Applications and Challenges of Carbon-fibres reinforced Composites: A Review

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Applications and Challenges of Carbon-fibres reinforced Composites: A Review

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Abstract: Carbon-fiber reinforced polymers (CFRPs) or Carbon-fiber reinforced plastics composites is a material that has caught the interest of many industries due to its excellent properties like strength, lightweight, crashworthiness, style, looks, and many more. This paper discussed the manufacturing of carbon fibres and CFRPs. The properties of carbon fibres and carbon-fiber reinforced plastics composites are discussed in detail. The applications of Carbon-fiber reinforced plastics composites in the field of automotive and aerospace elaborated in detail. The challenges, recycling of CFRPs, and new approaches in the field of fibres reinforced plastic composites are also addressed in this paper.

Keywords: CFRPs, CFRP properties, recycling, automotive, aerospace.

1. Introduction

The rapid growth of the manufacturing industry has required the development of materials related to fatigue properties and sustainability. Composites have emerged as one of the materials that meet these property requirements and have shown potential in various applications[1)]. One of them is Carbon-Fibre (CF) containing reinforced polymer which is known as carbon fibres reinforced plastics (CFRPs) composites. CFRPs are very strong and lightweight fibre reinforced plastic. The fibres are often bounded using a polymer thermosetting resin like epoxy, but sometimes thermoplastic polymers like polyester, vinyl ester, or nylon are also used. Reinforced composites of carbon fibers have few advantages over conventional materials such as strong strength, high durability, lightness, chemical resistance and high temperature tolerance. Carbon fibre reinforced composites are widely used in industries like civil, aerospace, automotive engineering, and sports equipment [2, 3)].The main objective of this paper is to discuss the methods of production of carbon fibres and carbon fibres reinforced plastic composites and, their potential applications in various field.

1.1 Classification of carbon fibres

Table 1 shows the classification of Carbon-Fibres based on strength, precursor fibre material, and heat treatment.

Table 1. Classification of carbon-fibres.

Modulus and Strength	**Precursor fibre Material**	**Heat treatment**
Ultra-High Modulus> 450GPa	PAN-based CF	High-heat-treatment carbon fibres. 1. Fibres are heat-treated below 2000°c. 2. It can be incorporated with high-modulus type fibre.
High Modulus 350-450GPa	Pitch based CF	
Intermediate Modulus 200-350GPa	Mesophase pitch-based CF	Intermediate-heat-treatment carbon fibres. 1. Fibres heat-treated below 1500°c.
Low Modulus & High Tensile Modulus<100GPa Tensile strength >3.0GPa	Isotropic pitch-based CF	
Super High-Tensile Tensile Strength>4.5GPa	Rayon-based CF	Low-heat-treatment carbon fibre. 1.The fibres heat-treated above 1000°c 2. It can be incorporated with low modulus and low strength materials
	Gas-phase-based CF	

1.2 Making of carbon-fibers

The raw material called precursor is used in the manufacturing of carbon-fibres. Basically, polyacrylonitrile PAN) is used as a precursor to the production of carbon fibers CF). The other precursor material may be petroleum pitch.These precursors are compounds of organic polymers where long strands of molecules are controlled by carbon atoms.

To produce carbon fibres, firstly the precursor is spun into fibres and after passing through various chemical and physical stages the polymer congeals and solidifies into fibre. After that, the fibres are washed and stretched to the desired diameter. During the starching process carbon crystals, and atoms become tightly bound. Before carbonization, the fibres are left out on hot rollers beds suspension by a flow of hot air 200-300^{o}c) for the better thermally stable ladder bonding, after that carbonization of fibres is carried out at the temperature 1000-3000^{o}c for the stabilization of fibres. Furthermore, the surface of carbon fibres is required to slightly oxidize to improve bonding properties with the epoxies and other materials during the fabrication of composites. The oxidation of fibres should be carried out very carefully to avoid any surface defects such as pits etc because it leads to fibre failure[3, 4)]. The carbon fibres production process is depicted in Figure 1.

