route, crushing or cutting is used to reduce scrap composite size. The percentage of CFRP scrap that can be recovered through mechanical recycling is typically in the range of 20-40%. This means that for every 100 kg of CFRP scrap, 20-40 kg of the scrap can be recycled into new products. The remaining 60-80% of the scrap is either too contaminated with resin or is too small to be recycled. The exact percentage of scrap that can be recovered depends on several factors, including the type of CFRP, the condition of the scrap, and the recycling process used. The equipment comprises (a) crushing, (b) grinding, (c) milling, and (d) shredding onto fine fibres and fine powder using cyclones and sieves. Component scrap sizes can be dependent on the speed of the crushing mill. Slow-speed crushing mills can reduce the scrap composite size to 50μm –100 mm while in high-speed milling, the components will be reduced between 50μm and 10mm [**42**]. However, a slow-speed crushing mill depends on the homogeneity of the composite, which means scrap material without any metal component. One of the main consequences of a fine recycled CFRP is the difficulty of minimizing energy consumption as well as the processing time. The energy demand of mechanical grinding lies between 0.1-4.8 MJ/kg, depending on the used machinery and process scale [**43**]. Recycled CFRP materials present lower mechanical properties than virgin CFRP materials [**16**] and are not suitable for lightweight or high modulus/strength applications. Fine recycled CFRP materials tend to increase economic and fibre property loss. That means such fine recycled materials can be used as fillers in short-fibre composites, especially as possible ingredients in concrete or other thermoplastic composite materials [**44, 45**]. Mechanical processes such as grinding have been applied to glass fibre-reinforced composites [**32, 46**] and carbon fibre-reinforced composites [**32, 47–50**]. Of interest for mechanical recycling is both the environmental and economic advantages. For instance, this process does not use any corrosive chemical solvents and does not produce any atmospheric or water pollution. However, continued flow is needed to minimize the amount of waste, while the mechanical equipment is not expensive. The mechanical properties of recycled CFRP materials are significantly lower than those of virgin CFRP materials (**table 1**).

TABLE I Mechanical properties of recycled CFRP.

Matrix	V_f(%)	E_T (GPa)	X_T (GPa)	U_{imp}(KJ/m2)	**Literature**
PP	24	21	101		[**49**]
ABS	24	12	102	19	[**50**]

Another mechanical recycling approach, high voltage fragmentation (HVF), involves several pulses to separate matrices from fibers [**51**]. The number of pulses determines the energy demand, efficiency as well as quality of the fibres. It has been mentioned that the lowest number of pulses gives the best energy demand and efficiency, but this gives lower-quality fibres [**51**]. A serious weakness of this process is that is too energy intensive compared with mechanical grinding (6.7 MJ/kg at 1.2 kg/h). However, both processes demand maximum capacity to make use of the basic energy demand of the machine [**52**].

The specific energy for HVF is at least 2.6 times higher than mechanical grinding. During the HVF process, the amount of residual resin varies between 32% and 37%, compared to 49-59% for mechanical grinding. With mechanical grinding, the length of the fibre is 5mm, compared with the HVF where the maximum retrieved fibre length spread to up to 9mm. The retrieved fibre presents a 20% reduction in mechanical properties.

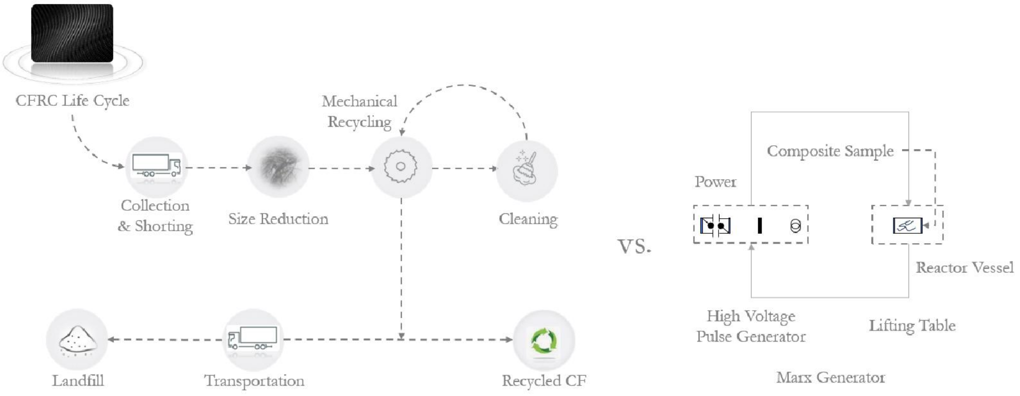

Fig. 2 Mechanical recycling process and high voltage (pulse) fragmentation process.

B. Thermal Recycling

B1. Pyrolysis

Pyrolysis is a thermal process which provides both economic and environmental issues when compared to mechanical and chemical recycling processes. This process (figure 3) was developed for recycling both CF and GF [**53**] and is dependent on atmospheric conditions such as a vacuum atmosphere, nitrogen atmosphere and superheated steam atmosphere which separate fibres from the solid pyrolysis products. Scrap CFRP composites are heated in the absence of oxygen between 450°C and 700°C in the near absence of oxygen, which decomposes the polymer matrix into gaseous form [**16**], depending on the nature of the scrap composite [**16, 54**]. Between 450°C and 700°C, all the organic matter decomposes into gases and is then partially condensed into a liquid. If scrap materials are heated between 500°C and 600°C, oxidation occurs. During oxidation, it is possible to completely remove resin residues. At temperatures below 500°C, the oxidation process of the char is relatively slow, resulting in an impractical timeframe for obtaining clean carbon fibers. Conversely, when the oxidation temperature exceeds 600°C, the carbon fibers undergo rapid combustion, leading to damage to the fibers.

Nevertheless, during oxidation an oxygen-rich surface is created. Such a surface will improve the adhesive nature of the fibre with resins [**55**]. As already mentioned in the mechanical recycling method, shredding preparation is also required in the pyrolysis method. By using pyrolysis, oil and gas products can be produced, and products like that can be used as chemical feedstock for any other process. The ratios of these products depend on the composite type and resin content [**56, 57**]. According to reports [**57, 58**], the composition of pyrolysis oil closely resembles that of heavy crude oil or fuel oil, possessing a calorific value ranging from approximately 30 to 37 MJ/kg.

As with any other recycling method, limitation such as the possibility of char formation on the fibre surface is the most challenging [**38**]. Pyrolytic char is the residue from the polymer that cannot be evaporated during the pyrolysis process. The presence of excessive char tends to reduce the 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 [**59**]. By suitable choice of the final temperature, some control is possible over the mechanical properties. The r-CF obtained from the pyrolysis process at a temperature of 500^{o}C has exhibited a reduction in tensile strength of 15% [**60**]. Compared to v-CF heated in air at the same condition, r-CF was found to lose about 25% in tensile strength (**table 2**).The mechanical properties of pyrolysis-recycled CFRP materials are lower than those of virgin CFRP materials, but they are not as significantly lower as the mechanical properties of mechanically recycled CFRP materials.

