Fibre Reinforced Polymer Composites

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Abstract Fibre reinforced polymer (FRP) composites are attractive engineering materials because they have excellent properties, such as high strength-to-weight, modulus-to-weight, magnetic and corrosion resistance. FRPs are formed by combining the fibres and polymer matrix, providing properties that could not be obtained from a single material component alone. Categories of fibre include carbon fibre, glass fibre, boron fibre, aramid fibre and others. The resin matrixes used are mainly thermosetting resin and thermoplastic resin. Besides, laminated and cylindrical FRPs are two common forms used in structural applications. Due to their excellent usability, FRPs have seen extensive applications in a wide range of industries including aerospace, aircraft, military, mobile phone, automobiles, infrastructure and sporting goods. Additionally, FRPs will be essential materials in many fields in the future.

1 Introduction

Fibre reinforced polymer composites (FRPs) are formed by a combination of the fibres and polymer matrix. In the FRPs, both fibres and matrix retain their physical and chemical identities. Still, they produce an excellent performance that cannot be achieved with either of the constituents acting alone. FRPs have many advantages, such as strength-to-weight (longitudinal tensile strength/density), high modulus-to-weight (longitudinal tensile modulus/density), fatigue strength, as well as fatigue damage tolerance. Categories of fibre mainly include carbon fibre, glass fibre, boron

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fibre and aramid fibre. The resin matrixes used are mainly thermosetting resin (e.g. epoxy resin) and thermoplastic resin (e.g. PE-polyethylene). Since most of FRPs are laminated by prepregs through interweaving or layered pavement. FRPs are being applied in an increasing range of fields, especially in aerospace applications. The number of composite applications has become an important index used to measure the aerospace industry's advancement. Due to their excellent usability, polymeric composites have also been increasingly applied to automobiles, infrastructure and sporting good. FRPs will be an essential material in many fields in the future.

The prime components of fibre reinforced composites (FPRs) are long and thin fibres possessing high strength and stiffness. The fibres are bound with a matrix material whose volume fraction in a composite is usually less than 50%. FRPs have high strength-to-weight, high modulus-to-weight, strong fatigue-cracking resistance, good designability, corrosion resistance and are convenient for large-scale shaping. They also have unique electromagnetic and wave-absorbing stealth characteristics [1]. FRPs have an evident characteristic of integrating structural bearing and function and have been widely applied in various fields, including in aerospace and automotive. They are vital to the creation of lightweight and high-performance components.

The performance of composites is closely related to the type of fibre and resin matrix used. Fibres are the principal load-carrying members. The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, the resin matrix keeps fibres in the desired location and orientation, acts as a load transfer medium between fibres, and protect fibres from environmental damages. Therefore, even though the fibres reinforce the matrix, both of them serve essential functions in FRPs.

New fibre and resin matrixes are continuously being developed. Currently, carbon fibre, glass fibre and aramid fibre are the widely used fibre types. This chapter discusses the types and characteristics of commonly used reinforced fibres, resin matrixes and composites. Their fields of application are also explored.

2 Classification of Polymer Matrix Composites

Fibres have significantly higher strength and stiffness in the length direction than in the other directions. This limits their use in a stand-alone form and underscores the need for a rigid matrix in the composite structure. The main fibre types are glass, carbon, aramid, boron, silicon carbide and alumina. The fibres also can be classified according to the shape and size into continuous, short and chopped fibres. According to the equivalent inclusion theory, the length-to-diameter ratio and volume content of fibre significantly influence the matrix reinforcement effect: the higher volume content and larger fibre length-to-diameter ratio strengthening effect to the matrix was more significantly [2]. Therefore, continuous fibres are mainly discussed in the following sections.

The matrix binds together the reinforcing fibres. The microstructure of a polymer matrix composite is shown in Fig. 1. The matrix resin protects the fibres from premature failure as a result of abrasion or environmental corrosion. More importantly, the matrix distributes an applied load and acts as a stress transfer medium so that when an individual fibre fails, the composite structure does not lose its load-carrying capability. Classification of FRPs is shown in Fig. 2. Typical mechanical and physical properties of fibres are shown in Table 1.

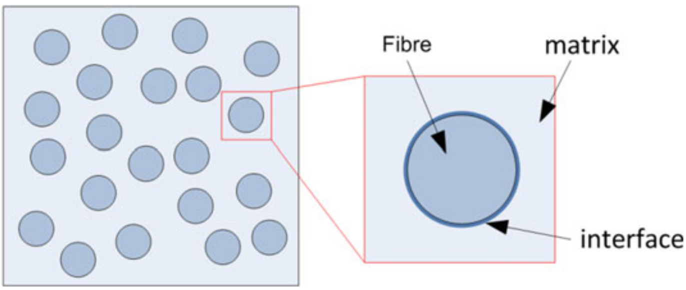

Fig. 1 The microstructure of a polymer matrix composite

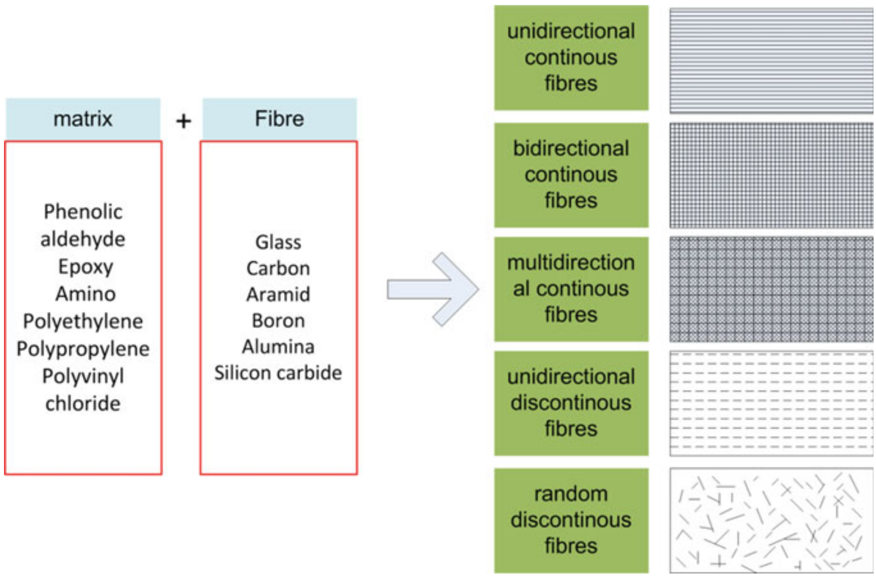

Fig. 2 Classification of FRPs

Table 1 Properties of different fibres [3]

	Density (g/cm^3)	Tensile strength (GPa)	Tensile modulus (GPa)
E-type glass fibre	2.54	3.45	72.4
Carbon fibre (T300)	1.76	3.65	231
Aramid fibre (Kevlar 49)	1.45	3.62	131
Boron fibre	2.7	3.1	393

2.1 Glass Fibre

Glass fibres are the most common of all reinforcing fibres for polymeric matrix composites, as shown in Fig. 3. Glass fibre provides good insulation, strong thermal endurance, high corrosion resistance, relatively low stiffness, high chemical and biological resistance and mechanical strength. However, it is brittle, sensitive to surface damage and has low abrasion resistance. Essential properties of glass as a reinforced fibre are their high strength which is maintained in humid environments but degrades under elevated temperatures [4].

Glass fibres are made from pyrophyllite, quartz sand, limestone, dolomite, borocalcite and camsellite using high-temperature melting. A molten mixture of silica (SiO_2) and other oxides is drawn through small holes in a platinum-alloy bushing. The fibres emerging from the bushing are drawn to size a constant speed and then quenched by air or water spray. A protective coating, or size, is applied to the

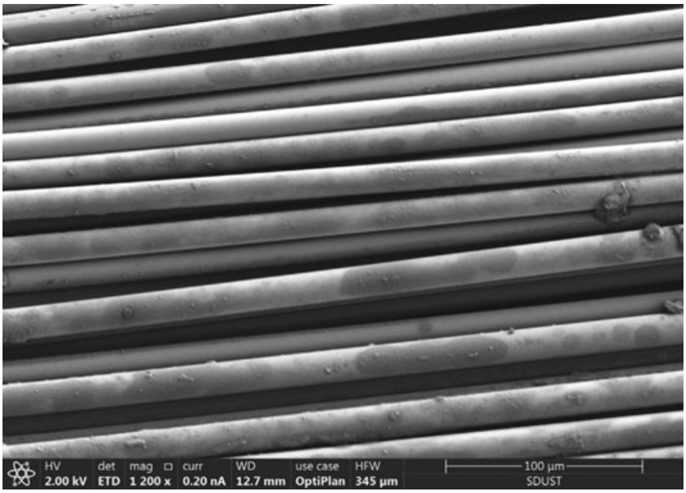

Fig. 3 Morphology of glass fibres [5]

fibres to protect their surface and enhance their binding to the polymer matrix. Glass is an amorphous material. Thus, it does not develop a preferred orientation in microstructure when drawn. It is, therefore considered isotropic. The diameter of glass fibre monofilament ranges from several to more than 20 μm. Fibre diameters for composites applications are in the range from 10 to 20 μm [6].