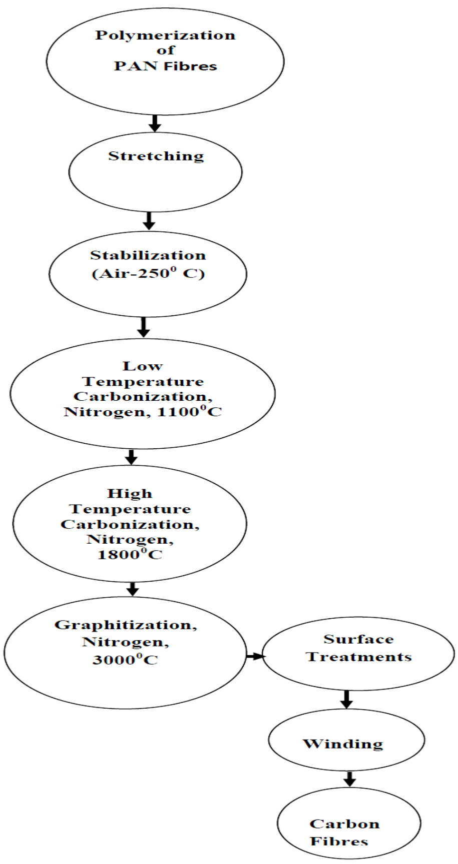

Fig.1: Carbon Fibre Production Process [4)].

2. Manufacturing of carbon fiber composites

The composite material structure contains two components matrix and reinforcement materials. The three-dimensional region between components matrix and reinforcement has specific characteristics and is known as the interphase region [1, 5)]. The carbon fibres are used as a reinforcement material in carbon fibre reinforced composites. The selection of matrix materials affects the properties of composites. The properties of the CFRCs also depend on the orientation of fibre in the composite and the strength of carbon resin bond [6)]. The various matrix materials used with carbon-fibre reinforcements are metals, ceramics, polypropylene, and epoxy resin. The volume of matrix materials is about 80% of composites [7)]. The carbon fibre reinforced plastics CFRPs) parts are formed with a single layer of CF that is reinforced with fiber glass or are made from layers of pre-impregnated sheets with an epoxy matrix [8, 78)]. The selection of fabrication methods of CFRPs composites are depend on the component being created, finish required, and quantity. The manufacturing methods of carbon-fibre reinforced plastics may include the following:-

2.1 Open-molding

CFRPs parts are produced by making layers of multiple sheets of carbon fibre fabric into the mould which is of the shape of the component to be produced. Increasing the strength and durability of the resulting material a certain weave and alignment of fibres is selected. In Open-moulding, one-sided mould is used which is a cost-effective process to make composite products. In an open-mould, the first mould release is applied to the mould. Using a gel coat, it is sprayed onto the mould when the unharnessed agent has been applied. The gel coat becomes hardened and mould is completed. In the spray process, the catalyzed resin and fibres are sprayed into the mould. The fibres may be short or continuous fibres. The fibres and resin materials are applied simultaneously in mould. Further, laminate is compressed with the help of hand rollers, and then the part is sent for curing. After it is cured, the part is cooled and removed from the mould. But now with the advancements in technology many faster and more technically precise methods are replacing open moulding via hand layup because of the slow process. Despite that, it is still widely used [9)].

2.2 Resin infusion processes

The demand for faster production and increased quantity of parts has forced the industry to make the processes automated. Resin transfer moulding RTM) is the most suitable alternative process. It is also referred to as liquid moulding. Figure 2 shows the method of the resin infusion process. RTM is the moulding process in which resin impregnates dry fabric. It requires mating.

The dry cloth reinforcement is positioned inside the mold and then it is closed. The resin and catalyst are metered and jumbled together in a metering system. The aggregate is pumped into the mould at low to slight strain through injection ports and follows a pre-set route. Unusually low viscous resin is used in Resin transfer moulding systems, especially thick sections, to ensure that the resin penetrates the preform quickly and completely. Both mold and resin can be preheated before certain applications. RTM produces high quality components without the need for autoclave. However, conventional RTM takes longer to achieve both appearance quality and mechanical property when cured and demoulded. A part destined for a high-temperature application is usually required to undergo post-cure [10, 11].