An elevated temperature of 1000 °C can be applied but it will result in significant degradation of the mechanical properties of the fibre products. At 1300°C this substance is completely removed, and the fibres are perfectly clean with highly activated surface, but their strength is significantly reduced [**61**]. The thermoset composite is heated to a temperature between 400–1000^{o}C enabling recovery of long carbon fibres with high modulus [**38**], which also exhibit 50–85% of the tensile strength of virgin carbon fibres [**62**]. The fibres also seem to have different sensitivity to pyrolysis conditions depending on their type [**61, 63, 64**]. In one study [**65**], the surface oxygen content of the recovered fibres was observed to be 83% higher compared to the virgin fibres. However, in another study [**66**], a reduction of approximately 18% in the surface oxygen content was found. Despite these differences, both studies noted that the oxygen in the recycled carbon fibres was present in similar bonds to the virgin carbon fibres. As a result, the recycled carbon fibres would still be compatible for bonding with a polymer matrix in composite applications.

To keep away the creation of char on the fibre surface, microwave is also reported [**67**]. In that case, the conventional heating source was replaced with microwave radiation. This method requires less energy consumption to increase the rate of thermal transfer without interfering with the principle of pyrolysis.According to a reference [**68**], it has been reported that a complete elimination of resin, reaching a ratio of 100%, was achieved within 300 seconds using a microwave operating at 700 W and 2.45 GHz. This process was conducted under an argon atmosphere with a flow rate of 2.5 l/min.

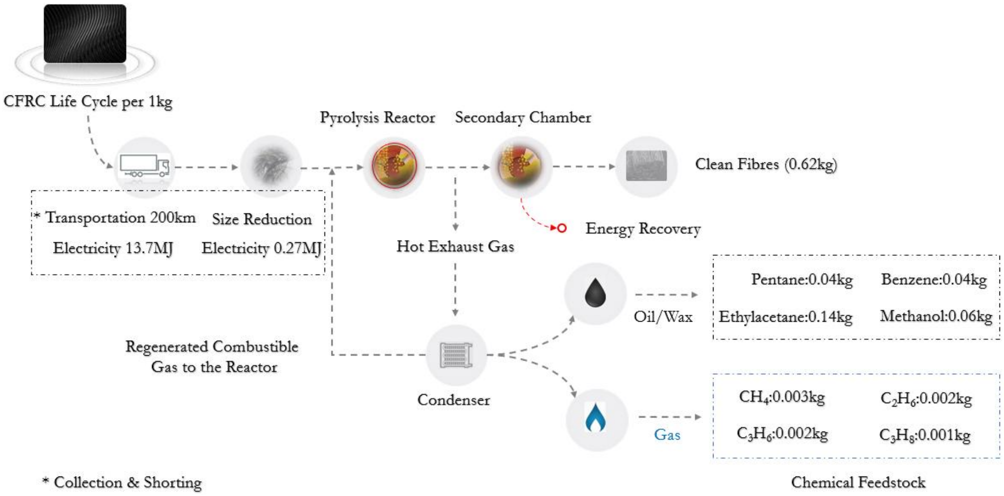

Fig. 3 Pyrolysis process flow diagram (modified from Pickering et al. [33]).

The r-CF had just a 0.7% decrease in tensile strength compared to v-CF. Similarly, CFRP recycling has also been conducted at 500°C for 30 min with a 0.70 m^3 min^{-1} nitrogen flow rate. The r-CF shows a clear fibre surface with mechanical properties very close to virgin fibres [**69**]. The pyrolysis gases are mainly CO_2 and CO, with a hydrocarbon gas content of less than 10%. Typically, the calorific value is relatively low, measuring around 14 MJ/Nm3 [**70**] or less than 18 MJ/kg. However, gases derived from epoxy and polypropylene exhibit a higher calorific value due to their methane and propene content, respectively. These gases have calorific values ranging from 42 to 44 MJ/kg [**71**].

B2. Other Alternative Pyrolysis Processes

There are also alternative processes for the pyrolysis processes for the recycling of carbon fiber composites. The treatment conditions of the pyrolysis process play a great role in the resulting properties, as do the different fibre types. There are three main processes such as superheated steam process, catalytic process, and gasification process. A simple overview of the processes is given in the next sections.

B2.1 Superheated Steam Process

In the basic processing route carbon fiber composites are heated at a uniform heating temperature of 550°C in a SiC furnace for 60 minutes [**72**]. In this process the key parameter is time. In literature has mentioned that reducing the time by 50% leads to a 10-15% decrease in fibre tensile strength and a mild decrease in tensile modulus [**72**]. Generally, when the pyrolysis time is increased, the tensile properties begin to decrease. The main disadvantage lies in heat treatment damage or surface oxidation. The surface of the superheated steam pyrolysis fibres was smooth, with little adhered resin. When the pyrolysis reaction extended to a duration of 60 minutes or more, the presence of epoxy char was effectively eliminated. Additionally, the regenerated carbon fibres can naturally reform the surface during the process without any additional surface treatment, which improves the interfacial property [**72**].

B2.2 Catalytic Process

This process, performed in a continuous pyrolysis reactor, combines low temperatures (typically around 200 °C) with the use of a catalyst at a processing time of 5 minutes. The polymer is completely degraded into low molecular weight hydrocarbons in liquid or gaseous form, and the remaining carbon fibres are substantially free from resin [**71, 73**]. For the catalytic process, the strength degradation of the recycled carbon fibres varied between 1 and 17% (Adherent Technologies). Upon analyzing the surface quality, it was observed that the surface oxygen content exhibited a range of changes, ranging from an 18% reduction to an 83% improvement compared to virgin fibres. Notably, in both cases, the oxygen bonds were found to be similar to those present in virgin fibres. Therefore, the recycled carbon fibres would be suitable for bonding to a polymer matrix in a composite [**71**].

B2.3 Gasification Process

In a controlled oxygen flow, scrap material is subjected to heating at 600°C. This thermal treatment leads to the conversion of the polymer into shorter-chain hydrocarbons and the release of gases such as H_2 and CO. Meanwhile, the carbon fibres can be effectively recovered for subsequent reuse. There is some char residue on the fibres, but this is generally less than 10%. When the polymer converted to lower chain hydrocarbon oils and gases, in the best trials, only 2% of the resin remained on the fibres [**67**]. For gasification, the loss of fibre properties is consistent with the effects of heat treatment of fibres. In the ReFiber process, glass fibres undergo heating up to 500°C, resulting in a loss of over 50% of their initial strength. However, the stiffness of the fibres remains largely unaffected during this thermal treatment [**74**]. López et al. [**34**] combined pyrolysis with gasification for carbon fibres, which gave a 28% reduction of tensile strength and about 10% reduction of stiffness concerning virgin fibres after 30 min of gasification at 500 °C. It must be mentioned that gasification may not be the most suitable option if the primary goal is high-quality fibre recovery.