Glass is also highly abrasive, which poses a significant challenge when machining GFRPs. Commonly used fibres include E-type glass fibre and S-shaped glass fibre. E-type glass fibre has the lowest cost of all commercially available reinforcing fibres, which is why its widespread use in the FRPs. S-shaped glass fibre has a higher tensile strength than that of E-type glass fibre. However, the compositional difference and higher manufacturing cost make it more expensive than E-type glass fibre [7].

2.2 *Carbon Fibre*

Development of carbon fibre was a natural step aiming at a rise of fibre stiffness which was not exhibited by glass fibre. Modern carbon fibre demonstrates much higher modulus than that of glass fibre.

Carbon fibre has many outstanding properties, including high axial strength and modulus, low density, high-temperature resistance in oxidizing environments, good fatigue durability, specific heat and conductivity between those of non-metals and metals, low coefficient of thermal expansion (which provides dimensional stability over a wide range of temperatures), excellent corrosion resistance, good X-ray permeability, high heat conductivity, and adequate electromagnetic shielding. Their cons include the low strain-to-failure, low impact resistance and electrical conductivity. Their electrical conductivity is harmful during machining, as fibre chips may penetrate machine tool controls and cause short circuit electrical equipment.

Carbon fibre is a microlite graphite material created by the carbonization and graphitizing of piled organic fibres, like flake graphite, along the fibres' axial direction. They are anisotropic (transversely isotropic), and their properties are mainly affected by the degree of orientation of the graphite layers concerning the fibre axis. Carbon fibre is an inorganic polymer fibre with a carbon content of more than 90%. With more than 99% carbon content, the fibre is called graphite fibre. The diameter of carbon fibre monofilament ranges is about 5–7 μm. Carbon fibre in a CFRP after machining is shown in Fig. 4.

Carbon fibres can be divided into polyacrylonitrile (PAN)-based carbon fibre and pitch-based, depending on the raw material type. The pitch-based fibres have a higher modulus, but lower strength than the PAN-based fibres. For PAN-based fibre, the process consists of three stages: stabilization, carbonization and graphitization.

The tensile modulus values of carbon fibre vary in a large area, ranging from 207 GPa on the low side to 1035 GPa on the high side [3]. Carbon fibres can also be divided into universal, high-strength, middle-modulus, high-modulus and ultra-modulus carbon fibres according to performance. The middle-modulus and high-strength grades are almost universally PAN-based. Higher-modulus fibres with much

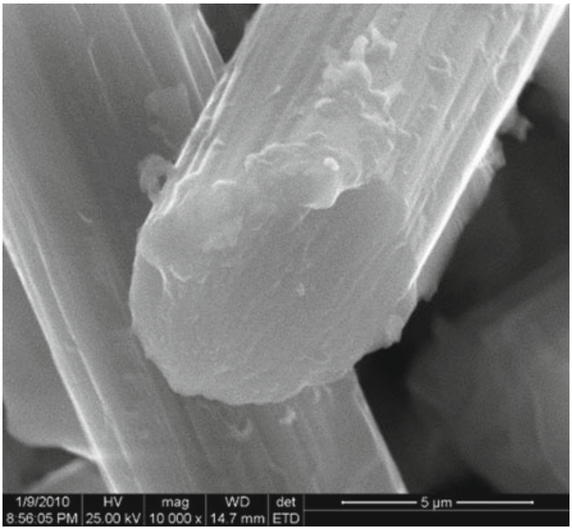

Fig. 4 Carbon fibre in a CFRP after machining

lower strength are most pitch-based produced at a lower cost. Generally, the low-modulus fibres have low density, low cost, higher tensile and compressive strength and higher tensile strains-to-failure than the high-modulus fibres.

The high stiffness and strength combined with low density and intermediate cost have made carbon fibres the second to glass fibre in use. However, their high cost has so far excluded them from widespread commercial applications. They are widely used mainly in the aerospace industry in the last century, where weight saving is considered more critical than the cost. Today, the cost of carbon fibre has decreased a lot. Decreased costs will allow penetration into more cost-sensitive markets such as automotive and sports goods.

2.3 Aramid Fibre

Aramid fibres are highly crystalline aromatic polyamide fibres with the lowest density and the highest tensile strength-to-weight ratio among the current reinforcing fibres [8]. Aramid fibres are organic fibres manufactured from aromatic polyamides (Aramids) by solution spinning. Polymer solution in sulfuric acid is extruded by spinning through small holes into fibres in which the molecules are aligned with the direction of shear. Further alignment of the fibres can be achieved by washing in a cold-water bath and stretching under heating.

Aramid fibres offer higher strength and stiffness relative to glass coupled with lightweight, high tensile strength, but lower compressive strength. As components of advanced composites for engineering applications, aramid fibres are characterized by low density providing strength-to-weight and stiffness, low thermal conductivity resulting in high heat insulation. Like carbon fibres, they also have a negative coefficient of thermal expansion in the longitudinal direction, which is used to design low thermal expansion composite panels and construct hybrid composite elements that do not change their dimensions under heating. It consists of very thin filaments (fibrils) for a system, and aramid fibres have very high damage tolerance. It tends to respond under impact in a ductile manner instead of carbon fibre, which tends to fail in a more brittle manner. Their high strength in a longitudinal direction is accompanied with relatively low strength under tension in a transverse direction. Aramid fibres are characterized by pronounced temperature and time dependence for stiffness and strength [9]. The main disadvantages of AFRPs are their low compressive strengths. The outstanding toughness of aramid fibres also creates a problem during machining. The fibres are difficult to cut, and special tooling and techniques are required. Aramid fibre in an AFRP after machining is shown in Fig. 5.

Due to variations in the polymer structure, the aramid fibre family covers many categories. Meta-position aramid fibre and para-position aramid fibre are the most representative aramid fibres and have the highest practical value. Generally, para-position aramid fibre is used as a reinforcing material in composites. Para-position aramid fibre has a range of excellent characteristics, including lightweight, high strength, high modulus, high robustness, high-temperature resistance, good insulation and anti-ageing performance. Currently, aramid fibre is mainly produced in America and Japan. Manufacturers and brands of para-position aramid fibre mainly include Kevlar® fibre (DuPont, USA), Twaron® fibre and Technora® fibre (Teijin, Japan), Heracron® fibre (Kolon, Korea) and Armos® fibre (Tver, Russia).

Kevlar 49 is the trade name of one of the aramid fibres available in the market, most widely used in AFRP composites. It is a kind of para-position aramid fibre. During the filament drawing process, Kevlar 49 molecules become highly oriented in the filament axis direction. Weak hydrogen bonds between hydrogen and oxygen

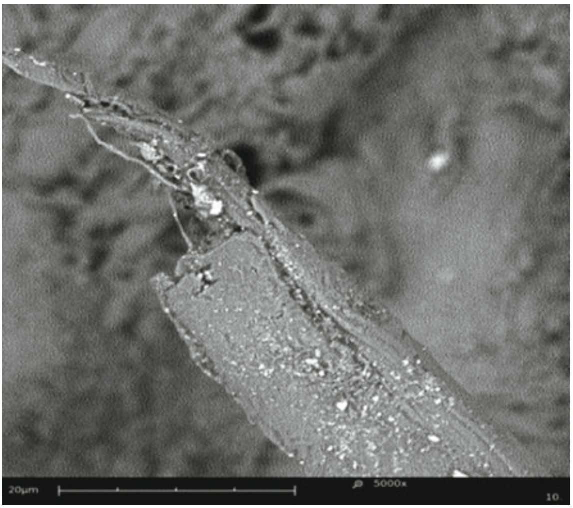

Fig. 5 Aramid fibre in an AFRP after machining

atoms in adjacent molecules hold them together in the transverse direction. As a result, the filament is highly anisotropic, with much better physical and mechanical properties in the longitudinal direction than in the radial direction. Especially, Kevlar 49 fibres exhibit a high degree of yielding on the compression side during bending. One application of this characteristic is found in soft, lightweight body armours and helmets [3].

