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REVIEW

Preparation, development, outcomes, and application versatility of carbon fiber-based polymer composites: a review

Tushar Kanti Das [1] · Prosenjit Ghosh [1] · Narayan Ch. Das [1]

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Abstract

The high strength to weight ratio of carbon fiber has made it as an attractive energy-saving material over the conventional strength-bearing materials like steel. Realizing the trend, the high-weight steel is being progressively replaced by the low-weight and corrosion-resistant carbon fiber composites in many strength applications. The carbon fiber-reinforced polymer matrix composite (PMC) have thereby become forefront material in aerospace, automobile, sporting goods, and other applications which demand high strength and high modulus. Moreover, the gradual reduction of its cost curtsy to the extensive research in the field of carbon fiber technology in recent years has been opened its market in different construction applications. This review is the discussion of carbon fiber loaded a variety of polymer matrix composites where the structural importance of these composites has been emphasized. The objective of this discussion is to provide information on the whole spectrum of carbon fiber-based polymeric composites. It also includes brief discussion about preparation and properties of carbon fibers along with processing, fabrication, and structural applications of these carbon fiber-based polymer composites.

Keywords Carbon fiber · Polymer matrix composite · Reinforcement · Structural applications

Abbreviations

CF	Carbon fiber
GF	Glass fiber
PMC	Polymeric matrix composite
FRP	Fiber-reinforced polymer composite
AF	Aramid fibers
PAN	Polyacrylonitrile
UHM	Ultrahigh modulus
HM	High modulus
IM	Intermediate modulus
SHT	Super high tensile strength
HIT	High-heat treatment
IHT	Intermediate-heat treatment
LHT	Low-heat treatment
PES	Polyethersulfone
PPS	Polyphenyl sulfide
PEEK	Polyetheretherketone
PEI	Polyetherimide
PI	Polyimide
RTM	Resin transfer molding
EMI	Electromagnetic interference
T_g	Glass transition temperature
PC	Polycarbonate
PLA	Polylactic acid
SEM	Scanning electron microscope
STM	Scanning tunneling microscope

✉ Narayan Ch. Das
ncdas@rtc.iitkgp.ac.in

[1] Rubber Technology Centre, Indian Institute of Technology, Kharagpur 721301, India

1 Introduction

Carbon fibers (CF), long fine thread materials having diameter in the range of micrometer, are structurally made of carbon atoms. The carbon atoms are bonded with each other in such a way that the crystal planes are organized almost parallel along the axis of fibers. This parallel arrangement of crystals makes fiber amazingly stronger than other fibers [1–4]. In 1879, Thomas Edison was first prepared CF from cellulosic fibers for use in electric lamp [5]. But the first commercial production was made by Bacon et al. in 1958 from rayon as precursor [6]. In the beginning, CF was divided into two sections: one was prepared by heat treatment in the range of 1000 to 1500 °C called “carbon fiber” and other was made by heat treatment above 2000 °C called “graphitic fiber.” Later, the distinction between them was abolished and both of them were recognized as CF. The CF is designated as “high-strength CF” for low-temperature treatment and "high modulus CF" for high-temperature treatment [7, 8]. CF, in comparison with other synthetic fibers, acquires pioneer position in structural application due to its high fiber structure in combination with physical and mechanical properties both in compression and tension mode. Starting from 1960s, CF is still now recognized as most significant industrial materials in modern day science and technology. Considering its strength, commercially as filler, CF-based polymer composites was first invented in 1960s and gradually these types of composites spread its legs in various application such as automotive industry, civil construction, mechanical engineering, aerospace application, aviation, and off-shore [9–12]. Most importantly, CF makes the composites lighter weight due to its high strength to weight ratio. The properties of CF-based composites are mainly governed by origin from which it is derived. To obtain required performance of the composites, precursors of CF should contain high amount of carbon [13], extending chain to make high molecular weight [14] and high degree of orientation of crystal plane along the fiber axis [15, 16]. The relationship between processing, structure, and properties controls the design, development, and fabrication of intricate objects which is core of material science and technology. Based on these key points researchers are developing various objects for applications in our modern society to accelerate growth in different sectors.

A composite is often defined as a combination of two or more components which possess significantly different physical and chemical characteristics from those of its constituent components. In a composite the constituents remain physically separable and distinct from each other. In general, a composite is made of a soft and weaker matrix in which a strong and stiff reinforcement is distributed within the matrix [17–19]. The purpose of making composite is to produce a lightweight material having improved mechanical properties which its individual ingredients are not able to provide. The improved properties of composites are primarily controlled by their microstructure and interaction between matrix and reinforcing materials in the inter-phase region [20]. The structural composites needed sanguine equivalence between physical and mechanical properties so that the structural materials can be used as efficiently and safe. The main objective of structural composites is optimizing its performance during service life. For the last few decades, we observed that polymeric materials have taken over the conventional materials for various field of applications. This is due to its advantageous properties over the conventional materials. The primary benefits obtained from polymers are easy processing, high productivity, and low cost of production. The commercial examples of reinforcing materials for structural applications include glass fiber (GF) or CF reinforced thermosetting polymer matrix such as epoxy, phenolic, and polyester resin. Among those synthetic fibers CF is second most widely used fiber as filler for structural applications. Thermoplastic resins are also used to manufacture these composites which could provide the added advantage of reprocessability. However, the production cost of fiber reinforced polymer composite is yet in the higher range which needs to overcome till date [21, 22]. To boost up mechanical, thermal, and electrical properties polymer with multifunctional capability filler should be used. Among those filler carbon-based polymeric composites can fulfill the requirement due to its multifunctional properties. One additional advantage of CF-based polymeric composites is low cost as well high aspect ratio of carbon fiber making the composites with improved properties [23–25]. Most of the research works were concentrated on strong physicochemical interaction between CF and polymer at their interface. These interactions were achieved either through van der Walls force or hydrogen bonding in between them [26, 27]. The interaction may improve the properties of the composites when binding energy in between polymer and fibers surpasses the cohesion energy of the individual polymer and fibers [28]. Sometimes, commercially treated CF was used to improve the interaction between the polymer matrix and CFs. But the properties of the CF-based polymeric composites are mainly governed by orientation of the CFs in the polymeric matrix [29]. To explore the theory behind the high mechanical behavior of CF-based polymeric composites more experiments have been performed and the mechanism for explaining the mechanical behavior is now well set up. Recently, polymer composites based on nanoreinforcement were started to use but cost of nanomaterials is so high that in commercial scale it is not viable. Though the properties improved of the nanocomposites are higher but till now high scalable production within limited cost is very difficult for researchers.

So, the fiber-reinforced polymer (FRP) composites are used in almost every aspect of engineering and structural applications including high structural applications such as in aircraft, helicopters, spacecraft, bridge, building, ships, and off-shore platforms to low structural applications like boats, sports goods, and chemical processing equipment [30–33]. Day by day the demand of these FRP composites is rapidly increasing because these materials are used in existing market as well as capturing the other markets like civil, biomedical, and microelectronic device applications. Current extensive research in this field to explore new polymer, fiber, and its arrangement within the polymer matrix to modify their properties has made their market more composite favorable [34–36]. High consumption of FRP composites in various applications leads to high extent of wastage after using. Hence, recycling of this wastage FRP composites is now primary task for sustainable economic growth of industries [37].

CF is now the most promising raw material for the fabrication of advanced structural composite material. The light weight, high strength, high stiffness, and outstanding fatigue resistance of CF has enabled carbon fiber-reinforced polymeric composite to be used in a large number of structural application such as aerospace, wind turbine blade, sports equipment, and transportation [39, 40]. Other commercially available fibers like glass, ceramic, and boron are also used in different structural applications [41]. But at strain (in between 0 and 4%), the ability to carry load is far better than other structural materials which is clearly shown in the Fig. 1.

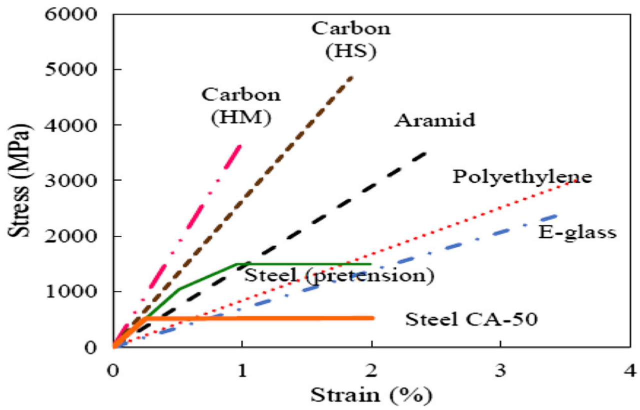


Fig. 1 Comparison of stress–strain plot of carbon fiber with other materials [38]

Hence, CF is gradually replacing these fibers and is becoming a strong competitor of other synthetic fibers. The organic nature of carbon fiber facilitates the composite fabrication with organic polymers, thus lead to the production of high strength, high stiffness, corrosion resistant, and lightweight product at a moderate cost. It is also used in the fabrication large-size component and intricate design [42].