B3. Incineration

Incineration of CFRP provides an alternative way to treat the CFRP waste and recovers the embodied energy. Advanced incineration facilities can co-produce heat and electricity to supply local thermal energy demands and export electricity to the grid. The utilization of a rotary kiln has potential advantages when working with composite materials, as it enables effective burnout, assuming the residence time of the waste in the furnace is appropriately managed [**75**]. It can replace petroleum coke (35.8 MJ/kg) on an energy equivalent basis with an efficiency loss of 3% (i.e., 0.35 kg petroleum coke/kg GFRP. After burning there is a solid discharge consisting of ash and residue [**76**]. The incinerator bottom ash can be processed into aggregates or construction applications but in some cases, it is still landfilled [**43**]. Over 60% of the scrap is left behind as ash after incineration.

Inorganic elements in composites lead to the emission of hazardous flue gasses [**77**]. Incinerating composite material with energy recovery can result in energy losses of around -400 kJ/kg [**78**]. Moreover, during this process fibres don't simply burn out, but shatter into fragments. If these fragments are not fully burnt, they are carried out of hot zones via thermal convection which can cause health, safety, and performance issues. The fragments and particles of dust have the potential to enter the respiratory system of workers, posing health risks and potential complications[**79, 80**]. The particles can also pass into the gas treatment installation, where they can cause problems with the filter, leading to hazardous emissions [**77**]. Carbon fibre fragments retain their electrical conduction capabilities, which can lead to electrical failures in the gas treatment installation, thus disabling the whole incinerator [**79, 80**]. To prevent these issues, it is important to obtain complete fibre disintegration. Therefore, the material must be thoroughly shredded in combination with a high temperature and considerate oxygen supply [**79**]. It should be mentioned that the tensile strength of incineration recycled CFRP materials is typically 50-60% lower than that of virgin CFRP materials, the Young's modulus is typically 40-50% lower, and the fatigue resistance is typically 50-60% lower. The mechanical properties are presented in table 3.

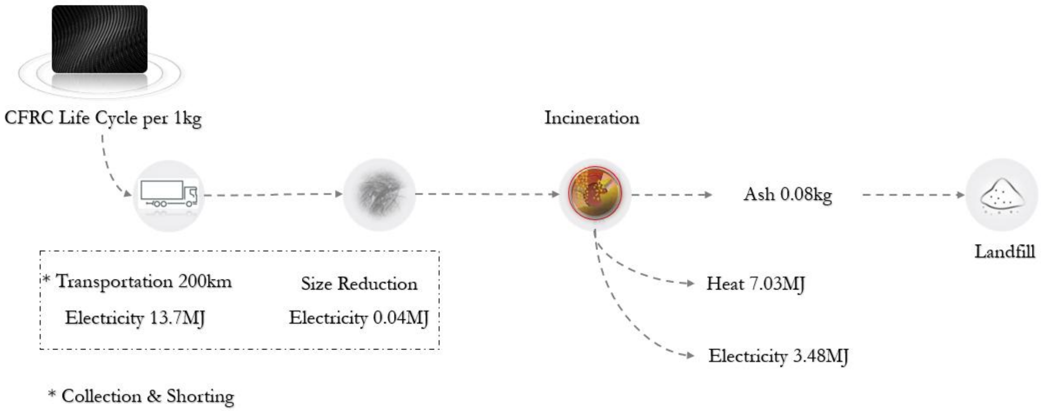

Fig. 4 Incineration process flow diagram.

B4. Fluidized Bed Process (FBP)

Central to an understanding of the fluidized bed process is the concept of hot air which is passed through a bed of silica sand to decompose the chopped scrap composite at a low temperature. Again, shredding preparation of CFRP wastes is needed [**81**]. The composite waste is fed into a bed of silica sand (with size <1 mm) which is fluidized by a stream of hot air at a temperature between 450^{o}C and 550^{o}C (operating temperature) under a pressure of 10–25 kPa [**62**]. The temperature is very important for the resulting fibre quality: too low and the fibres will not be fully cleaned, any higher and the fibres suffer from a reduction in strength[**78**]. A small amount of oxygen is also required to minimize char formation, as well as fine silica sand of 0.85 mm particle size is used as a bed, which is then converted into a fluidized bed by passing air in the velocity range 0.4–1.0 m/s. In the processing route, the scrap composite separates into fibres and fillers. This can be achieved by the air stream as individual particles [**33, 82**]. Oxidation, as a thermal process for CFRP recycling, involves the combustion of the polymeric matrix within a high-temperature environment enriched with oxygen, such as air at temperatures ranging from 450°C to 550°C. This method has been used by a few researchers [**83**], making the fluidized bed process (FBP) the most well-known implementation [**33**].

Carbon fibres are released by attrition and the thermal decomposition and degradation of the matrix, and then separated and collected. The reaction temperature is a critical parameter because it must ensure the decomposition of the thermoset matrix without significant fibre degradation. Most recycled fibre lengthsare in the range of 5–10 mm and retain 10–75% of the tensile strength of virgin carbon fibres [**62, 84**]. The limitations are noticeable in Pickering's process where a rotating sieve separator was used to separate glass fibres from fillers of recycled GFRCs [**85**]. During this process, only 50% of the tensile strength of the recycling glass fibre compared to virgin glass fibre is retained. The organic fraction of the resin was further degraded in a secondary combustion chamber at about 1000^{o}C, producing a clean flue gas (for energy recovery). At 450^{o}C glass fibre tensile strength was reduced by 50%, while at 550^{o}C the reduction was achieved by 80%. Carbon fibres show a lower strength degradation of about 25% when processed at 550^{o}C [**86**]. Analysis of their surface showed that the oxygen content resulted in a little reduction, indicating that the fibres have good potential for bonding to a polymer matrix [**33**]. The fluidized bed process does not allow the recovery of products from the resin apart from gases, whereas pyrolysis can enable the recovery of oil containing potentially valuable products.

Carbon fibres appear to undergo more damage compared to pyrolysis when subjected to the fluidized bed process, although the optimization of this process is yet to be achieved. Apart from the high temperature, the attrition caused by the fluidized sand could potentially contribute to fibre damage. One notable advantage of the fluidized bed process is its high tolerance for mixed and contaminated materials [**85**]. It can effectively process composite mixtures consisting of various polymer types, while also accommodating painted surfaces or the inclusion of foam cores in sandwich construction composites.

Metal inserts moulded into a composite do not have to be removed before being fed into the fluidized bed as any metals are retained in the bed and could be separated by the sand. The main differences among the incineration, pyrolysis and fluidized bed were presented in **Table II**.

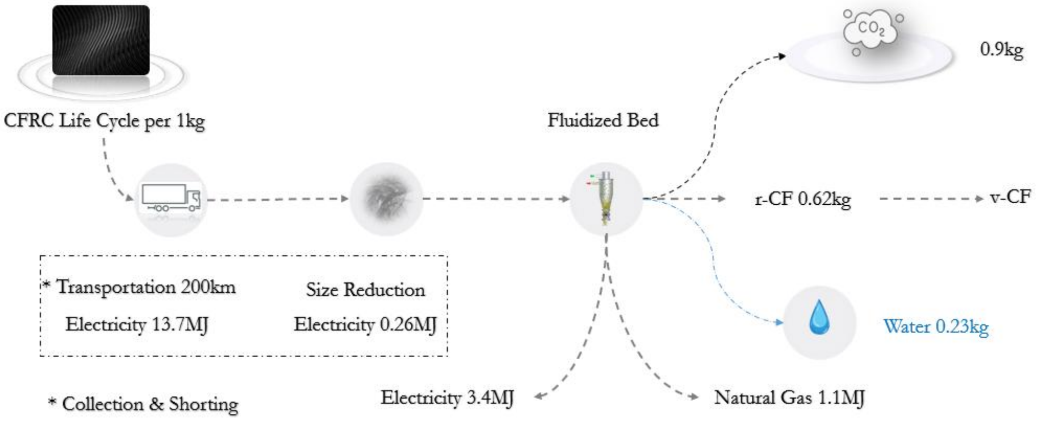

Fig. 5 Fluidized bed process flow diagram.