2.4 Boron Fibre

Boron fibres are manufactured by chemical vapour deposition (CVD) of boron onto about 12 μm diameter a heated substrate (either a tungsten wire or a carbon monofilament). When the substrate is a tungsten wire, hydrogen and boron trichloride reacts on a hot tungsten filament to replace the amorphous boron deposition on the tungsten surface. Boron fibres have a relatively large diameter, 100–200 μm, shown in Fig. 6. According to this, boron fibres offer excellent resistance to buckling, which contributes to high compressive strength for the BFRP composites. Boron fibre has good high-temperature resistance in inert gas. However, its tensile and compressive strength decreases significantly at air temperatures above 500 °C. To prevent this degradation, chemical vapour deposition covers the fibre surface with about 5 μm thick layer of silicon carbide or boron carbide. Comparing to carbon fibre, glass and aramid fibres, boron fibres have now somewhat limited applications [10].

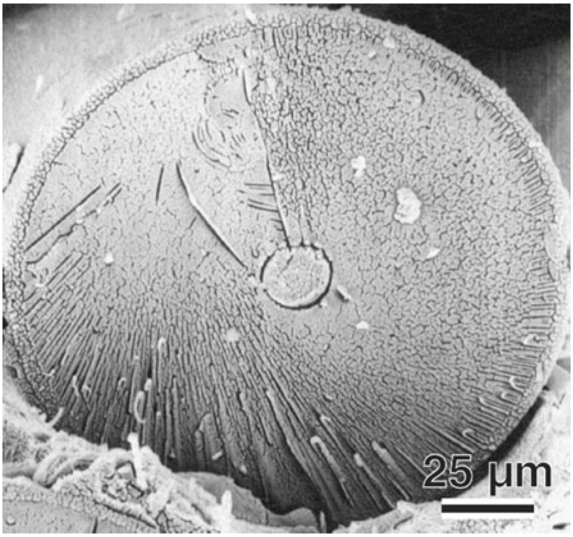

Fig. 6 Morphology of a boron fibre (with B4C coating) [11]

2.5 Resin Matrix

Matrix materials provide the final shape of the composite structure and govern the parameters of the manufacturing process. The resin matrix fulfils a variety of critical functions and merely maintains the shape of the composite structure and aligns the reinforcing fibres. Resin matrixes can be divided into thermoplastic and thermosetting resins. Optimal combination of fibre and matrix properties should satisfy a set of operational and manufacturing requirements. Fibre reinforced composites mainly use thermosetting resin, while the use of thermoplastic is in a gradual increase.

Thermosetting resin undergoes a chemical reaction under heating and pressurization, or a curing agent and ultraviolet light. The components further react into a single type of insoluble and in-fusible synthesized resin through cross-linking curing. Such resin is generally a solid or viscous liquid with low molecular weight before curing and can be softened or flowed in the forming process. It is plastic and can be shaped, accompanied by chemical reaction and cross-linking curing. Cured resin cannot be softened or flowed even upon pressurization and heating. Instead, the resin is decomposed or carbonized under excessive temperature. After thermosetting the resin, it forms a reticulate structure due to intermolecular cross-linking. Therefore, the thermosetting resin has the characteristics of high rigidity, high hardness, inflammability, but has the disadvantages of high brittleness and low mechanical properties. Thermosetting resins include phenolic aldehyde, epoxy, amino, unsaturated polyester and silicon ether resins.

The thermoplastic resin is a high-molecular-weight solid at room temperature. It is a linear polymer with a few branched chains and without intermolecular cross-linking. The thermosetting resin is only mutually attracted by Van Der Waals forces or hydrogen bonds. The resin is softened or flowed under pressure and heating (as shown in Fig. 7). As it makes no chemical cross-links, it can be shaped in a mould,

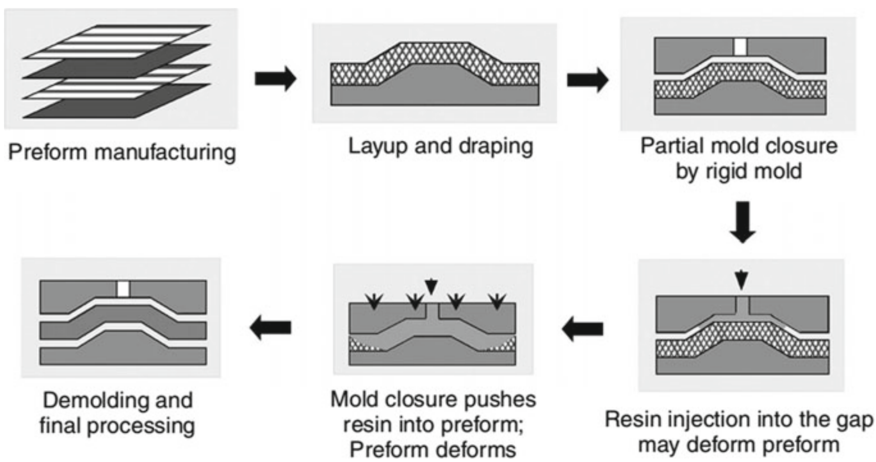

Fig. 7 The moulding process of resin [12]

Table 2 Maximum service temperature for some polymeric matrices [3]

Polymer	Tg (°C)	Maximum service temperature (°C)
DGEBA epoxy	180	125
TGDDM epoxy	240–260	190
PMR-15	340	316
Polyether ether ketone (PEEK)	143	250
Polyphenylene sulfide (PPS)	85	240
Polysulfone	185	160

with the finished product obtained after cooling. In a repeated heating process, the molecular structures remain constant. Thermoplastic resin can be degraded or decomposed under high temperatures for long durations; it has the characteristics of simple shaping and high mechanical energy but has low heat resistance and rigidity. Thermoplastic resins include polyethene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyamide (PA), polyformaldehyde (POM), polycarbonate (PC), polyphenyl ether, polysulfone and rubber.

For laminated composites, the mechanical properties of the interfaces between layers can be described by interlaminar shear strength or interlaminar fracture toughness. The interlaminar shear strength is an important design consideration for structures under bending loads, whereas the in-plane shear strength is essential under torsional loads. Matrix has a significant influence on the interlaminar shear strength, compressive strength, and in-plane shear strength of the FRPs. Besides, the interaction between fibres and matrix is essential in designing damage-tolerant structures. Therefore, the selection of a resin matrix has a significant influence on the properties of FRPs. Additionally, the manufacturing and machining of FRPs depend strongly on the processing characteristics of the matrix. Maximum service temperature for some polymeric matrices is shown in Table 2.

3 Properties of FRP Composites

Compared with traditional materials, composites have many advantages, including high strength-to-weight, high modulus-to-weight, anti-fatigue performance and good vibration damping performance. The components of the composites develop synergistic performance. In other words, the composite material properties are better than the property of each component, where the composite has new properties. Hence, the composite performs significantly better than the components alone.

Composite performance is related to many factors, including fibre direction, fibre content, resin type and curing technique. Compared with conventional metal materials, composites have outstanding mechanical properties. Composites composed of different fibres and matrix materials have different performances. Generally, strength-to-weight and modulus-to-weight are used to compare the significant mechanical properties, mainly expressed as the materials' bearing capacity and rigidity under equal weights. High strength-to-weight and high modulus-to-weight imply high performance. Strength-to-weight and modulus-to-weight are determined according to the strength and elongation measured at a single stretching test. The structural bearing conditions and failure modes are diverse. Under this circumstance, mechanical properties cannot be measured entirely by strength-to-weight and modulus-to-weight. Therefore, strength-to-weight and modulus-to-weight are only two coarse qualitative performance indexes. Properties of different FRP composites are shown in Table 3.

GFRPs have high strength-to-weight, corrosion resistance, electric insulation, easy manufacturing and low cost. They have a long history of application and are extensively used nowadays. However, glass fibre reinforced composites have the characteristics of high modulus-to-weight.