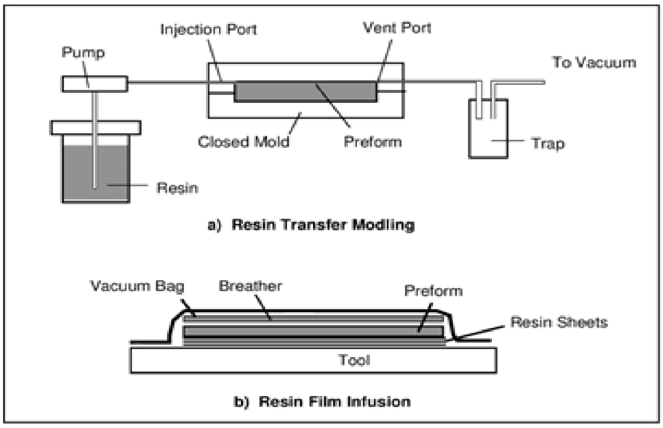

Fig.2: Resin infusion process [5].

The benefits of RTM are that it is cheaper than pre-preg material and stored at room temperatures. Thick, near-net-shape parts can be produced with this process. It also eliminates the work after fabrication. It produces dimensionally accurate with good surface of intricate parts. Inserts can be installed inside the preform before the mold closes, this provides an RTM method to accommodate core materials and integrate fittings and other hardware features into the structure [9].

2.3 Compression molding

This moulding process employs metal dies that are very durable and are an appropriate choice when a large number of parts are to be produced. In this system components are made on a group of mounted steel dies, using sheet moulding compound SMC) that may be a material product made from sandwiched sliced fibre reinforcement between the layers of resin paste. SMC is formed by transferring resin paste from a measuring device to a moving film carrier. Chopped fibre reinforcements are then embedded in the paste, and then a second film carrier is applied to place another layer of resin on the the prime of the reinforcement. Rollers are used to compress the sheet and saturate the reinforcement with an organic compound and squeeze out the trapped air. Once the sheet moulding compound is prepared for moulding, the sheet is cut into smaller pieces. These pieces are assembled on a heated mould. The mould is then closed and clamped, and pressure is applied. Because of materials viscosity dropping, the SMC starts to flow and fills the mould cavity. After cure, the part is removed from the mould [10, 12]. Hardened SMC formulations prevent micro-cracking. The process of compression moulding is depicted in Figure 3.

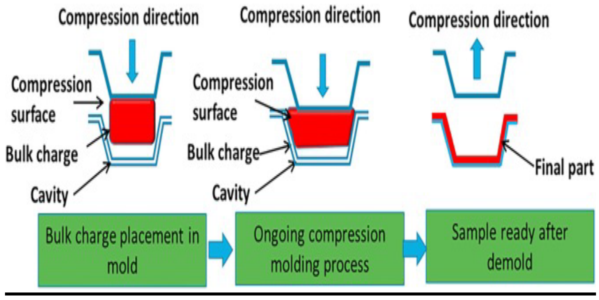

Fig.3: Compression moulding process [13].

2.4 Filament winding

The filament winding process has relatively lower production costs, and higher potency, and is automated. In this process, a mandrel is suspended horizontally. Computer-controlled filament winding machines equipped with 2 to 12 movement axes are used to apply the fibres, and move back and forth near a rotating mandrel, placing the fibre on the tool. In this process, the fiber material passes through the resin bath just before the material touches the mandrel. Pre-pegs can also be used for the process as they eliminate the need for an onsite resin bath. After this, the part is sent to cure and the mandrel is left in place or removed. Some mandrels used in more complex parts are made of soluble material, so they will dissolve or wash out of the part. Filament Winding produces components with exceptional hoop strength. The application with the most important filament winding is golf club shafts [9]. The process of filament winding is shown in Figure 4.

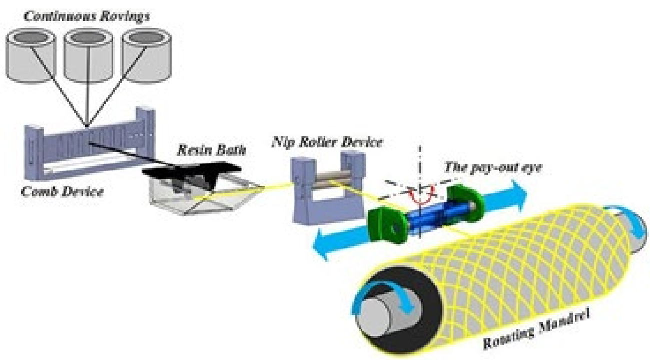

Fig.4: Filament winding process [11].

