CHAPTER

# Fiber-reinforced polymer: applications in biomedical engineering

12

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## 12.1 Introduction

Composite materials, commonly known as composites, comprised two or more constituent materials with different physical and chemical properties, which remain separate and distinct within the finished structure. Composites have become indispensable today and play a major role in daily life, directly or indirectly. The use of composite material in the form of mud bricks is a 1000-year old technology.

The engineering performance of any composite depends on the material that makes up the individual components including the quantity, form and arrangement of the components, and interaction between these components. The desired properties of a composite depend on the reinforcement system. Fiber-reinforced polymer (FRP) is defined as a composite material, which can be formed by the reinforcement of polymer matrix with fibers. Matrix is the continuous bulk phase in composite materials, and reinforcement is the dispersed noncontinuous phase, which usually gives superior mechanical and thermal properties to the matrix. The region between the two is called interface or interphase. Glass, carbon, aramid, paper, wood, and asbestos are mostly used as fibers, whereas vinyl ester, epoxy, polyester thermosetting plastic, and phenol formaldehyde resins are mostly used as polymers in FRP.

Composites can be classified on the basis of the shape, size, orientation, composition, distribution, and manner of incorporation of the reinforcement. Biomedical composites are broadly classified as fiber-reinforced composites (FRCs) and particle-reinforced composites. Besides FRPs, different types of engineered composite materials include composite building materials, such as cements, concrete, metal matrix composites (MMCs), ceramic matrix composites, and polymer matrix composites.

Fig. 12.1 shows further divisions within these groups. The MMCs are advanced composites uncommon in biomedical applications and are mostly used for high-temperature applications.

Materials for Biomedical Engineering: Bioactive Materials, Properties, and Applications.
DOI: https://doi.org/10.1016/B978-0-12-818431-8.00012-X

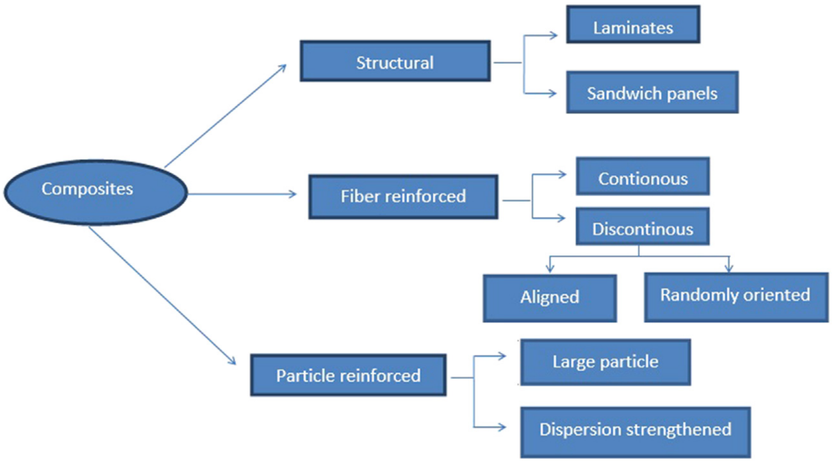



**FIGURE 12.1**

Types of composites.

Research on engineered composite materials has been done since the mid-1960s. The priority of composite materials over traditional materials is due to its different physical characteristics, mechanical behaviors, and processing methods. By introducing fibers into (resins) polymers the mechanical properties of the polymer, particularly the strength and modulus, can be enhanced (Chandramohan and Marimuthu, 2011). These are essential characteristics of FRP composites for applications in civil infrastructure (Jain and Lee, 2012).

Commercial materials can be made of glass or carbon fibers (CFs) in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. There are the further classes of composite in which the matrix is a metal or a ceramic. In these composites the reasons for adding the fibers (or in some cases, particles) are often rather complex, for example, improvements may be sought in creep, wear, fracture toughness, thermal stability Matrix, fibers, and particle classification and their examples are illustrated in Fig. 12.2A–C.

Fibers are thread-like structures that are long, thin, and flexible. On the basis of origin, there can be two different types of fibers: natural and synthetic. The FRPs are developed primarily using synthetic fibers, such as glass, carbon, aramid, and Kevlar. The synthetic FRP composites have unique advantages, such as high mechanical strength and stiffness. Additional improvements can also be done regarding corrosion resistance, wear resistance, appearance, temperature-dependent behavior, environmental stability, thermal insulation, and conductivity (Isaac and Ishai, 2006).