CFRPs have relatively high strength-to-weight and high modulus-to-weight, high-temperature resistance, anti-fatigue performance and good thermostability. They are high cost and have been increasingly used [7].

AFRPs are a type of composite with high strength-to-weight and high modulus-to-weight. Although they have a higher cost than GFRPs, they have a lower cost than CFRPs. AFRPs are becoming a popular material.

Generally, FRPs have advantages shown as following:

(1) High strength-to-weight: especially high-strength carbon fibre and aramid fibre reinforced composites.
(2) High modulus-to-weight: except for GFRPs, composites have significantly higher modulus-to-weight than metals, especially high-modulus carbon fibre reinforced composites.
(3) Designability of materials: composites have significant differences compared with metallic materials. Composite performance is determined by fibre content and pavement and the performance of the fibre and matrix. Hence, fibres in composites can be designed in appropriate amounts and good pavements according to the loading conditions and structural shape. This aims to meet the design requirements with the least material used and maximum material performance.

Table 3 Properties of different FRP composites [3]

	Density (g/cm^3)	Tensile strength (GPa)	Tensile modulus (GPa)
CFRP (unidirectional)	1.55	1550	137.8
GFRP (unidirectional)	1.85	965	39.3
AFRP (unidirectional)	1.38	1378	75.8

(4) Simple manufacturing techniques and low cost: composite components generally do not require complicated machining equipment and require few production procedures. Thin-walled components with complicated shapes can be manufactured with low consumption of materials and processes.
(5) Some composites have good thermostability. For example, carbon fibre and aramid fibre have a negative coefficient of thermal expansion. Composites with a minimal thermal expansion coefficient can be prepared by combining carbon fibre or aramid fibre with a matrix material with a positive coefficient of thermal expansion. Structures only have minimal thermal stresses and thermal deformation upon changes in the environmental temperature.

Besides, various composites have many different useful characteristics, such as fatigue resistance, impact resistance, electromagnetic permeability, damping properties and corrosion resistance.

Generally, FRPs have disadvantages shown as following:

(1) Serious anisotropy. Although composites have good performance along the fibre direction, their performance perpendicular to it is mainly determined by the performance of the matrix material as well as the bonding strength between the matrix and fibres. Generally, the mechanical properties perpendicular to the fibre direction is lacking. In particular, the interlayer shearing strength is deficient in laminated composites.
(2) Composites have a great range of properties, making it challenging to realize quality control and detection. However, material quality can be improved by improving processing and detection technologies, which will also reduce performance disparities.
(3) Composites have high costs. At present, boron fibre reinforced composites are the most expensive. Carbon fibre reinforced composites are more expensive than metals, while glass fibre reinforced composite is low-cost.
(4) Some composites have low robustness and difficult mechanical jointing.

Based on the above disadvantages, some disadvantages can be mitigated through the design of the material. This is why composites are extensively used in many fields and have promising development prospects.

The interface is the region with a certain thickness (several angstroms to hundreds of angstroms) formed by physical and chemical interactions between fibres and the resin matrix [13]. The structural, chemical and physical properties of the interface are different from those of the fibres and resin. The interface is also called the interface phase or interface layer. However, the notion of interface or interphase remains relatively vague, as the interfacial zone does not exist in itself but is created during the implementation of the composite.

Properties affected by the interface include strength, modulus, and toughness. A weak interface also reduces fatigue endurance of aligned fibre composites. High adhesion between fibres and resin providing is a necessary condition for high-performance composites. The properties of the interface layer are affected by the reinforcement materials, matrix material, curing technique (e.g. pressure, temperature and density) and service conditions [14, 15]. Proper adhesion can be reached for properly selected combinations of fibre and matrix materials under some additional conditions. Based on this, the fibre-matrix interface can transfer the stresses efficiently so that these excellent properties are maintained, and are not degraded by the environmental and other factors encountered in use.

Currently, various mixed fibre reinforced composites have been manufactured, which have better mechanical properties than single fibre reinforced composites. Hybrid composites, a class of composite material, have two or more high-performance reinforcements combined at the micrometres or molecular level [16]. When hybrid composites contain two types of reinforcing fibres, it is called hybrid fibre composites. The three most basic configurations are shown in Fig. 8 [17].

The purpose of bringing two fibre types in a single composite is to maintain both fibres' advantages and alleviate some disadvantages. In other words, it is considered that some of the individual components are a more favourable balance between the inherent advantages and disadvantages. Therefore, the hybrid composite containing two or more fibre types will beneficially complement what is deficient in the other. The hybrid composite strength depends on the fibre content's properties, length of distinct fibres, fibres orientation, fibre to matrix bonding and fibres sequence arrangement of both the fibres.

The hybrid structure is a mixture of each material's required properties, such as the ratio of strength-to-weight, modulus-to-weight, fatigue strength, and fatigue damage tolerance. The goal is to increase the failure strain, ductility, and toughness. The failure strain of individual fibres will justify the strength of the hybrid composite and highly strain compatible fibres will determine the maximum hybrid results. For example, replacing carbon fibres in the middle of a laminate by cheaper glass fibres can significantly reduce the cost, while the flexural properties remain almost unaffected [17]. If a hybrid composite is loaded in the fibre direction in tension, then the more brittle fibres will fail before the more ductile fibres.

Composites can improve material properties, prolong service life and strengthen functionality. Figure 9 shows the product life cycle of FRPs, beginning with fibres and polymers and ending with recycling the material [18]. To obtain an automated high

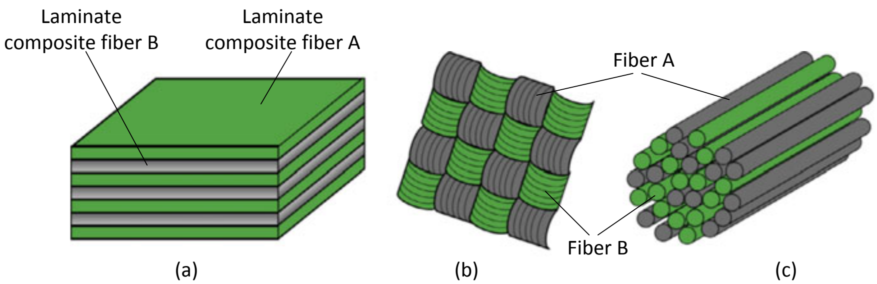

Fig. 8 The three main hybrid configurations **a** interlayer or layer-by-layer, **b** intralayer or yarn-by-yarn, **c** intrayarn or fibre-by-fibre [17]

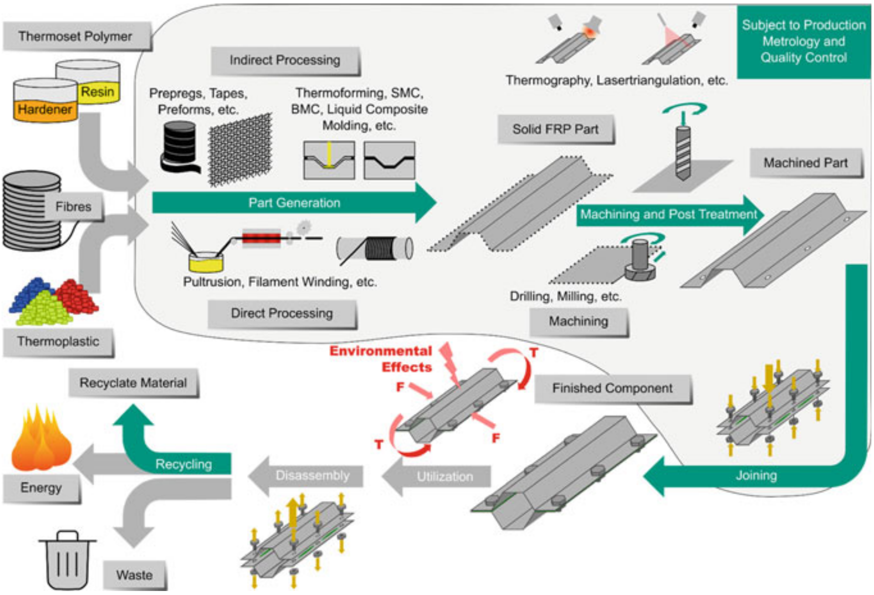

Fig. 9 The product life cycle for composite materials parts manufacturing [18]

volume FRPs in the future, considerable challenges in production technology still need to be mastered. Much attention is focused on conventional and unconventional machining technologies of FRP composites.