TABLE II A useful overview of the main characteristics of different thermal recycling processes.

Property	Incineration	Pyrolysis	Fluidized bed
Process	High-temperature combustion	High-temperature combustion	Fluidized bed reactor
Products	Char, ash, and flue gases	Carbon fibers, oils, and gases	Carbon fibers, char, and other byproducts
Damage to Fibers	High	Low	Low -to-moderate
Recovery of materials	Low	High	High
Environmental impact	High	Low	Low -to-moderate

C. Chemical Recycling

The chemical recycling process is concerned with waste composite disintegration by dissolving it into any chemical solution (e.g., acids, bases), which is based on the polymer substrate [**16**, **83**]. During this process, the recycled long fibres are washed to remove minor surface residue [**54**, **83**]. Compared with the mechanical recycling process as well as thermal recycling methods, there is also a higher resin decomposition ratio [**16**]. The chemical recycling procedure entails breaking down the polymer matrix of the composite into chemicals that can be utilized as fuel or to produce new polymers. Through this process, it becomes possible to recover both the polymer itself and reusable fillers and reinforcing materials from the thermosetting polymer composite. To better understand resin degradation, the chemical recycling process is evolved by using solvolysis or hydrolysis.

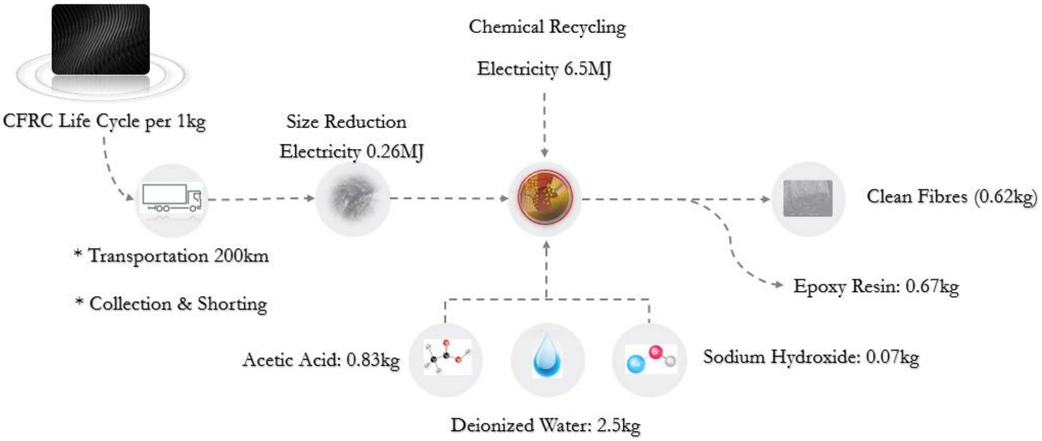

Fig. 6 Chemical recycling process flow diagram.

C1. Solvolysis

In a chemical recycling process, the polymeric matrix present in the waste composite is disintegrated by dissolving it in any chemical solution, such as acids [**87, 88, 89**], bases, and solvents [**21, 90**]. Depending on the solvent, it can be further classified as hydrolysis (water), glycolysis (glycols), and acid digestion. Normally, suitable chemicals and solvents are chosen based on the nature of the polymer substrate [**16, 91**].

Solvolysis is classified as solvolysis based on higher temperature and pressure (HTP) with temperatures > 200 °C and lower temperature and pressure (LTP) with temperatures < 200 °C [**21**]. Nevertheless, 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 to separate it from the CF [**92**]. The solvolysis process can regenerate clean fibres and fillers, while the matric resin feedstock could be used to make new resin again [**56**]. Researchers mentioned that downgraded resins are also suitable for use as thermoplastics or adhesives. During this process, the regenerated carbon fibre retains above 90% of virgin mechanical properties depending on the conditions [**43, 56**]. However, the surface quality appeared to be the weakness of this recycling process. Furthermore, for carbon fibres it is possible to use oxidant process conditions to completely remove the resin. Fibres without residue and with an oxygen content higher than virgin fibres, present lower fibre tensile strength [**21, 93**]. Moreover, solvolysis using supercritical fluids (SCF) is an emerging waste composite recycling technology, with the recycling process applying to both CFRP and GFRP. Two commonly used fluids in their subcritical and supercritical conditions are water and alcohol. Solvolysis using alcohols is focused on recycling waste CFRP to dissolve the resin and recover CF. However, there are fewer studies involving GFRP waste recycling. Water is a widely used solvent [**21, 85**]. Water and other co-solvents like alcohol, phenol, and amine have been used successfully in solvolysis. The frequently used alcohols in solvolysis include methanol, acetone, glycols, and propanol [**94**]. Sodium hydroxide (NaOH) or potassium hydroxide (KOH) are used as an alkaline catalyst [**89**]. Acidic catalysts are used only if the resin is highly resistant to degradation [**87, 89**]. It is easy to achieve a supercritical state with alcohol as opposed to water. By means of the chemical recycling process, it becomes feasible to

DOI: 10.48175/IJARSCT-17474

produce long recycled carbon fibers (RCFs) with a surface free from residue. Consequently, it is possible to obtain high-quality carbon fibers with only a slight reduction in mechanical properties.

The quality of the carbon fiber produced depends on the type of chemical solution used for soaking, the temperature and time of immersion, and stir energy if available. In contrast to pyrolysis, the chemical treatment method employs lower processing temperatures and yields cleaner and longer recycled fibers. However, solvolysis, which is a part of the chemical treatment, necessitates costly equipment capable of withstanding corrosion under high temperatures and pressures. Additionally, the solvents used in the process may have adverse effects on the environment and human health. These characteristics of the fluidized bed process often limit its industrial-scale application [**24**]. As a note, the drawback of improper fiber alignment in discontinuous r-CF with a length of more than 5 mm can be suppressed using a centrifugal alignment rig concept [**95**] or by applying calendaring through rollers with a 0.10 - 0.15 mm gap at a temperature of 110^{o}C [**96**]. Moreover, the chemical reaction taking place within the carbon fiber leads to a weakening of the binding strength between the fiber and the matrix resin in CFRP composites. In addition, this chemical method is also very susceptible to causing pollutants that are very dangerous to human health and safety and have the potential to cause environmental pollution [**59**]. Environmentally speaking, some of the chemical solvents used in low temperature solvolysis can be toxic to the environment [**16**].