2.5 Fused deposition modelling

Pure plastic materials have poor strength. The desired strength and properties of pure plastic materials can be improved by reinforcing materials like carbon fibres into plastic materials. These reinforced materials are known as carbon fibre reinforced plastic CFRP) composite. Fused deposition modelling FDM) is a popular additive manufacturing technique and the most common method used for manufacturing carbon fibre reinforced plastic (CFRP) composite [14)]. In this process, a 3-D object is built by creating one layer at a time using FDM. The material used is a plastic filament that is unwound from a spool and then fed into a heated extrusion died. The die controls the flow of materials. The nozzle can be moved horizontally and vertically. The nozzle is mounted on a mechanical platform. The nozzle moves across the plate depositing a fine droplet of extruded plastic. The sequential extruded layers bind to previous layers and harden quickly. The whole system is placed in a room stored in a warm place slightly below the level of freezing of plastic [9, 83)].

3. Properties of carbon-fiber reinforced polymer

High-performance carbon-fibre are black, and shiny and is produced with a diameter of 8-9 µm. Carbon-fibres have high strength and modulus which makes them superior to steel and other conventional metals. The high stiffness of carbon-fibre makes it an important supporting material in engineering applications [15)], Due to these mechanical properties, carbon fibres are used as reinforcing materials in pure plastic to increase Young's modulus and the tensile strength of the overall product [14)]. Some properties of carbon-fibres are mentioned as follows:-

3.1 Light-weight Material

Carbon-fibre has a high specific strength that is high strength to weight ratio which makes it a strong and light-weight material. This property of CFRPs has offered great opportunities to the material in various industries such as automobile and aerospace engineering, and medical applications [3)].

3.2 Strength and Rigidity

Ultimate strength is defined as the maximum load that a material can withstand without fail when it is stretched or pulled. Carbon fibers, which are brittle material, do not always fail at the same level of stress due to internal defects. It fails under small loads. Carbon fibres are fully elastic up to the breaking point. This is why carbon fibres are made into composites of the required shape for testing [3, 71)]. The rigidity of a material depends on its Young's Modulus. The carbon fibre reinforced composites having a high Young's modulus makes them stiffer than Glass fibres reinforced plastics (GFRPs)[80)] and other conventional materials [3, 4, 79)]. In CFRPs, the fibre along the lengths has low thermal and electrical conductivities [15, 18, 19, 76)].

3.3 Fatigue resistance

Carbon Fibre Composites have good fatigue resistance. But when it fails, usually fails suddenly without indicating its sudden break3. When implying CFRP for critical cyclic-loading applications, engineers are needed to style in large strength safety limits to produce the element reliableness over its service life-span. For example, maintaining the strains at reasonable values like 0.3% provides CFRP with infinite fatigue strength [16, 72)].

3.4 Environmental effects

Carbon fibres show good heat resistance in inert conditions and volatilization occurs when the temperature is above 3000oc. It starts to oxidize in air at 410-450^{o}c. Now considering a humid environment, carbon-fibre is resistant to corrosion and is a chemically stable material, though carbon-fibres do not decay, the epoxy and other matrix materials are reactive. Sometimes, it react with sunlight and required to be protected. Humidity over a wide temperature range can affect the mechanical properties of CFRP, especially at the fibre-matrix interface, and lead to their deterioration [17)]. The various types of carbon fibres reinforced composites fabricated by researchers for the numerous applications and properties of composites studied are reported in Table 2. Table 1 revealed that carbon fibres were reinforced in various matrix materials Polymers/Plastics) for the fabrication of CFRP composites for various applications. Furthermore, Table 2 showed the properties of matrix materials such as impact strength, shear strength, tensile strength, flexural strength, interface shear strength, compressive strength, thermal stability, young's modulus, flexural modulus, thermal conductivity, electrical conductivity, interlaminar shear strength, interlaminar fracture toughness, density, wettability, interlaminar shear strength, interfacial strength, interfacial bonding and mechanical interlocking improved due to reinforcing of carbon fibres.