This review mainly focused on CF-based polymeric composites for structural applications and outlook on its markets. Besides this, the review briefly discusses about preparation and properties of different precursor-based carbon fibers and technique of fabrication of carbon fiber polymer composites for structural applications. Few studies have been also done on the other applications field of polymer-based carbon fiber composites. Lastly, we discussed about the research challenges which are encountered by technologist during fabrication of carbon fiber-based polymer composites.

2 Carbon fiber microstructure

CF is fiber having diameter in the range of 5–10 μm and contained carbon in the range of 95–99%. It consists of hexagonal graphene layer network but the interaction between the layers is so weak that disorder frequently takes place, resulting in the formation of two-dimensional ordering referred as "turbostratic" structure (as shown in Fig. 2). These structures are present with some defects compare to that of graphitic fibers where interaction is too high to make it three-dimensional ordering. Interplanar distance between graphene layers of CF is significantly higher than graphite. During heat treatment the parallel layer structures like graphite in CF are distorted and the planar layer structures are lost. But the core of the material is almost in turbostratic form [44]. This turbostratic structure is considered to be basic structural unit of CF. To form various types of micro-domain within CF, this structural unit can join, fold, twist, and split with each other [45]. The internal structure of CF is not purely homogenous but it consists of various chaotic micro-domains from by the structural units [46]. Briefly, carbon fiber is a blend of amorphous and graphitic carbon [47]. In CF each crystalline plane consists of aromatic rings where carbon atoms are positioned on hexagonal lattice. All CF synthesized from different precursors have unorganized crystalline structure. This imperfectness in crystalline structure can be defined as stacking disorder in between neighboring graphitic layers or defects in single layer or stacked layers. This crystalline disorder can easily measure by X-ray diffraction pattern (XRD) [48, 49]. Small angle X-ray diffraction pattern also revealed that CF have looked like lobe-shape and the needles like defects appeared in between crystallites. The size, pattern of the crystallite, and the size of the defects can also be easily determined by these techniques. These results show good agreement with the results obtained from electron microscopic techniques [50]. The defect in orientation of the crystalline planes of core-skin structure of CFs is schematically shown in Fig. 3. The schematic clearly demonstrated that the chain is more oriented in the skin than its internal core.

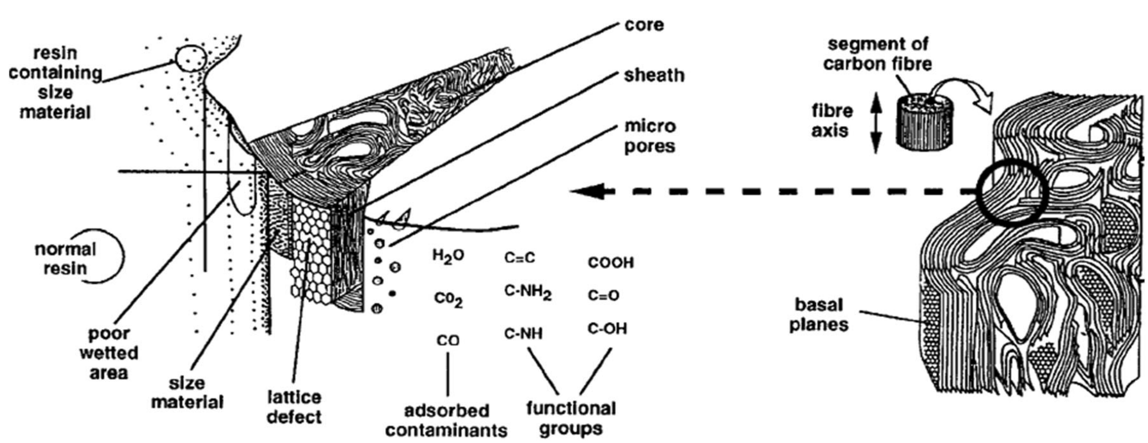


Fig. 2 Model "turbostratic structure" of CF produced from polyacrylonitrile (PAN) [43]

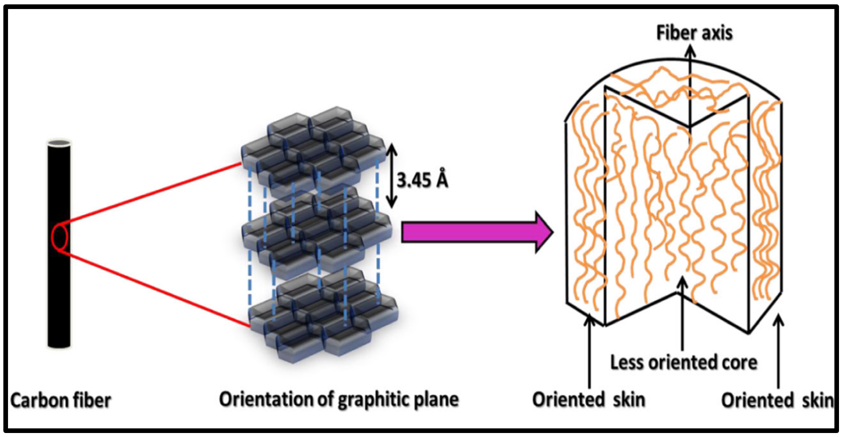


Fig. 3 Schematic of internal crystal structure of carbon fiber

In 1879, Thomas Edison converted cotton and bamboo into CF using incandescent lamp filaments [5]. After that in late 1950s, synthetic rayon was carbonized to form CF. But high scalable commercial use of CF started after introduction of PAN as precursor in 1960s. This is turn out to be economically more favorable from yield point of view as well as physical and chemical properties compared to that of rayon-based CF [51, 52]. Later, it was trying to prepare from pitches obtained from petroleum, coal tar, asphalt, etc., but the properties of these CFs were inferior to that obtained from PAN-based CF [53]. The preparation of high-performance CF is not simple work as synthesis process passes through controlled and optimized multiple steps. Simultaneously, other parameters related to steps should be cautiously monitored during synthesis process. Hence, preparation of CF from PAN through pyrolysis is considered to be core of carbon fiber production industries. It is believed that polymeric material which does not undergo melt upon pyrolysis and leaves a part of carbon as residue can be a potential candidate for production of CF [54].

Though the manufacturing of CFs from different sources requires different technique, primary features of synthesis are almost similar. The production of CF from its precursors passes through mainly three stages: oxidation, carbonization, and graphitization, and in each stage, the properties and structure CF are different from each other. The stages of production from PAN-based fiber are schematically shown in Fig. 4. The three zones have different temperature and depending upon the carbon fiber various temperatures have been selected to obtain best quality of CF from its precursors [55]. Commercially, CF is made from PAN which follows the mechanistic pathway as shown in Fig. 5. At first, PAN was heated at 3000 °C, which leads to cyclization to form ring structure. Further heating at 7000 °C ring structure converted to aromatic pyridine groups by losing hydrogen gas. After that, heat is gradually applied to fuse the ring structure resulting ribbon like structure and lastly, to form extended ribbon-like structure, heated at high