Therefore, when compared to mechanical and thermal recycling methods, chemical recycling is considered to be the least environmentally friendly. However, a recent advancement in chemical recycling called sub- or supercritical fluid solvolysis has shown promise in producing recycled carbon fibres (RCFs) with minimal mechanical degradation. This process utilizes non-toxic and cost-effective solvents [**92**]. It is important to note that research on this innovative technology has thus far been limited to laboratory experiments.

Ultimately, chemical recycling has the potential to produce great quality recycling carbon fibre 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.

Disadvantages of solvolysis include that the process efficiency depends on the resin types, which means that the pre-separation of a composite type is critical. This makes the process suitable for processing production scraps for which the material characteristics are well known, but it can be very difficult to use when treating mixed post-consumer composite scrap [**56**]. Also, reactors can become expensive, as they need to withstand high temperatures and pressures, as well as corrosion due to modified aggressive solvents [**21**, **43**]. The high energy consumption of the process meant that the environmental efficiency of the process was lower than mechanical recycling but comparable to pyrolysis.

C2. Hydrolysis

Hydrolysis occurs when resin undergoes degradation due to the presence of water. This process involves the decomposition of chemical materials through solvolysis, where water acts as the solvent. Lab studies have shown that it is likely to degrade polyester resin of the sheet moulding compounds into liquid products like the industrial chemicals that were initially used in the manufacturing. The recovered filler, as well as fibre materials, can replace around 50% of material in fresh dough moulding compounds with the same mechanical properties (table 5). However, grinding composite to a fine powder to an acceptable level of degradation in the limited hydrolytic condition is possible [**87, 97**]. This method needs additional deliberate disposal. Recycled carbon fibres collected from the chemical method, as well as pyrolysis, have the same strength as compared to the strength of virgin fibres while the recycled carbon fibres' strength is lower than that of a virgin when obtained via a fluidized bed. The choice of solvolysis or hydrolysis will depend on the specific application and the requirements of the manufacturer. If the mechanical properties of the CFRP are critical, then solvolysis may be a better option. However, if cost is a major factor, then hydrolysis may be a better option.

III. CONCLUSION

Choosing the method of recycling for GFRP is not a simple matter. The EU community tries to minimize the impacts of waste on the environment and preserve resources. Composite recycling is a critical issue for the sustainable use of lightweight composite materials in the fields of transportation, construction, and sports equipment. Current recycling methods include mechanical recycling, high voltage fragmentation, pyrolysis, fluidized beds, and chemical and thermochemical recycling by solvolysis. Recycled CFRP has the potential to provide both economic and environmental benefits. Energy consumption is a critical issue, that must be reduced. A critical comparison was carried out based on factors such as process conditions, process outcomes, mechanical properties, ease of reuse, environmental impact, and cost-effectiveness. Regardless of whether the landfill is considered to have a moderate environmental impact, the European Community, by legislation must limit landfilling and incineration methods for disposing of carbon fibre reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP) waste by increasing taxes per kg of waste composite product.

According to the recycling methods,

1. The mechanical recycling technique can be used as a pre-recycling process for thermal and chemical recycling, respectively. It has been found that the mechanical recycling technique is able to reduce GHG emissions, primary energy use, and landfill waste generation relative to landfilling. Recycled carbon fibers by this method have low mechanical properties; for that reason, they must be used to low-value applications.
2. Commercial-scale FBP is capable of recycling clean and high-quality fibres with a fraction of the energy consumption needed to manufacture virgin fibres. However, fibres are discontinuous but can be used in the aviation sector because they reduce weight by optimizing potential environmental and cost benefits.
3. By using pyrolysis, gas and liquid can be produced as feedstocks. Char formation directly affects the mechanical properties of both carbon and glass fibres. To eliminate minor resin impurities, a secondary heat and chemical treatment is needed. A crack-free surface and low energy usage are the main concerns in the chemical recycling process. Solvents like water and strong acids in various conditions can be used. This process offers a maximum resin elimination ratio and higher retention of mechanical properties by using cheap and sustainable solvents.

The effort to recover carbon fiber from CFRP waste is a crucial activity for the present and the future. Development and innovation of methods and technology are still needed to build a CFRP waste recycling company that is profitable in business.

REFERENCES

[1]. S.J. Park andM.K.Seo, Carbon fiber-reinforced polymer composites: preparation, properties, and applications, in Polymer Composite Germany: Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2012, vol. 1.

[2]. S.J. Park, S.Y. Lee andF.L. Jin, Surface modification of carbon nanotubes for high-performance polymer composites, in Handbook of Polymer Nanocomposites: Springer,2015, vol B.

[3]. M. Kim, D.H. Sung, K. Kong, N. Kim, B.J. Kim, H.W. Park, Y.B. Park,M. Jung, S.H. Leeand S.G. Kim,“Characterization of resistive heating and thermoelectric behavior of discontinuous carbon fiber-epoxy composites,” Composites Part B: Engineering, vol. 90, pp. 37-44, 2016.

[4]. H. Xu, X. Zhang, D. Liu, C. Yan, X. Chen, D. HuiandY. Zhu, “Cyclomatrix-type polyphosphazene coating: Improving interfacial property of carbon fiber/epoxy composites and preserving fiber tensile strength,” Composites Part B: Engineering, vol. 93, pp. 244-251, 2016.

[5]. F.S. Wang, Y.Y Ji, X.S. Yu, H. Chen and Z.F. Yue,“Ablation damage assessment of aircraft carbon fiber/epoxy composite and its protection structures suffered from lightning strike,” Composite Structures, vol. 145, pp. 226-241, 2016.

[6]. M. Dawood, M.W. El-Tahan and B. Zheng,“Bond behavior of superelastic shape memory alloys to carbon fiber reinforced polymer composites,” Composites Part B: Engineering, vol. 77, pp. 238-247, 2015.

[7]. N.M. Chowdhury, W.K. Chiu, J.Wang andP. Chang,“Experimental and finite element studies of bolted, bonded and hybrid step lap joints of thick carbon fibre/epoxy panels used in aircraft structures,” Composites Part B: Engineering, vol. 100, pp. 68-77, 2016.

[8]. J.H. Lu andJ.P. Youngblood,“Adhesive bonding of carbon fiber reinforced composite using UV-curing epoxy resin,” Composites Part B: Engineering, vol. 82,pp. 221-225, 2015.

[9]. T. Yamamoto, K. Uematsu, T. IrisawaandY. Tanabe,“Controlling of the interfacial shear strength between thermoplastic resin and carbon fiber by adsorbing polymer particles on carbon fiber using electrophoresis,” Composites Part A: Applied Science and Manufacturing, vol. 88, pp. 75-78, 2016.

[10]. H. Dhieb, J.G. Buijnsters, K. ElleuchandJ.P. Celis,“Effect of relative humidity and full immersion in water on friction, wear and debonding of unidirectional carbon fiber reinforced epoxy under reciprocating sliding. Composites Part B: Engineering, vol. 88, pp. 240-252, 2016.

[11]. S. Mazumdar, D. Karthikeyan, D. Pichler, M. Benevento and R.Frassine (2017) State of the Composites Industry Report for 2017, Composites Manufacturing Magazine.