Recycling of FRPs has a significant impact on production processes. The resin will produce plastic flow, and the resin matrix size will be reduced when FRP is recycled, decomposed and reproduced. It will lead the FRP properties decreased on reprocessing. Hence, attention should be paid to the recyclability of composite parts. The use of FRPs has created an immediate legacy problem and business opportunity regarding the waste produced from manufacturing and end of life products.

The recycling of composite parts is complicated, and they can cause adverse impacts on the environment. Polymer-based composites are mainly inflammable substances and may release abundant toxic gases during combustion that pollutes the environment. Moreover, volatile components such as matrix solvents may be diffused into the air during moulding. Composites are composed of multiple components and are multi-phase materials. Composite parts should be degraded into single-material parts, but it is difficult to grind, thin, melt and degrades. As a result, such decomposition techniques have high costs, and the regeneration cost is relatively high. It is challenging to recover the original properties.

Different recycling processes are needed for thermoset and thermoplastic. Mostly, thermosetting resin composites cannot be melted and remoulded due to three-dimensional cross-linking structure. Recycling of thermosetting resin composites is more complicated than that of thermoplastic resin composites. Because thermosetting composites are widely used, unique high-efficient recycling technology is required.

Easy disassembly of parts is one of the major requirements for recycling. Recycling requires single materials as much as possible. Composites should be comprised of as few material categories as possible.

Considering the above principles, the usage rate of thermoplastic polyolefin and polypropylene foam material may be increased significantly. On the contrary, the usage rate of thermosetting resins is restricted. Currently, significant progress is achieved in regeneration and degradation under thermoset and thermoplastic of thermosetting resin composites.

4 Manufacturing Techniques of FRP Composites

Transformation of uncured or partially cured fibre-reinforced matrix into composite parts or structures involves curing the material at elevated temperatures and pressures for a period. High cure temperatures are required to initiate and sustain the chemical reaction that transforms the uncured or partially cured material into a fully cured solid. High pressures are used to provide the force needed for the flow of the highly viscous resin or fibre–resin mixture in the mould, as well as to remove volatiles and excess air, to facilitate the consolidation of the laminate, and to apply temperature and pressure to ensure good bonding during cure. For example, the most critical processing characteristics include the liquid viscosity, the curing temperature, and the curing time for epoxy resin polymers.

There are numerous methods for fabricating composite components. The selection of the fabrication method for a particular part is the most crucial before the part design and end-use or application. The first manufacturing method for FRPs structural parts used a hand lay-up technique. Recently, there is more emphasis on the development of manufacturing methods that can support mass production. Modern techniques of fabrication are developed such as vacuum bagging, autoclaves, Resin Transfer Moulding (RTM), Vacuum-Assisted Resin Transfer Moulding (VARTM), Resin Film Infusion (RFI), injection moulding, filament winding, pultrusion, and many other to produce a reliable and robust composite structure or component in primary composite fibres [19–21].

Different techniques can manufacture composites according to the structural shape required. Rotating components, such as pressure vessels and shells, can be prepared by fibre interweaving techniques. However, large plane structures can use the autoclave moulding technique.

4.1 Laminated Composites

Composites formed by the layered pavement of prepregs are called laminated composites. The laminate composite is produced by stacking several thin layers of fibres and matrix (called prepreg) and laying them into the desired thickness. The ply consists of several fibres through the thickness that is aligned and continuous. Typical volume fractions of fibre are on the order of 60% [4]. In the preparation of composites, an epoxy resin matrix is infiltrated into the fibre and then dried into prepregs used to manufacture various products with a variety of specific manufacturing techniques. The structure of continuous fibre reinforced resin composites is shown in Fig. 10.

Unidirectional fibre prepregs are paved according to the designed angle and number of layers to manufacture plate or large-curvature components. Next, the material is put between platforms or moulds for pressurization and curing shaping with heat. Consequently, laminated-structured composites are formed. Thermosetting prepreg must be kept refrigerated until they are assembled and placed in the curing process. Thermoplastic prepreg, on the other hand, does not have to be stored under refrigeration. They tend to be stiff and are usually softened before assembly. The final manufacture could involve heating and form in matched moulds. The unidirectional prepreg can be cut and stacked to form the final product. Because the individual fibres are relatively straight, the use of a unidirectional prepreg provides a method, along with filament winding, of achieving finished products with excellent mechanical properties.

Laminating moulding is done to pave prepregs in different layers and then mould them at a specific temperature and pressure. After chemical curing, no plastic formability remains for thermosetting matrix FRPs. However, a subsequent plastic deformation is possible for thermoplastic matrix FRPs by reheating after cooling down. The modulus and strength of the thermoplastic matrix FRPs are lower compared to the thermosetting matrix FRPs. Besides, creeping is easily generated on thermoplastic matrix FRPs caused by long-term loads. Furthermore, the curing temperatures of thermoplastic polymers are higher than those of thermoset polymers.

Fibre direction in each layer and the stacking sequence of different layers in a laminate can be designed to produce a wide range of physical and mechanical properties for the laminated composite. The characteristics of the manufactured FRPs can be quasi-isotropic or anisotropic depending on the fibre orientation inside the composite. With fibre reinforcements, quasi-isotropic semi-structural FRPs can be produced by highly automated production processes. If fibres in the laminated composites are

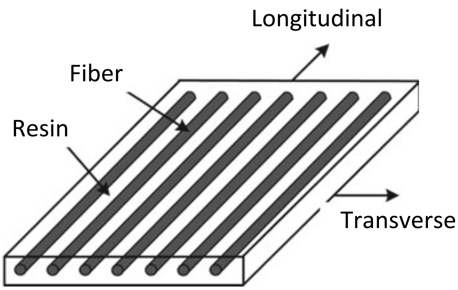

Fig. 10 Structure of monolayer fibre reinforced composites [22]

paved in the same direction, they are called a unidirectional composite. If fibres are paved in different directions, it is called a multidirectional composite.

Due to the fibre lay-up direction, unidirectional composites generally have high strength and modulus along with the fibre directions, but low mechanical properties perpendicular to them. In the preparation of FRPs, the fibre's lay-up direction can be chosen according to the stresses expected in the components, thus improving the usability of components.

Also, a relatively sizeable residual stress is generated in the curing process due to the significant difference in the coefficients of thermal expansion of fibre and resin. To reduce material deformation caused by stress, laminated prepregs are generally set symmetrically. A typical lay-up mode of laminated FRPs is shown in Fig. 11a. The cross-section microstructure of a multidirectional CFRP profile is shown in Fig. 11b.

According to the properties expected for FPRs, sometimes fibres are weaved in two orthogonal directions, in which the weft alternatingly crosses over and under the warp. This creates the highest crimp with the tightest fabric and poorest drape ability and the most resistant to in-plane shear movement. A typical lay-up mode of FRPs is shown in Fig. 12a. Furthermore, the cross-section microstructure of a multidirectional AFRP profile is shown in Fig. 12b.

4.2 Cylindrical Structures

The typical method for fabricating cylindrical composite structures is filament winding. Filament winding is an efficient automated process of placing resin-impregnated roving or monofilaments onto a rotating mandrel removed after curing the composite part. The matrix may be added to the fibre by running the fibre tow

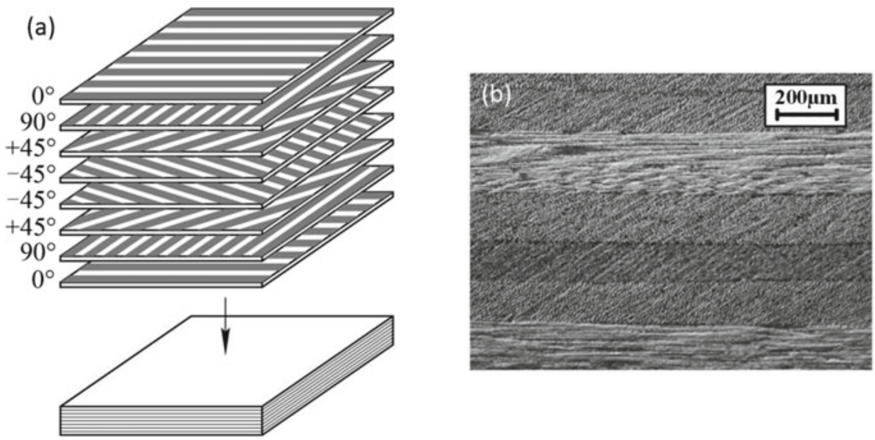

Fig. 11 Structure of a CFRP composite **a** stacking sequence, **b** cross-section