Table 2. Carbon fibres reinforced polymer composites.

S. No.	Composites	Properties studied	Reference
1.	Graphene oxide/Polyhedral oligomeric silsesquioxane POSS) grafted CF	wettability, Interfacial reaction¥ Interlaminar shear strength.	34)
2.	Carbon-nanotube CNT) grafted CFRP	Interfacial shear strength, Tensile strength, Fibre splitting.	35)
3.	Thermoset Polyurethane bend CFRP	Tensile strength, Flexural strength, Thermal Stability	36)
4.	Graphene foam GF)/poly-dimethylsiloxane PDMS)/CF	Tensile strength, Young's modulus, Thermal conductivity	37)
5.	Carbon fiber/Graphene oxide-epoxy	Flexural strength, Flexural modulus, Interlaminar shear strength	38)
6.	Thermally reduced graphene oxide TRGO)/CF	Interlaminar shear strength, Flexural strength, Interfacial bonding between the matrix and Carbon fibres.	39)
7.	CFRP reinforced concrete CFRPRC)	Flexural strength, Compressive strength.	40)
8.	Carbon fibre reinforced epoxy/Clay nanocomposites CFRENCs)	Interlaminar fracture toughness, Flexural strength.	41)
9.	CFthree dimensional 3D))–CNTCarbon Nanotube)	Flexural strength, Flexural modulus.	42)
10.	Polyethersulphone PES)/ Graphene oxide GO)/Cf	Tensile strength, Flexural strength	43)
11.	Sisal/Carbon/Polymethyl methacrylate PMMA)	Tensile strength, Flexural strength, Thermal stability.	44)
12.	HFRPGlass, Carbon fibre, and Epoxy)	Density was reduced, Tensile strength, Flexural strength.	45)
13.	Short Carbon Fibre SCF)/ Polyamide66 PA66) 40% SCF)	Tensile, flexural, and compression properties.	46)
14.	Graphene Oxide GO sheets2D)/ Carbon fibre	Interlaminar shear strength, Interfacial strength.	47)
15.	Carbon black CB)/ CF	Interlaminar shear strength, Interface shear strength, Impact strength, Tensile strength.	48)
16.	Graphene oxide/ Carbon fibre-reinforced cement-based materials	Flexural strength.	49)
17.	Low-temperature thermal stabilized Polyacrylonitrile PAN)-based carbon fibres	Tensile strength.	50)
18.	Carbon fibre/Phenolic resin/ Coupling agent glutaric dialdehyde	Flexural strength increased, Electrical conductivity.	51)
19.	Plasma-treated CFF reinforced composites	Tensile strength, Interfacial bonding, Mechanical interlocking.	52)
20.	Polyketone PK)/ Carbon fibre CF)	Thermal stability, Conductivity, Young’s modulus	53)
21.	Polyphenylene sulfide PPS)/ Graphene oxide GO)/ Short carbon fiber SCF)	Tensile modulus, Flexural Modulus	54)
22.	Electrowetting Carbon fibre surface	Interfacial shear strength, Wettability.	55)
23.	CFEC / XD-grade carbon nanotube XD-CNT)	Flexural and Tensile strength, Flexural modulus	56)
24.	Multi-layered Short Carbon Fiber reinforced Polyurethane composite.	Absorbing Property	58)
25.	Carbon Fibers reinforced in Polyurethane Matrix	Adhesion properties of carbon fibres with Polyurethane	59)

26	HNO_3-treated CF	Improved hydrophilicity for candida tropicalis restriction in Xylitol fermentation.	60)
27	HNO_3-treated CF in polyetherimide matrix	Mechanical and abrasive wear properties	61)
28	Carbon fiber reinforced in Polyamide	Hardness and Wear	62)
29	Carbon fiber reinforced PTFE.	Tribological performance	63)
30	Short carbon fibre reinforced in phenolic resin.	Tribological performance	64)
31	Recycling of carbon fibers in polymer matrix	Tribological performance	65)
32	Carbon fiber reinforced in epoxy resin.	Porosity and interlaminar fracture behaviour.	70)
33	Carbon fiber reinforced in polyphenylsulfone and polyetherimide	Impregnation quality	77)
34	Deposition of carbon nanotubes on the carbon fiber (CF).	Electrospray techniques Improved properties.	80)
35	Hybrid composite of SiC/PyC/CNF/Gr	Anodic performance	87)

4. Applications of carbon-fiber composites

Now a day carbon reinforced composite becoming potential material for various applications [66-68]. The applications of carbon-reinforced composites in fields is shown in Figure 5.