[12]. S.J. Pickering, Recycling thermoset composite materials. In Wiley Encyclopedia of Composites, John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; p. weoc214. ISBN 978-1-118-09729-8

[13]. Composite World/articles/fiber-types. Available at https://www.compositesworld.com/articles/fiber-types

[14]. C.A. Navarro, C.R. Giffin, B. Zhang, Z. Yu, S.R.Nutt and T.J. Williams, “A structural chemistry look at composites recycling,” MaterialsHorizon, vol. 7, pp. 2479-2486, 2020.

[15]. G.Marsh, “Reclaiming value from post-use carbon composite,” Reinforced Plastic, vol. 52(7), pp.36-39,2008.

[16]. S. Pimenta and S.T. Pinho,“Recycling carbon fibre reinforced polymers for structuralapplications: technology review and market outlook,” Waste Management, vol. 31(2), pp. 378-392, 2011.

[17]. W. Carberry, Airplane recycling efforts benefit boeing operators,” Boeing AEROMag QRT, vol. 4(08), pp. 6-13, 2008.

[18]. T. Roberts,“Rapid growth forecast for carbon fibre market,” Reinforced Plastic, vol. 51(2), pp. 10-13,2007.

[19]. J. Chen, J. Wang and A. Ni, “Recycling and reuse of composite materials for wind turbine blades: An overview,” Journalof Reinforced Plastics and Composites, vol. 38, pp. 567-577, 2019.

[20]. C.K.Lee, Y.K. Kim, P. Pruitichaiwiboon, J.S. Kim, K.M.Lee and C.S. Ju, “Assessing Environmentally friendly recycling methods for composite bodies of railway rolling stock using life-cycle analysis,”Transportation Research Part D: Transport and Environment, vol. 15, pp. 197-203, 2010.

[21]. G. Oliveux, L.O.Dandy andG. Leeke, “Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties,” Progressin Materials Science, vol. 72, pp. 61-99, 2015.

[22]. European Council. Directive 200053EC of the European parliament and of the council on end-of life vehicles. Official Journal European Communities 2020, L269, pp. 1–15.

[23]. H. Sukanto, W.W.Raharjo, D.Ariawan andJ. Triyono, “Carbon fibers recovery from CFRP recycling process and their usage: A review,” In Proceedings of the IOP Conference Series: Materials Science and Engineering, Malang, Indonesia, vol. 1034, p. 012087, 7–9 October 2021.

[24]. Y. Liu, M. Farnsworth andA. Tiwari, “A review of optimisation techniques used in the composite recycling area: State-of-the-art and steps towards a research agenda,” Journal of Cleaner Production, vol. 140, pp. 1775-1781, 2017.

[25]. S. Verma, B. Balasubramaniam andR.K. Gupta, “Recycling, Reclamation and remanufacturing of carbon fibres,” Current Opinionin Green Sustainable Chemistry, vol. 13, pp. 86-90, 2018.

[26]. J. Zhang, V.S. Chevali, H. Wang and C.H. Wang, “Current status of carbon fibre and carbon fibre composites recycling,” Composites Part B: Engineering, vol. 193, 108053, 2020.

[27]. K. Anane-Fenin andE.T. Akinlabi, “Recycling of Fibre Reinforced Composites: A Review of Current Technologies. In Proceedings of the 4th International Conference on Development and Investment in Infrastructure—Strategies for Africa, Livingstone, Zambia, 30 August–1 September 2017, p. 12.

[28]. E.Pakdel, S. Kashi, R. Varley andX. Wang, “Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes.,”Resources, Conservationand Recycling, vol. 166, pp.105340, 2021.

[29]. A Review on the Recycling of Waste Carbon Fibre/Glass Fibre-Reinforced Composites: Fibre Recovery, Properties and Life-Cycle Analysis. Available online: https://link.springer.com/article/10.1007/s42452-020-2195-4 (accessed on 18 May 2021).

[30]. Y. N. Kim, Y.O. Kim, S.Y. Kim, M. Park, B. Yang, J. Kim and Y. C. Jung, “Application of supercritical for green recycling of epoxy-based carbon fiber reinforced plastic,” Composites Science and Technology, vol. 173, pp. 66-72, 2019.

[31]. S.H. Lee, H.O. Choi, J.S. Kim, C.K. Lee, Y.K. Kim and C.S. Ju, "Circulating flow reactor for recycling of carbon fiber from carbon fiber reinforced epoxy composite," Korean Journalof Chemical Engineering, vol. 28, pp. 449-454, 2011.

[32]. J. Palmer, O.R. Ghita, L. Savage and K. E.Evans, "Successful closed-loop recycling of thermoset composites," Composites Part A: Applied Science and Manufacturing, vol. 40, pp. 190-498, 2009.

[33]. Pickering SJ. Recycling technologies for thermoset composite materials – current status. Composites Part A: Applied Science and Manufacturing, vol. 37, pp.1206-1215,2006.

[34]. F. A. López, O. Rodríguez, F. J. Alguacil, I. García-Díaz, T. A. Centeno, J. L. García-Fierro and C. González, "Recovery of carbon fibres by the thermolysis and gasification of waste prepreg," Journal of Analyticaland Applied Pyrolysis, vol. 104, pp. 675-683, 2013.

[35]. U. Kenji, K. Nobuyuki, S. Morihiko,"Recycling of CFRP by Pyrolysis," Journal of Society of Materials Science, Japan, vol. 44, pp. 428–31, 1995.

[36]. Y.N. Kim, Y.O. Kim, S.Y. Kim, M. Park, B. Yang, J. Kim and Y.C. Jung, "Application of supercritical water for green recycling of epoxy-based carbon fiber reinforced plastic,"Composites Science and Technology, vol. 173, pp. 66-72, 2019.

[37]. N. Perry, A. Bernard, F. Laroche and S.Pompidou,"Improving design for recycling—Application to composites," CIRP Annals, vol. 61, pp. 151-154, 2012.

[38]. F. Meng, E.A. Olivetti, Y. Zhao, J.C. Chang, S.J.Pickering andJ. McKechnie, "Comparing Life cycle energy and global warming potential of carbon fiber composite recycling technologies and waste management options," ACS Sustainable Chemistry & Engineering, vol. 6, pp. 9854-9865, 2018.

[39]. S. Utekar, V.K. Suriya, N. More andA. Rao, "Comprehensive study of recycling of thermosetting polymer composites—driving force, challenges and methods," CompositesPart B: Engineering, vol. 207, pp. 1085-1096, 2021.

[40]. B. Pillain, P. Loubet, F. Pestalozzi, J. Woidasky, A. Erriguible, C. Aymonier andG. Sonnemann, "Positioning supercritical solvolysis among innovative recycling and current waste management scenarios for carbon fiber reinforced plastics thanks to comparative life cycle assessment," Journal of Supercritical Fluids, vol. 154, pp. 1046-1057, 2019.

[41]. A.K Bledzki, H. Seidlitz, J. Krenz, K. Goracy, M. Urbaniak andJ.J. Rösch, "Recycling of carbon fiber reinforced composite polymers—Review—Part 2: Recovery and application of recycled carbon fibers," Polymers, vol. 12, pp.3003, 2020.