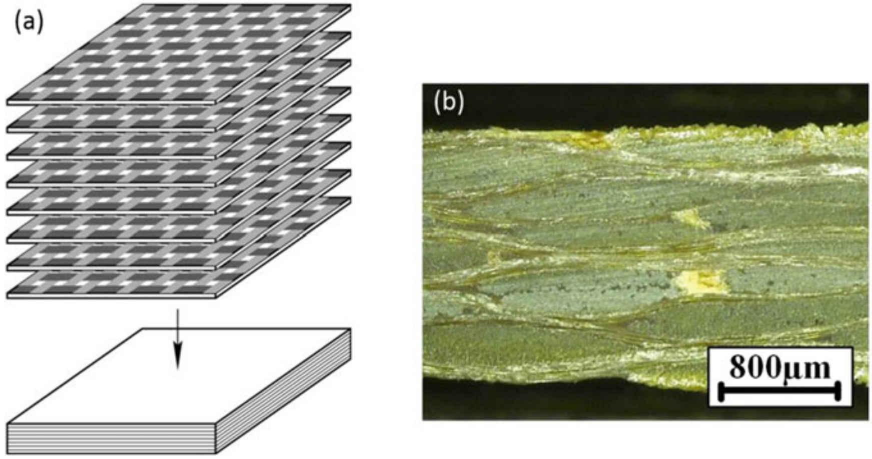

Fig. 12 Structure of an AFRP composite **a** stacking sequence, **b** cross-section

through a matrix bath at the time of placement, or else the roving may be prepregged before winding. The filament winding process consists of winding continuous-fibre tow, yarn, or tape around a form or mandrel to form the structure. Usually, the component's cure is done at room temperature or by applying heat without vacuum bagging or autoclave consolidation. Filament winding is typically a low-cost method because of the use of fibres and resins in their lowest-cost form, as well as highly automated and repeatable.

Preliminary tension applied to the roving in winding induces pressure between the layers providing compaction of the material. Varying the winding angle, it is possible to control material strength and stiffness within the layer and through the laminate thickness.

Filament winding processes can be subdivided into two groups regarding the basic design and the machine kinematics. On the one hand, the mandrel itself rotates. Simultaneously, the fibre placement is controlled to move longitudinally in a prescribed way to generate the required fibre inclination angle to the axis of rotation. The motion may be synchronized using CNC machines or by conventional machines similar to the lathe. On the other hand, there is a flexible robot winding.

Filament winding is a continuous fabrication method which has emerged as the primary process for composite cylindrical structures and axisymmetric hollow parts. Filament winding has been widely used for making automotive drive shafts, helicopter blades, oxygen tanks, pipelines, spherical pressure vessels, conical rocket motor cases, glass-fibre pipe, rocket motor cases, golf shafts, drilling risers, energy absorption tube, large underground gasoline storage tanks and other similar products.

The filament-winding process is also used to manufacture prepreg sheets or continuous fibre-reinforced sheet-moulding compounds. The most advantageous of filament winding is manufacturing thin-walled shells of revolution, though it can be

Fig. 13 Filament winding setup [23]

Fig. 14 GFRP cylindrical shells [23]

used in building composite structures with more complicated shapes. Besides, several specialized techniques are being considered for more complicated shapes. Filament winding setup and GFRP cylindrical shells are shown as in Figs. 13 and 14.

5 Applications of FRP Composites

Material selection is one of the most important and critical steps in the structural or mechanical design process. The properties of FRPs (especially strength and modulus) should be considered in the selection process depending on the performance requirements and possible mode of failure.

FRP composites have proven to be flexible and adaptable engineering material for many applications, including aerospace, aircraft, automotive, construction, marine, commodity, and sports. Commercial and industrial applications of FRP composites are so varied that it is impossible to list them all. Here, several application areas are given, including aircraft and military, automotive, infrastructure, and sporting goods. FRP composites are also used in electronics, building construction, furniture, power industry, oil industry, medical industry, and many industrial products, such as oxygen tanks, and power transmission shafts. The potential use of FRPs exists in many engineering fields, based on their unique mechanical, physical, and thermal characteristics.

Large-scale research projects undertaken in 1993 in the USA and Canada involving CFRP/GFRP composites confirmed the decision to use such materials in construction [24]. The USA is the largest producer and user of FRP composites and leads the world's composite technology development and implementation. The US composite industry is expanding despite the overall slow-down in the US economy in the past couple of years. FRP manufacturing is predicted to rise at a yearly rate of 4–5% over the next five years [25].

5.1 Aircraft and Aerospace Applications

Composites are the most typical materials used in the aerospace field. Using advanced composites in aerospace structures can reduce weight by 20–30%, which is beyond other advanced technologies. Advanced composites have become one of four structural materials used in the aerospace field after aluminium alloy, titanium alloy and high-strength steel. The increasing amount of advanced composites used has become an essential symbol of aircraft advancement. Composites for aircraft commenced with non-load-bearing components (e.g. cabin doors and antenna housings). Then they were used for secondary and principal load-bearing components (e.g., empennages and wing boxes) over the last 50 years [26].

The number of composite applications has become an important index used to measure the aerospace industry's advancement. Two iconic enterprises in the aerospace field, Boeing and Airbus, have given much attention to composites' use. In 1985, Airbus first used composites in aircraft manufacturing for the empennage of the A310 passenger plane. Subsequently, Airbus used composites in the wings of the A350 passenger plane. The Boeing 787 aircraft includes many technological innovations. The most attractive is that the main body structure (including wings and fuselage) uses about 50% composites [27, 28]. It is the first jetliner for civil use that uses composite in the main structure. To maintain competitiveness with Boeing, the Airbus A350 is also extensively comprised of composites. About 25% of the primary members of the A380 are made of advanced lightweight materials, and the mass of composites is about 32 tons, accounting for 22% of the total weight [26]. The components made of CFRPs used in Airbus 350 aircraft is shown in Fig. 15 [29]. It

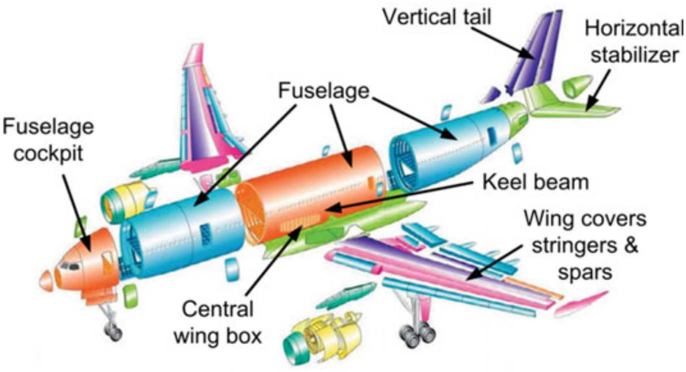

Fig. 15 Large-size CFRP composite components used in Airbus 350 [30]

is a fact that, rather than metals, composites have become the primary material used in aircraft structures.

Advanced composites have made outstanding contributions to the aerospace technological field and will occupy a vital role in aerospace technologies' future development. Since a satellite launch may cost tens of millions of dollars, it is important to use light structural materials with high performance. Therefore, composites play an irreplaceable role in launchers, missiles, satellites and aircraft.

5.2 Military Applications

Advanced composites have promising application prospects in weapon equipment. Increasing the use of composites is crucial to reduce weight and improve performance. For instance, the range of a strategic missile can be increased by 16 km for each 1 kg reduction in weight, and the range of a warhead can be increased by 20 km for each 1 kg reduction. The weight of a missile launcher can be reduced by more than 20% by using advanced composites, which increases its manoeuvrability and improves its fatigue and corrosion resistance.

With their outstanding impact resistance, aramid fibre reinforced composites have been highly useful in bulletproof equipment. After long-term perfection and development, the successful application of aramid fibre reinforced materials has become an important milestone in the strengthening and lightweight, protective armour design.

The traditional homogeneous armour used in tanks cannot resist attack by advanced antitank weapons, whose destructive power gradually increases. Although thickening armour can enhance the protection of tanks, it also may restrict their manoeuvrability. Composite armour is a kind of heterogeneous armour composed of multiple layers of protective materials with different properties. AFRP is an essential component of the multilayer structure of composite armour. Composite armour is widely used in the third generation of main battle tanks to improve protection. For instance, Kevlar fibre reinforced composites are used in the interlayered composite armour structure in the M1A1 (as shown in Fig. 16) main battle tank (United States).