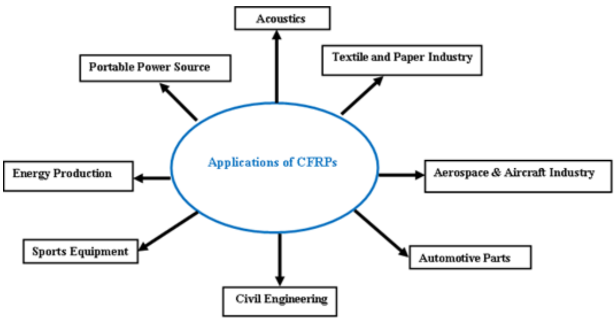

Fig.5: Applications of CFRP.

4.1 Automotive industry

Reducing fuel consumption and emissions has forced the automotive industry to focus on fuel efficiency and the idea of making vehicles lighter without compromising consumer safety arose. The use of carbon fibre reinforced plastic offers the best potential for lightweight materials to realize lightweight concepts due to its excellent physical properties compared to commonly used metals. It could be seen in the production of structural elements, monohulls, cabins, and semi-trailers. In addition, carbon fibres are also found in the roof of automotive roof, motorsport, and passenger train applications [1, 8, 15, 21-24, 73-74, 81, 84]. Apart from this, its various properties including crashworthiness ability to absorb impact energy) have increased its applications in body structures like [25-26]:-

- Bumpers used to protect the vehicle from a collision).
- Bonnet which is one of the heaviest part).
- Tailgates, fenders, and side-doors

Considering the referred to it ought to additionally be lightweight to decorate the overall performance of the car and its fuel efficiency. The use of CFRPs in racing vehicles improves the general dynamics of the auto as carbon-fibre strengthened plastic is two times as more potent and at the equal time a whole lot lighter than aluminium or metal material. Carbon fibre reinforced silicon carbide CSi) finds applications in braking materials for heavy vehicles, high-speed trains, and emergency brakes on cranes, as the temperature in the braking system can reach several thousand degrees Celsius. Wheel rims are important components essential to the safety of an automobile. Currently Al and Mg alloys are used to reduce the weight of motorsports. The carbon fibre wheels rims are also being used to replace Al alloys wheel rims. Studies show that carbon fiber rims have significantly reduced weight by 42% while improving the safety feature by 41% compared to Al alloys wheels [27].

4.2 Aerospace industry

Aerospace industries require highly thermal-resistant, durable, and light-weight materials for the aircraft structure and the CFRPs composites which exhibit outstanding mechanical properties have emerged as a potential material fulfilling these requirements [1]. Carbon fibre reinforced polymer composites are the most well-known material used in the aircraft industry. Carbon fibre is a toughened epoxy matrix that is stiff, light-weight, and exhibits superior fatigue life; this provides a potential use in the manufacturing of large engines that consist of fan blades with excess lengths [28, 29, 85, 86]. Most of the parts of current generation of passenger/airliners are made of composite materials. More than 30% parts of Airbus A350 and 50% parts of Boeing B787 made of composite materials [6]. Applications of Carbon fibre in the aerospace industry are:-

• The fabrication of empennage and floor beams of a B777 made of intermediate-modulus carbon-fibre.
• The spoilers and outboard ailerons of a B737 are fabricated from PAN-primarily based standard-modulus 220 GPa) carbon fibres epoxy matrixes composites.
• Engine fan blades.

4.3 Biomedical

The three characteristics of carbon-fibre that have caught the attention of medical professionals are:-

- It is radiolucent. It means X-rays of the intensity used for medical imaging pass through it.
- It has good biocompatibility. The body accepts carbon fibre implants [3]. The strength characteristics and biocompatibility of carbon fibre-reinforced composites have shown prospects and attainable applications within the field of medicine and orthopedics. Technological advances are discovered in the style of sports prostheses for the lower extremities.
- Carbon fibre is lightweight, offers greater energy storage, and provides a more dynamic response than a human foot can provide. The carbon fibre prosthetic feet can offer an advantage to athletes with a disability and can also provide performance improvements when incorporated into athletic shoes.
- Similar in density and elasticity to bone [1, 20].