[42]. S.J. Pickering,"Recycling technologies for thermoset composite materials current status," Composites Part A: Applied Science and Manufacturing, vol. 37, pp. 1206–1215, 2006.

[43]. S. Job, G. Leeke, P. Mativenga, G. Oliveux, S. Pickering and N. Shuaib, "Composites Recycling–Where Are We Now? 2016. Available online: https://www.researchgate.net/publication/329399859_Composites_Recycling_-_Where_are_we_now (accessed on 13 January 2023).

[44]. C.E. Bream andP.R. Hornsby,"Comminuted thermoset recyclate as a reinforcing filler for thermoplastics: Part I characterisation of recyclate feedstocks," Journal of Materials Science, vol. 36, pp. 2965-2975, 2001.

[45]. N.A Shuaib and P.T. Mativenga,"Effect of process parameters on mechanical recycling of glass fibre thermoset composites. In: Procedia CIRP, vol. 48. Elsevier B.V.; 2016. p. 134–9.

[46]. D.A SteenkamerandJ.L. Sullivan,"On the recyclability of a cyclic thermoplastic composite material," Composites Part B: Engineering, vol. 29B, pp. 745-752, 1998.

[47]. G. Schinner, J. Brandt andH. Richter,"Recycling carbon-fiber-reinforced thermoplastic composites,"Journal of Thermoplastic Composite Materials, vol. 9, pp. 239-245, 1996.

[48]. C.E. Kouparitsas, C.N. Kartali, P.C. Varelidis, C.J. Tsenoglou andPapaspyrides,"Recycling of the fibrous fraction of reinforced thermoset composites," Polymer Composites, vol. 23, pp. 629-689, 2002.

[49]. J. Takahashi, N. Matsutsuka, T. Okazumi, K. Uzawa, I. Ohsawa andK. Yamaguchi, et al.,"Mechanical properties of recycled CFRP by injection molding method," In: Proceedings of the 16th international conference on composite materials 8–13 July 2007, Kyoto, Japan.

[50]. K. Ogi, T. Nishikawa, Y. Okano andI. Taketa, "Mechanical properties of ABS resin reinforced with recycled CFRP," Advanced Composite Materials, vol. 16, pp. 181-194, 2007.

[51]. L. Bax, H. Vasiliadis, I. Magallón, M. Ierides, and B. Zaman, "Composites recycling," 2015.

[52]. P.T. Mativenga, N. A. Shuaib, J. Howarth, F. Pestalozzi andJ. Woidasky, "High voltage fragmentation and mechanical recycling of glass fibre thermoset composite," CIRP Annals - Manufacturing Technology, vol. 65(1), 45–48, 2016.

[53]. S.R. Naqvi, H.M. Prabhakara andE.A. Bramer et al.,"A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy," Resources, Conservation and Recycling,vol. 136, pp.118–129, 2018.

[54]. E.Asmatulu, J. Twomey and M. Overcash, "Recycling of fiber reinforced composites and direct structural composite recycling concept," Journal of Composite Materials, vol. 48, pp. 593–608, 2014.

[55]. L. Mazzocchetti, T. Benelli, E. D'Angelo, C. Leonardi, G. Zattini, L. Giorgini, "Validation of carbon fibers recycling by pyro-gasification: The influence of oxidation conditions to obtain clean fibers and promote fiber/matrix adhesion in epoxy composites," Composites Part A: Applied Science and Manufacturing, vol. 112, pp. 504–14, 2018.

[56]. Y. Yang, R. Boom, B. Irion, D.J. van Heerden, P. Kuiper andH. de Wit, H. "Recycling of composite materials," Chemical Engineering and Processing: Process Intensification, vol. 51, pp. 53–68, 2012.

[57]. A.M. Cunliffe, N. Jones and P.T. Williams, "Pyrolysis of composite plastic waste," Environmental Technology (United Kingdom), vol. 24(5), pp. 653–663, 2003.

[58]. C. N. Cucuras, A.M. Flax, W.D. Graham and G.N. Hartt, "Recycling of Thermoset Automotive Components," International Congress & Exposition, 18, 1991.

[59]. G. Jiang, S, PickeringandE. Lester et al.,"Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol," Composites Science and Technology, vol. 69, pp. 192–198, 2009.

[60]. M.H. Akonda, C.A. Lawrence and B.M. Weager. "Recycled carbon fibre-reinforced polypropylene thermoplastic composites," Composites Part A: Applied Science and Manufacturing,vol. 43, pp. 79–86, 2012.

[61]. L.O. Meyer, K. Schulte and E. Grove-Nielsen,"CFRP-recycling following a pyrolysis route: Process optimization and potentials," Journal of Composite Materials, vol. 43, pp. 1121–32, 2009.

[62]. J.H. Zhu, Py. Chen, Su Mn, C. PeiandF. Xing,"Recycling of carbon fibre reinforced plastics by electrically driven heterogeneous catalytic degradation of epoxy resin," Green Chemistry, vol. 21(7), pp.1635-1647, 2019.

[63]. J.M. Gosau, F.W. Tyler andR.E. Allred,"Carbon fiber reclamation from state-of-art 2nd generation aircraft composites. In: Proceedings of the international SAMPE symposium and exhibition (ISSE 2009), May 18–21, 2009, Baltimore, MD, USA.

[64]. J.P. Heil and J.J Cuomo,"Study and analysis of carbon fiber recycling," Master thesis, North Carolina State University, Raleigh, NC, USA; 2011.

[65]. R.E Allred, A.B. Coons and R.J. Simonson,"Properties of carbon fibres reclaimed from composite manufacturing scrap by tertiary recycling Proccedings of SAMPE 28th International Technical Conference, 4–7 November 1996, Seattle, WA, USA 1996 p. 11.

[66]. R.E. Allred, G.C. Newmeister, T.J. Doak, R.C. Cochran andA.B. Coons,"Tertiary recycling of cured composite aircraft parts," Technical paper EM97-110. Dearborn, MI: Society of Manufacturing Engineers; 1997.

[67]. E. Lester, S. Kingman, K.H. Wong, C. Rudd, S. Pickering and N. Hilal,"Microwave heating as a means for carbon fibre recovery from polymer composites: A technical feasibility study," Materials Research Bulletin, vol. 39, pp. 1549–56, 2004.

[68]. K. Obunai, T. Fukutaand K. Ozaki. "Carbon fiber extraction from waste CFRP by microwave irradiation," Composites Part A: Applied Science and Manufacturing, vol. 78, pp. 160–165, 2015.

[69]. L. Jiang, C.A. Ulven, D. Gutschmidt, M. Anderson, S. Balo and M. Lee, et al.,"Recycling carbon fiber composites using microwave irradiation: Reinforcement study of the recycled fiber in new composites," Journal of Applied Polymer Science, vol. 132(41), pp. 42658, 2015.