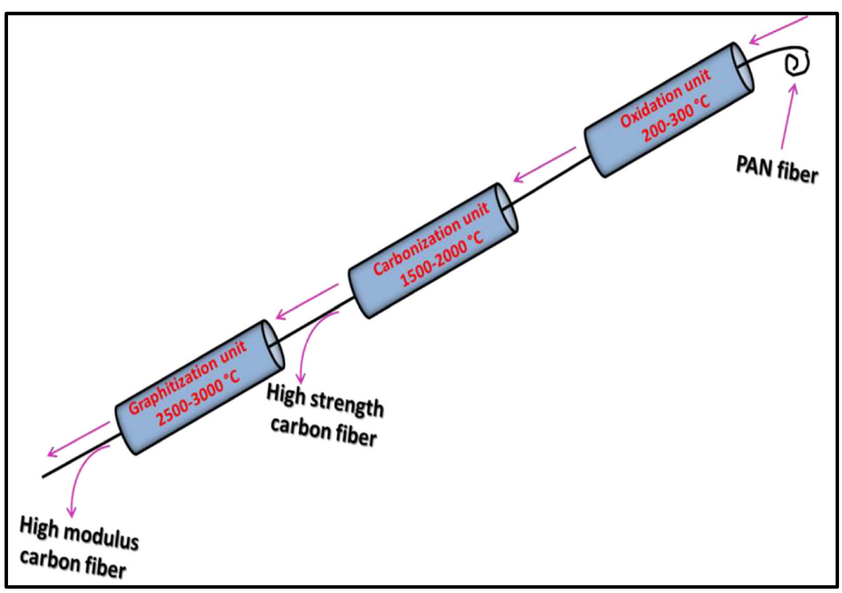


Fig. 4 Basic scheme of three-stage production of carbon fiber

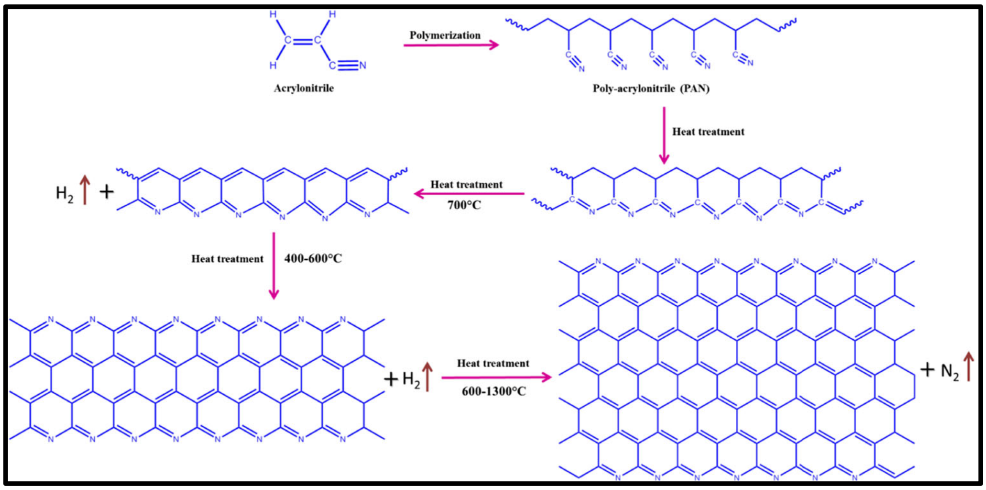


Fig. 5 Plausible mechanism of formation of CF from PAN (http://web.mit.edu/3.082/www/team2_f01/chemistry.html)

temperature by evolving nitrogen gas (http://web.mit.edu/3.082/www/team2_f01/chemistry.html). In today's market PAN-based CF have become standards one as its properties are overwhelming over rayon and pitch-based CF. The formation of CF from PAN-type fibers depends on various parameters. The parameters include the following [56].

- Molecular weight of PAN and its polydisparity index
- The solvent used form spinning process
- Concentration of the polymer in that solvent
- Temperature of the spinning process
- Shape and size of the holes of the spinning instrument trough which material pass
- Temperature and composition of the coagulation bath (if not air)
- The extent of stretching during coagulation
- Temperature of stretching during coagulation and
- State of the collapsed fiber in its final condition.

Thus, it is very difficult to optimize the condition in which we get high-quality CF. Hence, depending upon the control conditions, various type of CFs are obtained from its precursors.

CF shows wide variation in its properties depending upon the manufacturing conditions. Basically, the properties of CFs rely upon microstructures which directly change with variation of processing conditions.

During forming of CF, internal core structure of fiber is created by high binding symmetrical carbon elements, whereas outer structure is generated by low binding energy carbon elements. These unbalanced low binding energy outer skin carbon elements are responsible for its surface reactivity towards its further modification or forming an interaction with matrix in the inter-phase regions [45, 57]. So, highly reinforcing CF has better alignment with the axis of the fibers and entire structures almost consist of more number of graphitic basal planes. For this reason, it shows less reactivity towards modification and difficult to disperse in matrix. On the contrary, less reinforcing CF exhibits the almost opposite behavior because it consists of less oriented crystal planes along the fiber axis [58]. To achieve parallel orientation of the crystal plane along the fiber axis three different techniques have been employed. The techniques are high-temperature graphitization, high stretching of precursor, and control of crystallization during spinning process. Among them second and third processes are commercially available to control its orientation along the fiber axis [59, 60].

According to its properties, CF as shown in Table 1 compared to other fibers such as glass and aramid for load-bearing application is excellent material for production of low-cost, high-strength, lightweight, corrosion resistance, and long-life polymeric composite materials. For structural application most important parameter is compressive strength. In polymer-based composites this property is primarily governed by reinforcing material distributed within the polymeric matrix. CF has high tensile strength and low coefficient of thermal expansion (CTE) in comparison to that of Kevlar fiber and GF. The CTE values of fibers are generally lower than steel, which is one of the primary constitutes of structural applications. Among other commercially available fibers, CF has lowest magnitude of CTE. In addition to these, advantageous high-temperature stability, chemical resistance, and thermal and electrical conductivity of CF make them also potential candidate for other applications such as energy harvesting, EMI shielding, and heat sinkers. It is clearly shown in Table 1 that in comparison to other conventional fibers such as natural fibers and AF, CF exhibits better compressive strength. This high compressive strength makes the researches' interest to use carbon fiber as reinforcing material for structural applications. It was already explored that compressive strength of a materials depends upon size of crystallite, orientation of the crystalline planes, density, inter-planar distance between the graphitic planes, and void space in the materials [62, 63]. It

Table 1 Qualitative comparison with other fibers [61]

Properties	Types of fiber used with composites		
	Carbon fibers (CF)	Glass fibers (GF)	Aramid fibers (AF)
Tensile strength	Very good	Very good	Very good
Compressive strength	Very good	Inadequate	Good
Young modulus	Very good	Good	Adequate
Long-term behavior	Very good	Good	Adequate
Fatigue resistance	Excellent	Good	Adequate
Bulk density	Good	Excellent	Adequate
Alkaline resistance	Very good	Good	Inadequate
Cost	Moderate	Moderate	High

was also found that compressive strength of PAN and pitch-based CF is inversely related with each other [64, 65]. For a specific modulus-based CF, compressive strength can be improved by perfect orientation and creation of smaller-size crystallites [66, 67].

3 Classifications of carbon fiber

Depending upon precursor, strength and final heat treatment temperature carbon fibers can be classified into the following groups [68]:

1. Based on precursor CF classified into following groups:

   i. PAN-based carbon fiber
   ii. Pitch-based carbon fiber
   iii. Mesophase pitch-based carbon fiber
   iv. Isotropic pitch-based carbon fiber
   v. Rayon-based carbon fiber
   vi. Gas phase grown carbon fiber

2. Based on carbon fiber strength classified into following groups:

   i. Ultrahigh-modulus (UHM) type
   ii. High-modulus (HM) types
   iii. Intermediate-modulus (IM) types
   iv. Low-modulus and high-tensile-strength (HT) types
   v. Super high-tensile (SHT) types

3. Based on final heat treatment temperature carbon fibers classified into following groups:

   i. High-heat treatment (HIT) carbon fiber (heat treatment temperature ≥ 2000 °C)
   ii. Intermediate-heat treatment (IHT) carbon fiber (heat treatment temperature = 1500–2000 °C)
   iii. Low-heat treatment (LHT) carbon fiber (heat treatment temperature = 1500–2000 °C).