4.4 Other applications

Carbon fibres can efficiently reflect heat, if it is moulded near surfaces of polymers or thermosets it significantly improves their fire resistance [31]. CFRP because of its high strength to weight quantitative relation is being employed in a variety of high-end products that are needed to be stiff and light-weight. These embrace music instruments, laptop shells, fishing rods, high-performance drone bodies, carbon woven fabrics [32] and firearms. It is also used in other industries like the civil and marine industries. Due to the better fabric damping in comparison to steel, components comprised of CFRP can enhance the precision of system tools [33].

5. Recycling of carbon fibre reinforced polymer composites

The challenge for Carbon Fibre Reinforced Composites is the question of recyclability [18, 65, 75, 82]. Pyrolysis and Solvolysis are the processes used for recycling Carbon Fibre Reinforced Composites. However, recycled fibres can only be used to replace a small number of pure fibres in products. Because of this recycling of CRFPs is uneconomical and environmentally unsound. It is not possible to re-incorporate the recovered carbon fibres from high-tech applications into the same applications from which they were recovered. It can be incorporated into industrial applications that do not require full-length carbon fibres [57].

5.1 Methods of recycling

5.1.1 Pyrolysis

Pyrolysis can be carried out in the absence or presence of oxygen. Nowadays, it is carried out in the presence of steam. This process degrades matrix and produces oil, gases, and solid products that are likely fibres, possibly char, and fillers. The char contaminates the fibre and requires post-treatment. This process has become popular on an industrial scale and is used commercially for recycling carbon fibre reinforced matrixes. Carbon fibres are unaffected by temperature. Furthermore, it can get contaminated with a carbon-like substance and it lost the ability to bond well with a new resin if the process temperature is below 450oc. When it heated at 1300^{o}c, the carbon-like substance is completely removed and the fibres become perfectly clean with a highly activated surface. If the temperature is above 600^{o}c, the tensile strength of RCF Recycled Carbon fibres) is reduced by more than 30%. Epoxy resins degrade under oxidizing conditions, but under inert conditions and temperatures between 500 to 600^{o}c complete removal of resin residues is possible. Therefore, the temperature in the range of 500 to 550^{o}c can be considered as the maximum temperature limit of the process to maintain admissible strength for carbon fibres [57].

5.1. 2 Solvolysis

Solvolysis is a process that uses a solvent to break down the resin. It was first used for unsaturated polyesters UPs) about 30 years ago. It is the most common method used for thermoset resins. This process is followed by hydrolysis taking place in a temperature range of 220-275^{o}c with or without added solvents or catalysts to break down into its monomers and a copolymer of styrene-fumaric acid. In this process, maintaining a lower temperature is required to degrade polymers, particularly for epoxies. The amount of temperature and pressure required to degrade the resin depends on the nature of the resin. It is easier to dissolve a polyester resin as compared to an epoxy resin and it degrades at lower temperatures. In the last decade, this process is used extensively for the recycling of composite materials, especially CFRPs [57].

6. Conclusion

Development of new materials which satisfy the consumer needs has always been the focus of the industries and researchers have worked well to substitute the conventional materials to satisfy their consumers. Carbon-fibre and its properties make it versatile that it fits itself in any industry fulfilling the demand for strong and lightweight materials in various industries. The problems such as its cost and slow production are becoming a major concern to industries. The research and development sector is working on these problems. They are also developing a substitute material that can provide similar properties and fits closely to the CFRPs applications. Many fibre reinforced plastics using natural fibres are being considered the next era of materials. The biodegradable plastics/ polymers are also being used as matrix material in natural fibre reinforced composite to overcome the problem of the environmental issue of polymers composites. The carbon fibre reinforced plastic composites are stiff, light-weight high-performance material because of this it used in many application in the field of biomedical, automotive and aircraft industries for making various components such as drone bodies, laptop shells, prosthetic feet, roof of automotive roof, bumpers, bonnets, side doors etc.

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