AFRP composites have replaced traditional massive metals in the physical armour field and become the primary material used in bulletproof helmets and personnel armour. In the 1970s, Natick Research Lab first produced a type of soft personnel armour using Kevlar fibre reinforced composites to replace steel materials and named it the Personnel Armour System for Ground Troops (PASGT). With ongoing development, PASGT has been improved and perfected continuously. Currently, the Advanced Combat Helmet (ACH), shown in Fig. 17, and Improved Outer Tactical Vest (IOTV), issued to US ground forces, as well as the Lightweight Helmet (LWH) and Modular Tactical Vest (MTV) used by the US Marine Corps, are all updated versions of PASGT. They all use Kevlar fibre reinforced composites as the primary bulletproof materials.

Aramid fibre reinforced materials have been widely used in the aerospace field as an advanced composite. In the 1970s, the L-1011 TriStar wide-body passenger plane developed by Lockheed Corporation (USA) used 1135 kg of Kevlar fibre reinforced composite. In 1977, the main body of the S-76 Spirit civil helicopter manufactured by Sikorsky Aircraft Corporation (USA) applied Kevlar fibre reinforced composites for as much as 50% of the aircraft's' area. In 1980, the An-124 heavy transport machine designed by Antonov Design Bureau of the Soviet Union mainly used aramid fibre reinforced materials in the main body, and the total weight was 3000 kg.

To manufacture high-pressure vessel structures similar to solid rocket engine casts, aramid fibre composite has become the first choice for replacing glass fibre reinforced composites. The three-stage solid rocket engine casts of the Trident submarine-based ballistic missiles and Peacekeeper ground-to-ground ballistic missiles, made in the USA in 1970, were all manufactured with interwoven Kevlar fibre reinforced

Fig. 16 Aramid composite armour [31]

Fig. 17 Aramid composite helmet [32]

composites. These casts were 50% lighter than the same size of glass fibre reinforced composite cast. Besides, aramid fibre reinforced materials are widely used in antenna structures for their excellent heat-insulating properties and electromagnetic wave permeability.

5.3 Mobile Phone Applications

Aramid fibre composites were viewed as strategic materials in the armour, aerospace and military industries. With the end of the cold war and rapid technological development, the market for aramid fibre reinforced composites in civil services opened and expanded quickly. In the competitive mobile phone industry, some mobile phones' rear shells use aramid fibre reinforced composites. Due to their strong robustness and friction resistance, aramid fibre gives mobile phones an excellent appearance and outstanding user experiences. The application of aramid fibre in the mobile phone is shown in Fig. 18.

5.4 Automotive Applications

Currently, there is increasing concern about the relationship between humans and nature. Environmental and energy challenges have become the key to each country's survival and development in the world. With the increasing consciousness of environmental protection and increasing environmental protection laws, green cars have become an essential trend in automobile development. Therefore, making cars that

Fig. 18 Mobile phone case of aramid fibre [33]

meet environmental protection requirements is on the agenda of automobile manufacturers. As the mainstream material used in cars, composites will play a vital role in future automobile development.

Composites can meet the requirements of lightweight car bodies. In the automobile field, composites are used in auto-body panels, interior trim parts, structural components and functional components. Replacing steel components with composites can reduce the structural weight by 40–60%, thus improving energy efficiency significantly.

Manufacturing and design of fibre-reinforced composite materials for automotive applications are significantly different from those for aircraft applications. One noticeable difference is in the production volume, which may range from 100 to 200 pieces per hour for automotive components compared with a few hundred pieces per year for aircraft components [3].

Composites can also lower fuel consumption and improve safety. Traditional car bodies mainly use thin steel plates alone, which cannot adapt to high speed and lightweight pursuit. Many automobile manufacturers have been researching and using new materials to reduce the weight of car bodies and fuel consumption and improve wind resistance coefficients. The driving distance attained with 1 L of fuel can be increased by 2 km if the car's weight is decreased by 50 kg. Fuel economy can be improved by about 5.5% if the car weight is decreased by only 10%. Many types of composites have been used successfully to achieve lightweight car bodies.

Moreover, racing cars made of CFRP maintain good stability even under high wind resistance, attributed to composites' higher rigidity than steel. Energy-saving, environmental-friendly and safe electric vehicles are a global development trend in the automobile industry. The main structure and energy storage flywheel can also be made of composites. A composite component is shown in Fig. 19.

Fig. 19 The surface geometry of a composite component is checked [34]

Boat structures and hulls incorporate composites to a large extent. GFRPs dominate in pleasure boat building because of its lightweight and resistance to corrosion. CFRP composites are also used in high-performance race boats.

5.5 Infrastructure Applications

In the industrial field, composites can be applied in various infrastructure fields, including roofs, bridges, tunnels and relevant concrete projects. Several reinforced concrete specimens are shown in Fig. 20. Replacing ordinary steel rebars with fibre reinforced polymer rebars increases the strength and fatigue resistance of the structure and can also offset ordinary rebars' ready corrosion. Also, composites are extensively used in the fences of drilling platforms, tunnels, drill collars and drilling tubes due to their strong corrosion and friction resistance.

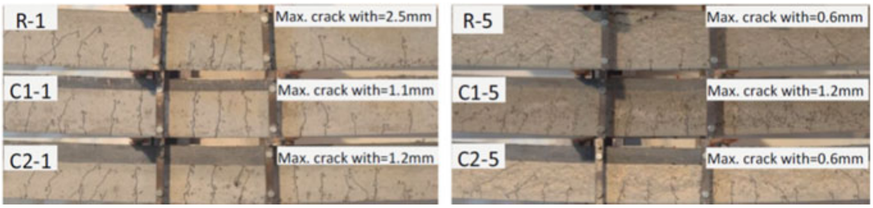

Fig. 20 Crack patterns and the measured maximum crack width of different reinforced concrete specimens [35]

Development of new energy resources and energy-saving and energy-storage technologies is an essential part of the current high-tech field. Energy technologies also need lightweight materials with high strength and resistance to high temperature and corrosion. For example, a single generator capacity has to be increased continuously (reaching about 1.5–2.5 MW) to lower wind power generation costs. The blade length can reach 50 m, which requires blades to have lightweight, high strength and high modulus. CFRP are the ideal material for this. Moreover, composites have promising application prospects in solar energy, atomic energy, ocean energy and super-conduction equipment [36–38].

5.6 Sporting Goods Applications

Composites have also been widely applied in the sports and leisure fields, after the aerospace and aircraft industries. Brassies, tennis rackets and fishing poles are three main composite products. Besides, composites have been used in bicycles, automobile racing, speed boats, skis and stay bars. Composite softball and baseball bats are shown in Fig. 21. CFRP composites dominate in sports applications because of its extraordinary strength and stiffness.

The lightweight, high strength and damping performance of composites can significantly improve the usability of sports products and help athletes achieve good performance. The advantages of using fibre-reinforced polymers are weight reduction, vibration damping, and design flexibility. Weight reduction achieved by substituting carbon fibre-reinforced epoxies for metals leads to higher speeds and quick manoeuvrings in competitive sports, such as bicycle races and canoe races. Some applications, such as tennis rackets or snow skis, sandwich constructions of carbon or boron fibre-reinforced epoxies as the skin material and a soft, lighter weight urethane

Fig. 21 Composite softball and baseball bats [39]

foam as the core material produces a higher weight reduction without sacrificing stiffness. Faster damping of vibrations provided by fibre-reinforced polymers reduces the shock transmitted to the player's arm in tennis or racketball games and provides a better feel for the ball. In archery bows and pole-vault poles, the high stiffness–weight ratio of fibre-reinforced composites is used to store high elastic energy per unit weight, which propels the arrow over a longer distance or the pole-vaulter to jump a greater height. It is an ongoing trend to apply fibre reinforced composites to sports products in the future.