Qualitative comparison of CF based on source PAN-based CF showed better mechanical properties compared to pitch, rayon as shown in Table 2. Along with properties, the surface morphologies of CF vary with change in precursor, which can be easily examined by scanning electron microscopy (SEM) as well as scanning tunneling microscopy (STM) [70, 71]. The PAN-based CF has almost circular appearance and various notches were observed on the surface CF depending upon the tension applied during formation [55]. Whereas fiber-based upon rayon shows much more notches on the surface in comparison to that of PAN based. Pitch-based fibers exhibit notch intermediates between these two fibers [72]. Kumar et al. clearly showed the difference in cross section of PAN and pitch-based CF by SEM (as shown in Fig. 6) [73]. These surface notches or groves on the fiber create interaction via mechanical interlocking with polymer or other matrixes and results of interaction can be correlated by enhanced mechanical or related improved properties in CF-based composite materials [74, 75]. So, to improve interaction with matrixes, different surface modifications of CF or pretreatments have been already reported for creation of notches [76, 77]. The notches are present in all types of CF, and it varies with precursors and heat

Table 2 Mechanical properties of carbon fibers obtained from various precursors [69]

Precursor	Tensile strength (GPa)	Modulus (GPa)	Elongation at break (%)
PAN	2.5–7.0	250–400	0.6–2.5
Mesophase pitch	1.5–3.5	200–800	0.3–0.9
Rayon	≈1.0	≈50	≈2.5

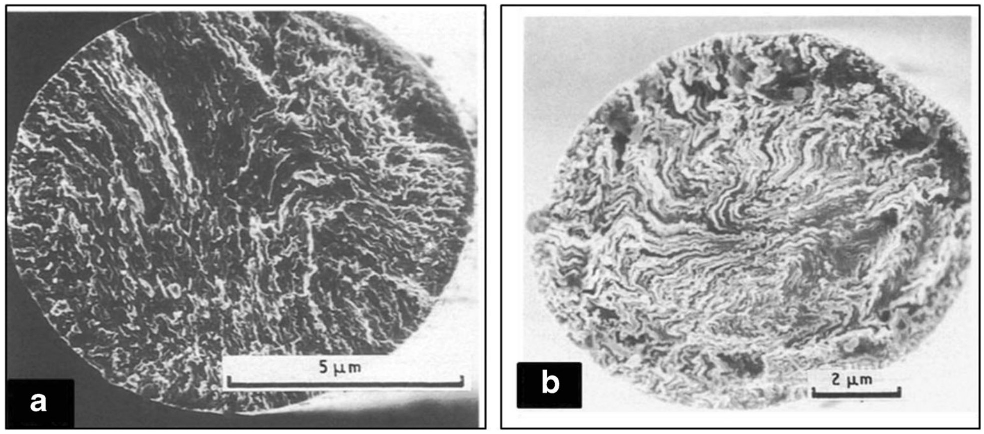


Fig. 6 SEM images of cross section of **a** PAN- and **b** pitch-based carbon fibers [73]

treatment during processing. Low processing temperature CF exhibits small pores but higher in numbers, whereas high processing temperature shows large pores but less in numbers. The pores are generally in the range of 1–10 nm [78]. The diameter of CF has dramatic effect upon the crystallite thickness, degree of graphitization, and amount of carbon content. With reduction of diameter of CF degree of graphitization and amount of carbon content increase but the thickness of crystallite became small in size [1]. Besides these latest technologies developed vapor grown CF which has superior properties than CF obtained from pyrolysis of raw material such as PAN, pitch, and rayon. But the use of vapor-grown CFs is very much limited in structural applications due to its high production cost [79].

4 Polymer carbon fiber composites

Composites are fabricated to fill the deficiency of each constituent and improved the properties in each section. Reinforcement by CF can sufficiently improve the properties of polymeric matrix. Basically, two types of CF are available in the markets depending upon their size. One is continuous carbon fiber and other is short carbon fiber. Though improvement in mechanical properties by continuous CF-based polymeric composites is high, fabrication of these types of composites faces problems in each steps of processing. For making parts of low-cost commercial structural applications, the polymers are reinforced with short CFs. The mechanical properties of short CF-based polymer composites depend upon the aspect ratio of CFs and its distribution and orientation in the polymeric matrix [80–82]. Other parameters such as fiber breakage during processing, processing conditions, loading of fiber, and fraction of void in the final composites also influence the properties of CF-based polymeric composites [83, 84]. Although CF-based polymer composite was reported in 1960s but used for structural application started in 1980s. Large variety of carbon in conjugation with diminish in their price day by day and invention of large-variety polymeric material as matrix make them easier to hold their position in market where they had. Epoxy, phenolic, and furfuryl resin is used as thermosetting polymeric matrix and polyethersulfone (PES), polyphenyl sulfide (PPS), polyetheretherketone (PEEK), polyetherimide (PEI), and polyimide (PI) are used as thermoplastic polymeric matrices for fabrication of mainly structural parts. Generally, thermoset (mostly epoxy) matrix have been extensively used with CF as only in presence of heat and pressure thermosetting polymer progressively strengthen due to crosslinking of polymer. But recently, thermoplastic matrix is also used due to its high ductility, less processing time, and accessibility of thermoplastic which can withstand at high temperature. In contrary, thermosetting resin will cure step by step which is time consuming. For these reasons, technologists are trying to develop composites based on thermoplastic matrix.

In comparison to thermoplastics as shown in the table, epoxies have comparable tensile strength (30–100 MPa), modulus of elasticity (2.8–3.4 MPa), and density (1.25 g/c.c) but less elongation (≈0–6%) [85]. Major difference between thermoplastic and thermosetting lies in their processing temperature, and thermosetting have lower processing temperature (epoxy $T_p = 150–200$), sometime cure at room temperature in presence of hardener or catalyst (Table 3).

Much more modification of epoxies have been done to improve the interaction in carbon fiber-matrix interface [88, 89], increasing ductility [90] [91], and moisture resistivity [87]. It is already explored that other than epoxy, polyimide and bismaleimiden [92] can be used with carbon fiber for load-bearing applications. There are many methods for improving bonding between polymer matrix and fiber surface interface. These methods include wetting of surface fiber,

Table 3 Properties of thermoplastic used with carbon fiber as composite

Properties	PES	PPS	PEEK	PEI	PI
Glass transition temperature (T_g) (°C)	230[a]	86[a]	170[a]	225[a]	256[b]
Decomposition temperature (T_d) (°C)	550[a]	527[a]	590[a]	555[a]	550[b]
Processing temperature(T_p) (°C)	350[a]	316[a]	380[a]	350[a]	304[b]
Tensile strength (MPa)	84[c]	66[c]	70[c]	105[c]	138[b]
Modulus (MPa)	2.4[c]	3.3[c]	3.8[c]	3.0[c]	3.4[b]
Elongation at break (%)	30–80[c]	2[c]	50–150[c]	50–65[c]	5.0[b]
Izod impact (lb.ft./in)	1.6[c]	0.5[c]	1.6[c]	1.0[c]	1.5[c]
Density (gm/c.c)	1.37[c]	1.3[c]	1.31[c]	1.27[c]	1.37[b]

[a] From reference [86]

[b] From reference [87]

[c] From reference [85]

mechanical interlocking, and chemical bonding [91]. Generally, to improve adhesion between CF and matrix, the non-reactive surface of the CFs is treated before supply to the consumers.

To improve bonding between carbon fiber and polymer matrix different treatment is employed such as oxidation, modification with coupling and wetting agent, and surface coating. But it should be kept in mind that these treatments must be stable at high temperature as processing of carbon fiber with either thermoplastic or thermosetting polymer has been done at higher temperature.

To separate weak fiber on the surface, oxidation treatment can employed by gaseous, electrochemical, plasma, and solution methods [93]. It is also reported that more violent oxidation treatments roughen the surface which help to enhance mechanical interlocking with polymer matrix [94, 95]. Much more work has been done to introduce chemical groups (such as =CO, −COOH, −OH) on surface of carbon fibers by coupling, wetting agent, and surface coating. But this modification contributes little improvement in adhesion of fiber with polymer matrix [93].

Although after oxidation treatment of carbon fibers the magnitude increase in inter-laminar strength of composite is very high but the correlation between oxygen concentration on the surface and increase in strength is still unknown (http://web.mit.edu/3.082/www/team2_f01/chemistry.html), [96]. After removing oxygen containing functional groups by treatment with diazomethane the composite strength again closed to the value of untreated fiber composites [97]. So, we cannot ignore oxygen-containing functional group contribution to inter-laminar shear strength. Hence, determination of oxygen content in CF is very much important for inter-laminar shear strength.

Generally, coupling agent acts as compatibilizer, which is short-chain hydrocarbon molecule with polar groups at one end which bind with carbon fiber surface groups and other end bind with polymer. Commercially, organosilanes, organotitanates, organozirconates, etc., are used as coupling for carbon fiber-based composites. It is demonstrated that only small amount of organotitanates and organozirconates (0.1–0.5 wt.%) can enhance bonding significantly with thermoset (e.g., epoxy, polyester, vinyl resin) [98].

In function of wetting agent like coupling agent, difference lies in the fact that coupling agents form chemical bond with surface functional groups of carbon fibers but a wetting agent does not. Actually, it forms protective layers around carbon fiber which helps in wetting of polymer by carbon fiber [93].