[70]. A. Torres, I. De Marco, B. M. Caballero, M. F. Laresgoiti, J. A. Legarreta, M. A. Cabrero and K. Gondra, "Recycling by pyrolysis of thermoset composites: characteristics of the liquid and gaseous fuels obtained," Fuel, vol. 79(8), pp. 897–902, 2000.

[71]. S. J. Pickering, "Recycling technologies for thermoset composite materials—current status. Advanced Polymer Composites for Structural Applications in Construction: ACIC 2004, 37, 1206–1215, 2005.

[72]. K. W. Kim, H.M. Lee, J.H. An, D.C. Chung, K.H. An and B.J. Kim, "Recycling and characterization of carbon fibers from carbon fiber reinforced epoxy matrix composites by a novel super-heated-steam method," Journal of Environmental Management, vol. 203, pp. 872–879, 2017.

[73]. R.E. Allred, (Adherent T. I., & Salas, R. M. (Adherent T. I. (1994). Chemical recycling of scrap composites. In Environmental, Safety, and Health Considerations: Composite Materials in the Aerospace Industry. NASA. Retrieved from https://ntrs.nasa.gov/search.jsp?R=19950016617

[74]. ReFiberApS. (2004). Technology. Retrieved from ReFiberApS: http://www.refiber.com/technology.html

[75]. Environment Agency. (2001). Guidance for the Incineration of Waste and Fuel Manufactured from or Including Waste, (1)

[76]. J.W. Crowder, (Crowder E. A. I. ., & Richards, J. R. (Air C. T. P. C. . (2003). Inspection of Gas Control Devices and Selected Industries Student Manual Inspection of Gas Control Devices and Selected Industries.

[77]. K. Larsen, "Recycling wind turbine blades," Renewable Energy Focus, vol. 9(7), pp. 70–73, 2009.

[78]. S. Halliwell, "End of Life Options for Composite Waste Recycle , Reuse or Dispose ?," National Composites Network Best Practice Guide. National Composites Network, pp. 1–41, 2006. Retrieved from https://compositesuk.co.uk/system/files/documents/endoflifeoptions.pdf

[79]. A. Hedlund-Åström, "Model for End of Life Treatment of Polymer Composite Materials,| 165, 2005.

[80]. M. Limburg and P. Quicker, "Disposal of Carbon Fiber Reinforced Polymers – Problems During Recycling and Impacts on Waste Incineration," Waste Management, vol. 6, pp. 221–235, 2016. Retrieved from http://www.vivis.de/phocadownload/2016_wm/2016_wm_221-236_quicker.pdf

[81]. F. Meng, J. McKechnie, T.A Turner andS.J. Pickering,"Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres," Composites Applied Science and Manufacturing, vol. 100, pp. 206-214, 2017.

[82]. S.J. Pickering, R.M.Kelly andJ.R. Kennerley et al.,"A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites," Composites Science and Technology,vol. 60, pp. 509–523,2000.

[83]. B.J. Jody, J.A. Pomykala and E.J. Daniels EJ et al.," A process to recover carbon fibers from polymer-matrix composites in end of-life vehicles," Journal of the Minerals, Metals & Materials, vol. 56, pp. 43–47, 2004.

[84]. S. Pickering, T. Turner, F. Meng, C. Morris, J. Heiland K. Wong, et al.,"Developments in the fluidised bed process for fibre recovery from thermoset composites. In: Proceedings of 2nd annual composites and advanced materials expo. Dallas, Texas USA; 2015. Conference, Conference.

[85]. S.J. Pickering, R.M. Kelly, J.R. Kennerley, C.D. Rudd andN.J. Fenwick,"A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites," Composites Science and Technology, vol. 60, pp. 509-523, 2000.

[86]. J.R. Hyde, E. Lester, S. Kingman, S. Pickeringand K.H. Wong,"Supercritical propanol, a possible route to composite carbon fibre recovery: a viability study," Composites Part A: Applied Science and Manufacturing, vol. 37, pp. 2171-2175, 2006.

[87]. Y. Liu, L. Meng, Y. HuangandJ. Du,"Recycling of carbon/epoxy composites," Journal of Applied Polymer Science, vol. 94, pp. 1912-1916, 2004.

[88]. J. Li, P-L. Xu andY-K. Zhu et al.,"A promising strategy for chemical recycling of carbon fiber/thermoset composites: self-accelerating decomposition in a mild oxidative system," Green Chemistry, vol. 14, pp. 3260–3263, 2012.

[89]. P. Feraboli, H. Kawakami, B. Wade, F. Gasco, L. DeOto and A. Masini, “Recyclability and reutilization of carbon fiber fabric/epoxy composites,” Journal of Composite Materials, vol. 46,pp. 1459-1473, 2012.

[90]. R. Pinero-Hernanz, C. Dodds, J. Hyde, J. García-Serna, M. Poliakoff and E. Lester, et al., “Chemical recycling of carbon fibre reinforced composites in nearcritical and supercritical water,” Composites Part A: Applied Science Manufacturing, vol. 39, pp.454-461, 2008.

[91]. G. Oliveux, J.L. Bailleul and Salle, E. L. G. La, “Chemical recycling of glass fibre reinforced composites using subcritical water,” Composites Part A: Applied Science and Manufacturing, vol. 43(11), pp. 1809–1818, 2012.

[92]. C. Morin, A. Loppinet-Serani and F. Cansell, et al.,“ Near- and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: state of the art,”Journal of Supercritical Fluids, vol. 66, pp. 232–240, 2012.

[93]. Y. Bai, Z.Wang and L. Feng, “Chemical recycling of carbon fibers reinforced epoxy resin composites in oxygen in supercritical water,” Materials & Design, vol. 31(2), pp. 999–1002, 2010.

[94]. H. Yan, C. Lu, D. Jing, C. Chang, N. Liu and X. Hou, “Recycling of carbon fibers in epoxy resin composites using supercritical 1-propanol,” Nitrogen-Doped Carbon Material, vol. 31, pp.46-54, 2016.

[95]. N. van de Werken, M.S. Reese, M.R. Taha and M. Tehrani,“Investigating the effects of fiber surface treatment and alignment on mechanical properties of recycled carbon fiber composites” Composites Part A: Applied Science and Manufacturing, vol. 119, pp. 38–47, 2019.

[96]. B. Xiao, T. Zaima, K. Shindo, T. Kohira, J. Morisawa and Y. Wan, et al., “Characterization and elastic property modeling of discontinuous carbon fiber reinforced thermoplastics prepared by a carding and stretching system using treated carbon fibers,” Composite Part A: Applied Science and Manufacturing, vol. 126, pp. 105598, 2019.

[97]. S.H. Patel, K.E. Gonsalves, S.S Stivala, L. Reich and D.H. Trivedi, “Alternative procedures for the recycling of sheet molding compounds,” Advancedin Polymer Technology, vol. 12, pp. 35-45, 1993.

BIOGRAPHY

Panagiotis J. Charitidis was born in Athens, Greece in 1978. He holds a Ph.D. in Applied Mechanics from the University of Patras (Dept. Mechanical Engineering and Aeronautics). Nowadays is alecturer professor at Environmental Engineering School (Democritus University of Thrace, Greece).

DOI: 10.48175/IJARSCT-17474