6 Review Questions

(1) How do you select the appropriate preparation technique for composite components with different structures?
(2) In addition to carbon fibre, glass fibre and aramid fibre, what are some other new reinforced fibres and their mechanical properties and applications?
(3) What are the advantages and disadvantages of different types of composites?
(4) What are the major problems in the development of resin-based composites?
(5) Discuss the design and material selection consideration for drive shaft of an automobile, and why FRPs can be a good candidate material.
(6) Design a composite beam that is 30% lighter than the steel beam but has the same tensile strength.
(7) Discuss the use of FRP material components in human health in the future.
(8) Discuss the influence of fibre direction on the tensile strength of CFRP.
(9) What are the major impediments to widespread adoption of AFRP in the aircraft industry?
(10) Describe the major differences between thermosets and thermoplastics in the processing methods.
(11) Discuss the major differences between two composite material manufacturing with the same method, but the matrices are different (thermosets and thermoplastics).
(12) Discuss the terms isotropic and anisotropic as it applies to the matrix and fibres.
(13) Discuss the microstructure of the interface between carbon fibre and thermoset.
(14) Discuss the influence of FRP on the environment during manufacturing and machining.
(15) Discuss the development of environmentally friendly composite products.
(16) Indicate the general-purpose fulfilled by the matrix in fibre reinforced polymer composites.

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References

1. Munalli, D., Dimitrakis, G., Chronopoulos, D., et al.: Electromagnetic shielding effectiveness of carbon fibre reinforced composites. Compos. Part B Eng. **173**, 106906 (2019)
2. Eshelby, J.-D.: The determination of the elastic field of an ellipsoidal inclusion, and related problems. Proc. R. Soc. Lond. A **241**(1226) (1957)
3. Mallick, P.-K.: Fiber-Reinforced Composites: Materials, Manufacturing, and Design. CRC Press (1993)
4. Gardiner, G.: The Making of Glass Fiber [EB/OL]. https://www.compositesworld.com/articles/the-making-of-glass-fiber, 2020-06-01
5. Wang, D., Wang, Q., Wang, Z., et al.: Study on the long-term behaviour of glass fibre in the tensile stress field. Ceram. Int. **45**(9), 11578–11583 (2019)
6. Ahmad, J.: Machining of Polymer Composites. Springer-Verlag, DE (2009)
7. Dong, P.-A.V., Azzaro-Pantel, C., Cadene, A.-L.: Economic and environmental assessment of recovery and disposal pathways for CFRP waste management. Resour. Conserv. Recycl. **133**, 63–75 (2018)
8. Dixit, D., Pal, R., Kapoor, G., et al.: Lightweight composite materials processing. In: Lightweight Ballistic Composites, pp. 158–245 (2016)
9. Vasiliev, V.-V., Morozov, E.-V.: Mechanics and Analysis of Composite Materials. Elsevier (2001)
10. Vasiliev, V.-V., Morozov, E.-V.: Advanced Mechanics of Composite Materials and Structures (2018)
11. Luo, Z.-P., Sun, C.-Y.: Effect of the interfacial bonding status on the tensile fracture characteristics of a boron–fiber-reinforced aluminum composite. Mater. Charact. **50**(1), 51–58 (2003)
12. Advani, S.-G., Hsiao, K.-T.: Manufacturing Techniques for Polymer Matrix Composites (PMCs). Woodhead Publishing (2012)
13. Teklal, F., Djebbar, A., Allaoui, S., et al.: A review of analytical models to describe pull-out behavior—fiber/matrix adhesion. Compos. Struct. **201**, 791–815 (2018)
14. Karger-Kocsis, J., Mahmood, H., Pegoretti, A.: Recent advances in fiber/matrix interphase engineering for polymer composites. Progr. Mater. Sci. **73**, 1–43 (2015)
15. Sharma, M., Gao, S., Mäder, E., et al.: Carbon fiber surfaces and composite interphases. Compos. Sci. Technol. **102**, 35–50 (2014)
16. Supian, A.-B.-M., Sapuan, S.-M., Zuhri, M.-Y.-M., et al.: Hybrid reinforced thermoset polymer composite in energy absorption tube application: a review. Def. Technol. **14**(4), 291–305 (2018)
17. Swolfs, Y., Gorbatikh, L., Verpoest, I.: Fibre hybridization in polymer composites: a review. Compos. Part A Appl. Sci. Manuf. **67**, 181–200 (2014)
18. Fleischer, J., Teti, R., Lanza, G., et al.: Composite materials parts manufacturing. CIRP Ann. **67**(2), 603–626 (2018)
19. Abdewi, E.-F., Sulaiman, S., Hamouda, A.-M.-S., et al.: Effect of geometry on the crushing behaviour of laminated corrugated composite tubes. J. Mater. Process. Technol. **172**(3), 394–399 (2006)
20. Nirmal, U., Hashim, J., Megat Ahmad, M.-M.-H.: A review on tribological performance of natural fibre polymeric composites. Tribol. Int. **83**, 77–104 (2015)
21. Mamalis, A.-G., Manolakos, D.-E., Ioannidis, M.-B., et al.: On the crashworthiness of composite rectangular thin-walled tubes internally reinforced with aluminium or polymeric foams: experimental and numerical simulation. Compos. Struct. **89**(3), 416–423 (2009)
22. Liu, D., Tang, Y., Cong, W.-L.: A review of mechanical drilling for composite laminates. Compos. Struct. **94**(4), 1265–1279 (2012)
23. Panchagnula, K.-K., Panchagnula, J.-S.: Fabrication of hoop-wound glass fiber reinforced plastic cylindrical shells using filament winding machine. Mater. Today Proc. **27**, 1315–1318 (2020)
24. Mugahed Amran, Y.-H., Alyousef, R., Rashid, R.-S.-M., et al.: Properties and applications of FRP in strengthening RC structures: a review. Structures **16**, 208–238 (2018)

25. Hassan, W.-M., Hodhod, O.-A., Hilal, M.-S., et al.: Behavior of eccentrically loaded high strength concrete columns jacketed with FRP laminates. Constr. Build. Mater. **138**, 508–527 (2017)
26. Marsh, G.: Airbus A350 XWB update. Reinf. Plast. **54**(6), 20–24 (2010)
27. Boeing opts for composites for 7E7. Reinf. Plast. **47**(7), 10 (2003)
28. Marsh, G.: Boeing's 787: trials, tribulations, and restoring the dream. Reinf. Plast. **53**(8), 16–21 (2009)
29. M'Saoubi, R., Axinte, D., Soo, S.-L., et al.: High performance cutting of advanced aerospace alloys and composite materials. CIRP Ann. **64**(2), 557–580 (2015)
30. Hexcel Ready to Fly on the A350 XWB, pp. 25–26. Elsevier B.V. (2013)
31. Baidu: M1A1 Abrams [EB/OL]. https://baike.baidu.com/item/M1A1%E4%B8%BB%E6%88%98%E5%9D%A6%E5%85%8B/3721798?fr=aladdin, 2020-11-14
32. Kumalagov, S.: Aramid Composite Helmet 6B7-1M Russian Armed Forces [EB/OL]. https://www.worldmilitary.org/en/russia/ballistic_protection_russia/shlemy_kaski/RU-HE-00003 (2020)
33. Alibaba: High Quality Slim Mobile Cover Carbon Aramid Fiber Phone Case Cover Shell Black/Grey Twill Color for iPhone 12 iPhone12 Pro [EB/OL]. https://www.alibaba.com/product-detail/2020-High-quality-slim-mobile-cover_1600135591413.html?spm=a2700.galleryofferlist.topad_classic.d_image.54b13b9bFklQCF (2020)
34. Marsh, G.: Carbon composite car body panels gain traction with Gurit Automotive. Reinf. Plast. 24–27 (2011)
35. Turker, K., Torun, I.-B.: Flexural performance of highly reinforced composite beams with ultra-high performance fiber reinforced concrete layer. Eng. Struct. **219**, 110722 (2020)
36. Boisseau, A., Davies, P., Thiebaud, F.: Sea water ageing of composites for ocean energy conversion systems: influence of glass fibre type on static behaviour. Appl. Compos. Mater. **19**(3–4), 459–473 (2012)
37. Ferguson, A.-J., Blackburn, J.-L., Holt, J.-M., et al.: Photoinduced energy and charge transfer in P3HT:SWNT composites. J. Phys. Chem. Lett. **1**(15), 2406–2411 (2010)
38. Mao, S., Lu, G., Chen, J.: Three-dimensional graphene-based composites for energy applications. Nanoscale (2014)
39. Grande, D.-H., Greist, S., Jessie, T., et al.: 3.18 Composites in Sports Applications, 469–526. Elsevier (2018)