When the fibers are to be woven, sizing (coating) was applied to carbon fibers to enhance adhesion with polymers. Depending upon the polymer matrix, we have to choose coating materials. It includes polymers (cured or partially cured), prepolymers, silicon carbides, metals, and carbon. Commercially, epoxy is used as coating material for carbon fiber but it can be used with thermosetting-based composites not for thermoplastic as it cannot withstand at high processing temperature [86]. For thermoplastic matrix-based composites, polyimide or blend of polyimide-PES is used as sizing material for carbon fiber [99]. Depending upon polymeric matrix polyhydroxyether, polyphenyleneoxide, polysulfone, polybutadiene, block copolymer of maleic anhydride, and isoprene, copolymer of ethylene and acrylic acid can be used as sizing materials [93]. For making CF-based composites, other polymeric materials are already used, but in commercial scale for structural applications, the composites are not employed due to various difficulties.

5 Fabrication process

Fiber-based polymeric composites are manufactured by conventional polymer composite manufacturing technique. These processes include compression molding, extrusion, injection molding, resin transfer molding, and vacuum transfer molding. This well-developed process of fabrication techniques has been already proved to be producing good quality composite materials [100]. But for the fabrication of CF-based polymer composites pultrusion, molding, filament winding, and laminated composite beginning from prepregs are commonly used [101, 102]. For short carbon fiber-based thermosetting polymeric composite carbon fiber mixed with liquid unpolymerized resin matrix to form slurry then molded to make composites, whereas in case of thermoplastic polymer, either it dissolve in some suitable solvent or melted to make slurry with fiber [11, 88]. Conventional molding methods for thermoplastic such as injection molding, extrusion, calendaring, and thermoforming while on the contrary for thermosetting compression molding or matched die molding are also used. But in case of compression molding casting of slurry to mold should be done carefully as due to difference in density of fiber and polymer. There is also always chance to fiber sink and so it is better to spray the slurry than molded [103]. Researchers have been successfully produced epoxy carbon fiber composite using continuous spun staple yarns of short carbon fiber which retain 97% of tensile modulus and 70% of tensile strength than their counterpart of continuous fibers tows [87].

Continuous carbon fiber composites are prepared by hand layup technique in which either unidirectional fiber tapes or woven fabric impregnated into the resin, placed into the mold called bag mold, and forced to individual plies together by introducing high pressure or vacuum. For fabrication of skins of aircraft, this technique is comprehensively used [104].

For making unidirectional fiber composites part, generally simple pultrusion method is used where fiber is pulled from spools, dipped through a resin solution bath, and combine them according to their shape before enter into die as shown in Fig. 7 [60].

Resin transfer molding (RTM) is one of the methods of making continuous fiber composite of intricate shapes. This is one of the suitable techniques available in today's market. In this method, CF prepared by braiding impregnated within the resin is transferred through the one end of mold and force by pressure to perform at other end. Low-viscosity thermosetting materials such as epoxy-based carbon fiber composites are prepared by this method [105]. Flow diagram of RTM process is shown in Fig. 8. In this process preformed first placed into mold cavity of desired shape. After closing the mold, it is clamped and polymeric melt is sucked into the mold until it is filled. After filling the mold cure cycle starts and completion of cure cycle it is cooled and ejected the product [106]. RTMs are used for fabricate intricate parts of aerospace, civil, and automobile industries.

For making rod- or cylindrical-like object of continuous CF composites filament winding method is another suitable method. In this method fiber is wrapped around a mandrel, which may be dipped into the resin either before or after winding. The factors which control processing are temperature of mandrel, dipping time and temperature in the resin, tension of fibers, and winding pressure. It is already explored that wet winding continuous CF epoxy composites required temperature of mandrel 70–80 °C, dipping time 1–2 s, dipping temperature 80–85 °C, fiber tension 8.3–16.6 MPa, and winding pressure 6–8 MPa [68]. It is also reported that for making PEEK-based thermoplastic composite heated fiber impregnated within the resin and winding speed 0.5 m/s has to maintain to get best properties [107].

Another method of impregnation continuous fiber is the use of woven fabric where continuous CF twisted with continuous thermoplastic fiber. These twists can be both in yarn level or fiber level, and after that, these fibers of different materials are packed together in unidirectional bundle of fibers [87]. During processing stage of those fibers, melted thermoplastic fibers and wet carbon fibers are assembled together to

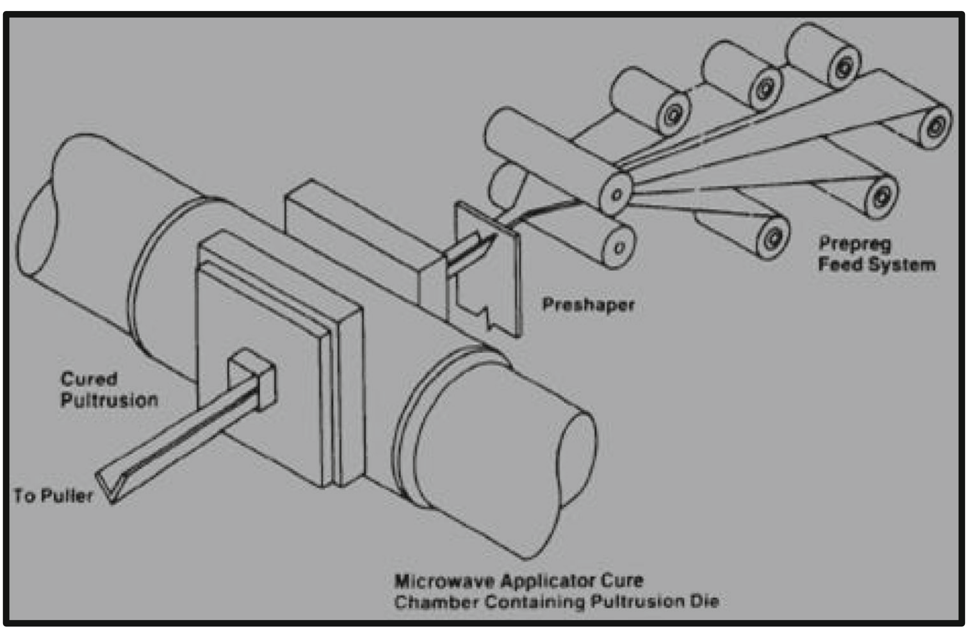


Fig. 7 Schematic of pultrusion process [60]

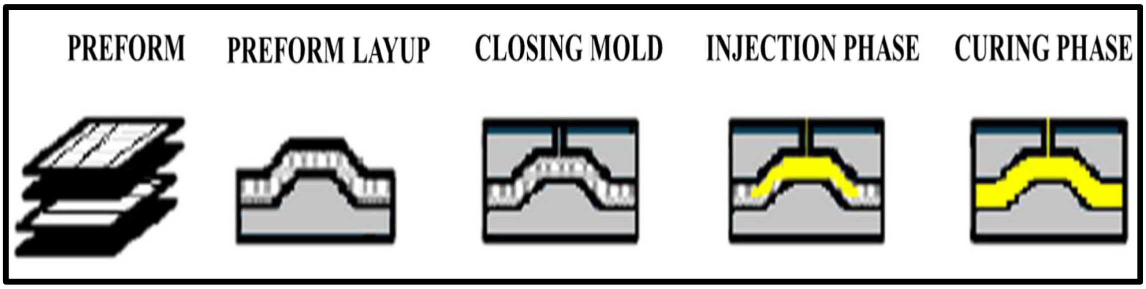


Fig. 8 Sequence of main steps of RTM process [106]

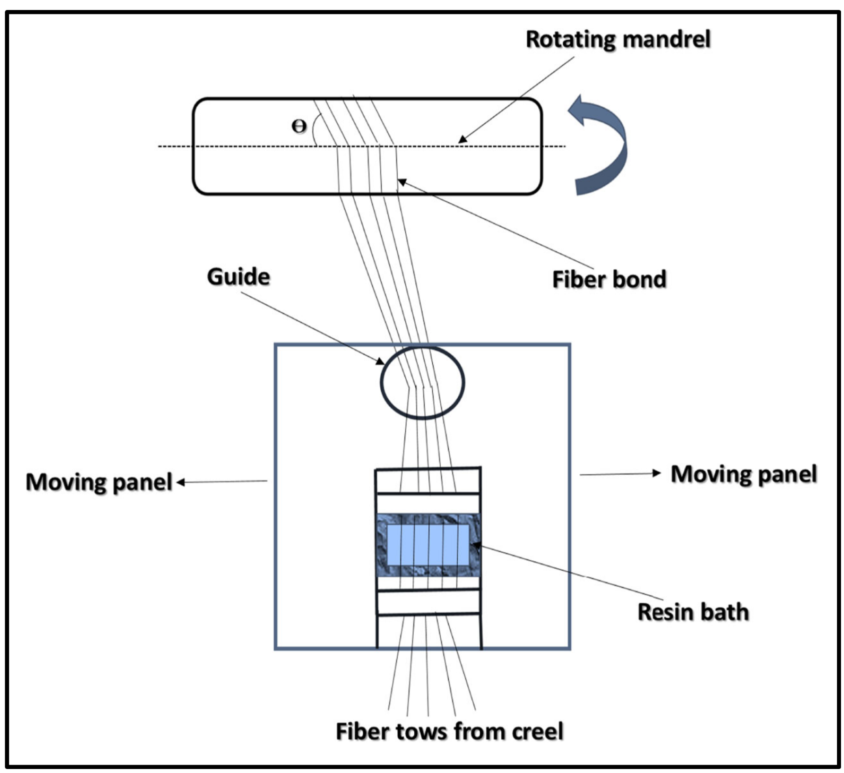
form matrix [108]; for example, PEEK is generally used with continuous CF, but it should be kept in mind that processing should be done at high temperature to remove its previous thermal history [109]. These types of impregnation methods enhance flexibility and drapeability [110] and net structure formation by three-dimensional bradding improve damage tolerance [111]. Schematic of simple filament winding machine is shown in Fig. 9.

Most of the methods use thermoplastic impregnation in the form of either melt or solutions into CF but thermoplastic in the form of fibers, slurries, or powder impregnation into carbon fibers is also reported [113, 114]. For example, CF can be dipped into thermoplastic powder suspension in mixture of aqueous and organic liquid to impregnate thermoplastic into fiber. There are lots of other methods for fabrication of carbon fiber polymer composites such as mill mixing [115] and electropolymerization [116] but these are commercially less important.

6 Properties of composites

The performances of CF-based polymeric composites primarily depend upon the orientation of fiber in the polymeric matrix. This is key factor for the performance of discontinuous CF-based composites. The problem is not a big factor for continuous CF-based polymer composites. The preferentially oriented CF not only improved its mechanical performance but also help in processing such require low molding pressure [117, 118]. Imperfect in orientation during fabrication of composites leads to the formation of void in the polymer matrix which acts as points of weakness resulting in reduction of strength. The weakness can also arise from surface—pits and large-size crystallite which also formed during fabrication of composites [29]. Although various problems of CF-based composites have been shown, its properties covered up all those defaults. CF-based polymer composites have the

Fig. 9 Schematic of filament winding machine [112]



following tempting properties which also endow its application [119]:

- Light weight and low density
- High strength and stiffness (strength like steel and much stiffer than titanium)
- Good resistance to creep
- Long fatigue life
- Good abrasion resistance and very low coefficient of friction
- By changing orientation of carbon fiber toughness and damage can be controlled
- High chemical resistance
- Good resistance to corrosion
- Excellent resistance to vibration
- High-dimensional stability
- High thermal conductivity
- High electromagnetic interference (EMI) shielding
- Low electrical resistivity.

Unidirectional CF-based polymeric composites are not isotropic in nature. Generally, tensile strength of this type of composite is higher in longitudinal direction than transverse direction but failure starts to take place in transverse direction as it encounters higher strain. Whereas compressive strength is higher when load applied vertical direction of fiber layers than parallel to the fiber direction as it cause delamination of fiber layers [120]. Table 4 shows mechanical properties of unidirectional carbon fiber epoxy composite [123].

Properties of unidirectional CF composites containing PEEK and PES thermoplastic matrix having 10 plies of prepeg tape are shown in Table 5. Although it is reported that similar loading of CF to epoxy matrix shows high flexural and modulus than thermoplastic (PEEK, PES)-based carbon fiber composite, superior residual compressive strength after impact test makes it attractive towards aircraft applications [124, 125]. On the other hand, high moisture absorption of epoxy-based carbon fiber composite than thermoplastic-based composite follows a trend towards thermoplastic-based composite for spacecraft application due to low-amount outgassing [126]. When we compare between PEEK- and PES-based CF composite, PEEK-based composite showed higher transverse tensile strength due to high crystalline nature leading to more interaction with CF [122, 127].

Table 4 Mechanical properties of unidirectional carbon fiber epoxy composite [121, 122]

Mechanical properties	Value
Tensile strength	2353 MPa
Tensile modulus	145 GPa
Flexural strength	1794 MPa
Flexural modulus	131 GPa
Short-beam shear strength	124 MPa

Table 5 Properties of unidirectional carbon fiber composites containing PEEK and PES thermoplastic matrix having 10 plies of prepeg tape [68]

Properties	PEEK matrix	PES matrix
Thickness per ply (mm)	0.14	0.13
Specific gravity	1.56	1.53
Fiber volume (%)	60.0	56.2
Void volume (%)	1.9	1.4
Flexural strength (MPa)	1687	1078
Flexural modulus (GPa)	108.0	93.8
Transverse tensile strength (MPa)	91.0	15.2
Water absorption (wt.%)	0.15	0.20

For structural application primary requirement is high compressive resistance after deformation by impact and high compressive strength at high temperature after disclose to humid atmosphere. These properties are totally governed by the polymeric matrix. Figure 10 shows how compressive strength varies with change in matrix [124, 128].

There is several ways to improve these properties which are given below [129, 130]:

i. Using high elongated grade of epoxy resin
ii. Use of blend of rubber and epoxy resin
iii. Use of blend of thermoplastic and epoxy resin
iv. Using of high elongated thermoplastic matrix
v. During lamination of prepeg layers recommended using distinct layers between them.

Whereas, damping ability improves with decreasing interaction between fiber and matrix and reverse trend is also observed. PPS-based composite showed higher damping ability, whereas epoxy based exhibits lowest and PEEK based is intermediate between them [68, 131].

Abrasion resistance and coefficient of friction of CF-based composites depend upon sliding orientation with respect to fiber in polymer matrix. For unidirectional fiber composite, fiber can be oriented in longitude direction, transverse direction, or normal with respect to sliding direction of carbon fiber. It is explored that for epoxy-based CF composites abrasion resistance is excellent and coefficient of friction is least in transverse orientation [132, 133].

Plastic memory phenomenon is another important property of thermoplastic materials for useful application in self-deploying of space structure such as antenna reflectors. It is defined as when thermoplastic material deformed above its T_g, its shape should be remembered and return to its original shape when it is heated above T_g. This phenomenon was shown not only by pure thermoplastic materials but also by thermoplastic, PEEK-based CF composites. These fiber-based composites showed significant improvement in shape recovery than neat thermoplastics [68, 134, 135].

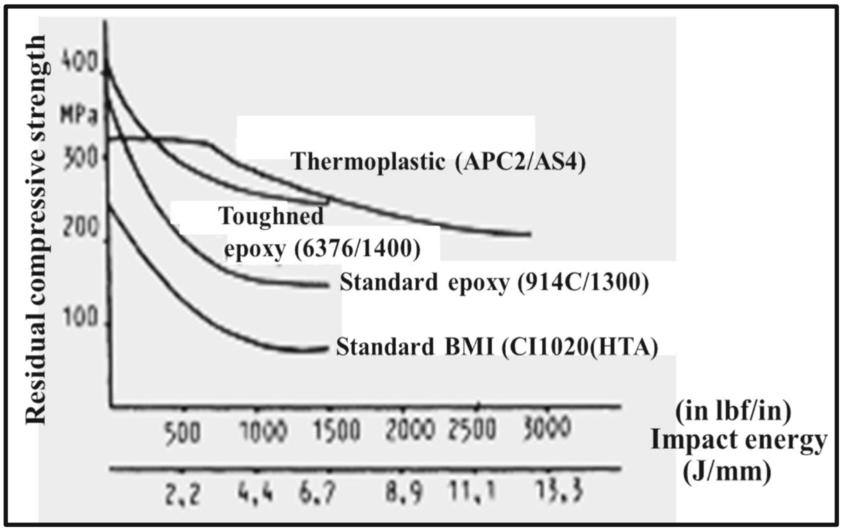


Fig. 10 Plot of residual compressive strength vs. impact energy for different polymeric matrix containing same loading of CF [124]

For electromagnetic interference (EMI) shielding, antistatic, and other electrical applications short CF is usually preferred than continuous fibers. After introduction of short carbon filament it is gradually replace short CF as short filaments provided large aspect ratio which is helpful for conduction path formation for electricity [136]. This means that for electrical resistivity short carbon filament-based composites have lower percolation threshold than short CF-based composites [137, 138].

As the strength and modulus of CF-based composites increase with decrement of temperature, these composites are potentially useful for application in cryogenic structural support members [139, 140].

7 Applications

In the beginning, CF-based polymeric composites are mainly fabricated for lightweight carrying structural materials because of its low density, high strength, and modulus. The applications of CF-based polymer composites include parts of military aircrafts, components of satellite, parts of launch vehicle, fuel tank, components of missiles, frame of solar panels, various components of automobile industries, sports goods, racing bicycles, and cars [141–144]. But, polymer-based CF composites are totally consumed by space industries and defense sectors due to its high strength to weight ratio, dimensional stability, high heat and chemical resistance, reusability, and thermal stability. Looking at its advantageous properties other structural industries such as automotive, marine, construction, sports, and wind blades are started to use this composites. So, from market point of view demand of carbon fiber-based polymeric composites increases day by day in comparison to other fiber-based composites.

Generally, load-bearing applications of CF-based polymeric composite are divided into two sectors:

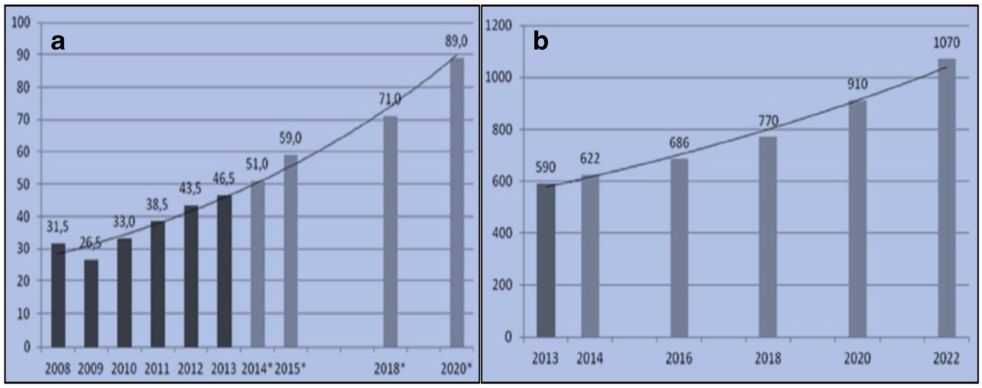
i. High-technology sector such as aerospace and nuclear engineering and
ii. General engineering and transportation sector such as bearing, gears, fan blades, and automotive bodies.

High-technology sector vastly uses these carbon fiber-based polymeric composites as their cost and production is not an issue. Their main objective is to obtain maximum performance and fuel efficiency. Whereas in case of general engineering and transportation sector, reverse is true. So, use of carbon fiber-based polymeric composites in these sectors is driven by cost constraints and high productivity. Recent trend shows that use of carbon fiber-based polymeric composites increases day by day. Researchers think that it will continuously increase for load-bearing application. Figure 11a shows the worldwide demand of CF increases and in upcoming year the demand of CF is so high that normal rate of productions cannot be sufficient. Mostly, for structural application the annual income of USA from only CF-based composites is around US$590 million in 2013 (as shown in Fig. 11b). They estimated that in the future the rate of growth of income from these sectors will be 6% in upcoming next 5 years [145].

Carbon fiber-based composite is mostly used in aerospace industry as shown in Fig. 8. Most of the part of an aircraft is made of carbon fiber-based composite. As day-by-day cost of carbon fiber is reduced in comparison to other fibers, applications of carbon fiber-based composite is comprehensively spread towards other areas that include automobile, sports, marine, biomedical, construction, and other industries.

Firstly, USA made a space shuttle in which payload bay door, remote manipulator arm, and solid rocket motor cases made of epoxy carbon fiber-based composites and booster

Fig. 11 **a** Global demand of carbon fiber (in thousands tones) in upcoming days and **b** revenue of USA (in US $ million) for structural applications of carbon fiber-based composites [145]



tails and fins used polyimide-based carbon fiber composites [146]. Nowadays, satellite structure and solar panel are also made of carbon fiber composites [29, 113, 147]. For aerospace application, high-modulus carbon fiber (modulus 350 GPa) along with multifunctional epoxy resin is used. High-strength necessity for this type of application precept use high quality of carbon fibers. Now, researchers use thermoplastic such as PEEK- and PES-based carbon fiber composite to replace epoxy-based composite to reduce cost [120, 148, 149]. Recently, Boeing 787 aircraft were fabricated by 50% continuous CF-based polymeric composites [150].

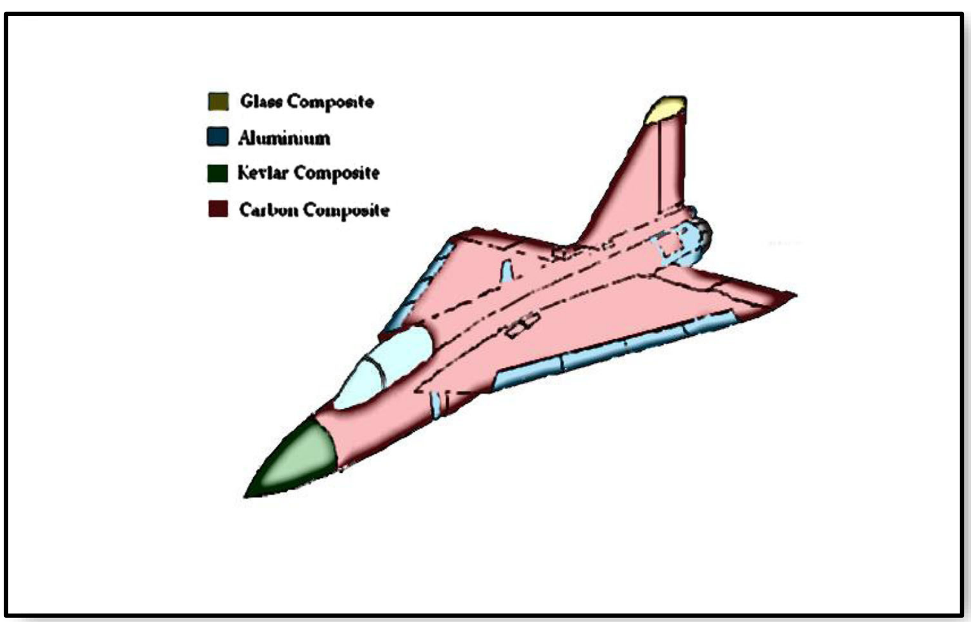
Military aircraft is another application area where carbon fiber-based composite is widely used. At first, carbon fiber (it may be high strength, high modulus, or intermediate modulus) based toughened thermosetting matrix bismaleimide was used for wings but it is now slowly replaced by epoxy matrix. Both military and commercial-use helicopters almost two-third part is made of carbon fiber epoxy-based composites, whereas one-third part is made of GF- and AF-based epoxy composites as shown in Fig. 12.

For aerospace application only aluminum is a lightweight material which can contest with carbon fiber-based polymeric composites. But high strength, required less energy to produce and more environment friendly carbon fiber polymer composites are gaining much more attention to oust aluminum [151].

In the construction industries, CF-based polymeric composites already started to be used due to its corrosion resistance, good fatigue resistance, high specific strength, and stiffness. To anchor earthquake proof building, curtains of cables are made by thermoplastic-based CF composites in Japan (http://inhabitat.com/kengo-kuma-anchors-an-earthquake-resistant-building-with-carbon-fiber-threads). The grids used for concrete reinforcement are also fabricated by thermosetting continuous CF-based composites. Replacement of steel wire mesh by CF-based composites grids is not only reducing its weight but also improves its corrosion resistance which extends its service life.

Main objective of use of carbon fiber in automobile industry is to make lightweight materials (i.e., indirectly saving fuel). Different car components such as body panels, wheel,

Fig. 12 Percent of application of carbon fiber composites compared to other in aircraft (http://www.aame.in/2012/12/use-of-composites-in-india-aircraft.html)



drive shaft, structural members, engine components, bumpers, and suspension system are mainly composed of epoxy-based carbon fiber composites [95, 152]. Spring elements of car suspension system are made by PEEK- and polycarbonate (PC)-based carbon fiber composites [68]. In brief, primary components of automotive industries are fabricated by thermoset polymer-based CF composites, whereas secondary parts are made by thermoplastic matrix-based composites [153].

High stiffness and strength to weight ratio of carbon fiber composites propels to use in wind energy markets. To attain high energy from wind turbine the change in the shape of blade is most crucial. This can be accomplished by increasing stiffness and stability of blade [154]. Wind turbine industries mostly used thermoset carbon fiber composites because of its advantageous properties such as high strength, easy processing, and stiffness. Due to disposal problems of after few cycles, turbine industries shifted to recyclable thermoplastic-based carbon fiber composites [155]. Kumar et al. reported that general carbon fiber-based, thermoplastic-based composites showed seven to eight times less strength than thermoset based. But recently, reported thermoplastic materials such as PEI-, PEEK-, and PPS-based composites exhibit almost comparable strength to that of epoxy-based thermoset composites [156].

The application of CF-reinforced polymer composites spreads its legs also for fabrication of musical instruments. As use of natural resources like wood is restricted in various countries, researchers are trying to manufacture musical instruments using CF-based polymeric composites due its high strength to weight ratio [157, 158]. Unidirectional CF-based polyurethane foams were used for fabrication of acoustic soundboards of guitar which almost shows similar properties like wooden soundboards. In addition to these, the fabrication of these CF-based musical instruments is much easy and provides extra stability against humidity [159, 160]. The uses of CF-based polymer composites in musical instruments like guitar are motivating to fabricate other wooden instruments replaced by these types of composites.

Uses of CF composites for fabrication of rollers for textile and paper industries were started many years ago. High stiffness and very low density of CF make them useful for potential candidate for fabrication of rollers [101]. Mostly epoxy-based CF composites are used for manufacturing smooth surface rollers [161]. Depending upon the performance required in the application, the best quality of CF was compounded with epoxy for making rollers. The rollers are used for application in lamination, air elimination, improving wear resistance, surface coating, and acting as ideal and guide rollers for rotogravure process in printing press (https://www.aimcal.org/uploads/4/6/6/9/46695933/comand_abstract.pdf).

Fiber-based composite material is also gaining importance in sports cars due to lightweight structure. Firstly, GF-based polyester composites were used in motor car, and gradually, CF-based epoxy composites replace it [162]. Now, all the major parts of formula 1 racing car such as chassis, interior, and suspension components are made of CF-based epoxy composites. Starting from bicycle up to racing bikes, parts used in sports are also manufactured by CF-reinforced epoxy composites [10]. The tennis racquets made of CF-based composites are much stronger and light weight than the racquets of woods. Besides these, the strings made of CF are also much tighter [163]. Conducting nature of CF makes them suitable for fabrication of conducting polymer composites which can be applied in various fields such as EMI shielding, sensor, antistatic agent, and conductor [164–167]. The orientation of CF within matrix has profound effect on the electrical conductivity. It has been found that the oriented CF-based polymer composites showed higher percolation thresholds but exhibit higher conductivity above percolation threshold than random oriented CF [168]. Pointing out these conductive properties of the composite, the casing of computer and cover of mobile are fabricated by CF-reinforced polymer composite due to its high shielding effectiveness towards EMI [169, 170]. Though recently various carbon-based polymeric composites are manufactured for EMI shielding applications, still now commercially CF-based polymeric composite materials surpass them [171–173].

Previously, bone plates for facture fixation were made from metals. But leaching problem metallic ion can cause local tissue reaction leads to formation tumor and application of stress leads to formation of crack. To overcome this problem, researchers used polylactic acid (PLA) like absorbable thermoplastic. As its mechanical properties are not enough for long bone fixation, it is reinforced with carbon fiber to make semiabsorbable composite [85, 174].

Nowadays, construction industry starts to perceive that high-strength material causes a problem of slow disintegration of infrastructure. So considering good engineering properties of carbon fiber construction industries began to use carbon fiber-based polymer composites [175]. Hence, gradually, steel reinforcement in concrete structure is replaced by continuous carbon fiber polymer composites due to the following properties [169, 176]:

i. Light weight,
ii. Commercially available in long length and continuous,
iii. Do not corrode by environment, and
iv. Lightweight composite structure makes them easier to install.

Generally, polymer-based carbon fiber composites are used in making cloths and sheets on the upper surface of bridge, roof, floors, beam, etc. The commonly used thermoset polymers are epoxy, vinyl ester, and polyester which also provide high strength to composites to make it comparable strength of steel-reinforced composites [177, 178]. On the other hand, commingling of short carbon fibers with graphite powder incorporated in polyimide matrix produces good abrasion resistant materials useful in bearing applications [179–181].

Use of lightweight carbon fiber polymer composites in marine industries makes the ship light weight, easy to transport, and reduces wear on shaft and bearing during installation. But the major problem of marine industry is biofouling due to adherence of flora and fauna under aquatic environment [182]. To protect from this aquatic environment polymer matrix is best choice as high surface energy metal surface is favorable for adhesion of microorganism. Simultaneously, the metal surface can easily corrode with topical marine seawater [183]. The rod-like structure having high surface area of CFs is suitable for decoration of nanoparticles over it for generation of heterogeneous catalytic nanocomposites. So, like other materials such as hydroxyapatite [184], halloysite nanotube [185], graphene [186], and silica [187], CFs are started to be used as supporting material as heterogeneous catalytic system [188, 189].

8 Research challenges

CF-based polymeric composite materials have the ability to arrest the conventional composite markets in terms of their quality and performance. There is always ambiguity that these composites can replace the current traditional composites and create a new market of composite by their exceptional properties. The processing and manufacturing technologies developed for fabrication of CF-based polymeric composite are not sufficient in terms of quantity and commercial value. There are also other difficulties faced by technologist for the last few decades. For an example, fabrications of composite based on CF are very difficult; due to its rod-like nature, it requires high volume fraction of the matrix for their close packing. In addition to these, the filling of space in the matrix by CNF can lead to formation pores which can ultimately effect on the mechanical properties of the composites [190]. For non-pre-stressed applications, glass fiber-based polymer composite is mostly used due to its low cost. But in case of pre-stressed applications, mostly CNF based are used because of its ability to sustain stress over its lifetime [191]. The problem of using CNF in polymer-based composites in non-pre-stressed application instead of other fibers is still now a challenging task. The major disadvantage of CF is that high loading of CF as filler in polymer composites leads to formation of weak and brittle composites. This problem was partly resolved by combining CF with other ductile fillers, i.e., called hybridization technique [192]. Increasing use of CF-based polymeric composites for structural application requires recycling of waste materials due to environmental and economic alertness (https://www.aimcal.org/uploads/4/6/6/9/46695933/comand_abstract.pdf). The costs of the products made by CF-based composites are very high because of high-consumption energy during fabrications [193]. In today's world, the main concern is that materials used for making composites should have no effect on living body and environment. But, CF like other carbonaceous material like graphite can cause skin diseases and infected the respiratory system which has been already explored by various literature surveys [194, 195]. Although various difficulties have been faced by technologist, its advantageous properties fell behind other synthetic fiber-based polymer composites in competition.

9 Summary

Multiphase composite materials are made by the art of man having desirable combination of best properties of the individual component phases. Generally, one phase is continuous matrix which completely surrounds another phase known as dispersed phase. In this discussion, carbon fiber-based polymeric (both thermoplastic and thermosetting) composites were classified and fabricated for mainly structural application. Among various types of fiber-based polymeric composites, the potential for reinforcement efficiency is best that are carbon fiber reinforced. With all these types of composites applied, load is transferred and distributed over fibers via matrix phase. The reason behind improving the properties of carbon fiber-based polymer composites as reinforcing filler was elaborated on the basis of its "turbostratic" structural unit. As there is strong interaction between carbon fiber and polymer, significant reinforcement is possible by carbon fiber polymer composites resulting in attention towards structural application. To get better interaction between polymer and fibers for improvement in properties, different modification of carbon fibers was also discussed. Orientation of carbon fibers in matrix is crucial for strengthening composites. The stress-strain behavior for different arrangement of carbon fiber in polymeric matrix was discussed. In case of continuous carbon fiber composites, mechanical properties are highly anisotropic as best properties are obtained in the direction of alignment of carbon fiber and least in transverse direction, whereas in case of short carbon fibers, properties of randomly oriented fibers are isotropic in nature. For uniform fiber distribution and high degree of arrangement, different fiber composite processing technique was discussed. For making component of continuous length and constant cross-section integrated composites, pultrusion is most suitable technique. Carbon fiber composites utilized in high structural application were generally prepared by either hand or automated layup operation. Some hollow structure (such cylindrical- or rod-like object) may be fabricated by filament winding, followed by resin-coated fiber strand curing operation. There are also other methods developed for carbon fiber-based composite fabrication but these are not commercially useful to produce structural application-based products. Finally, structural application of carbon fiber-based polymeric composites from high-technology sector to general engineering and transportation sectors and its upcoming trend in future for these types of structural application were also discussed.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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