These composites also have drawbacks, such as high cost, high density (as compared to polymers), poor recycling, and nonbiodegradable properties. For

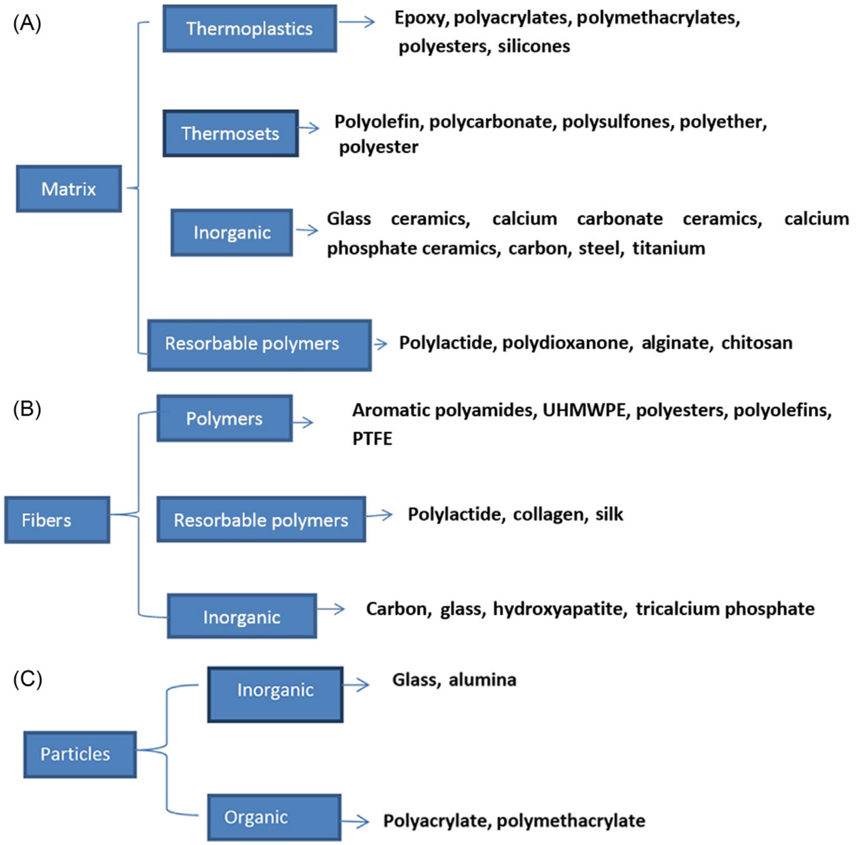



**FIGURE 12.2**

(A–C) Constituents of composites.

these reasons, over the last few years, natural plant FRP composites have increasingly gained attention as viable alternatives (Begum and Islam, 2013) to synthetic FRPs. Among all the fiber- reinforcing materials, natural fibers are key materials that can replace synthetic materials and related products. Natural materials are considered better as they possess low cost, low weight, less damage to processing equipment, good relative mechanical properties, abundant and renewable resources, and energy conservation applications (Yousif et al., 2012). High specific properties with lower price make natural fiber composites attractive for various applications (Ho et al., 2012; Sathishkumar et al., 2012), such as for building materials, particle boards, insulation boards, human food and animal feed, cosmetics, medicine, and for other biopolymers and fine chemicals (Reddy and Yang, 2005). However, this chapter deals with FRPs and their applications in biomedical engineering.

## 12.2 Milestones of fiber-reinforced polymer in biomedical engineering

Biomedical engineering is defined as the application of engineering principles and design concepts in medicine and biology for health-care purposes. Any material that is used for this purpose falls into the biomaterial class. In other words, these are materials of natural or man-made origin used to supplement or replace the functions of living tissues of the human body. In ancient civilization, artificial eyes, ears, teeth, and noses were used on Egyptian mummies. Similarly, there are instances of using wax and glues in reconstructed, missing, or defective parts by Chinese and Indians. With time, advancements in synthetic materials, surgical techniques, and sterilization methods have allowed the use of biomaterials in various ways. At present, these applications include bioimplants as bone plates, heart valves, vascular grafts, dental implants, and joint replacements. Medical devices, such as pacemakers, biosensors, artificial heart, and blood tubes, are also in use to replace or restore degenerated tissues/organs to assist healing, improve function, and correct abnormalities.

Plastics, such as vinyl, polystyrene (PS), and polyester, were developed in the 1900s. In the 1930s a report on biopolymers noted polyhydroxybutyrate as the starting point of FRP development in the biomedical industry (Bledzki and Jaszkiewicz, 2010). Owen Corning was the first to introduce the fiberglass in 1935. After this fiber polymer, application and development of biomaterials took off. However, the use of polymer alone may not give the desired/required mechanical properties as the strength and rigidity are the disadvantages of these materials. This problem is resolved by introducing fibers into polymers, the so-called FRPs.

With technology advancement, FRPs were further modified in 1970. Better plastic resins and improved reinforcing fibers were developed. An aramid fiber called Kevlar was developed by DuPont and is used for dental bridges as tendon ligament bone cement, etc. (Johnson, 2011). In addition to this, CF has been introduced to replace the metals. The use of metals, such as stainless steel and titanium, in bone repairing is basically due to their biocompatibility properties, but they may cause unnecessary pain and inconvenience in removing these metals over time through surgeries. Another disadvantage of such metals in bone repairing is the possibility of refracture of the bone due to differential effect of stiffness between bones and metals after the removal of these plates. The use of FRPs overcomes such type of problems faced by medical practitioners. Furthermore, fiber-reinforced composite posts make surgical procedure less traumatic for patients (Scholz and Blanchfield, 2011).

## 12.3 Characteristics of fiber-reinforced polymer

Resin-based composites with various reinforcing materials, such as glass, carbon, carbon nanotubes, and organic fibers, are specifically analyzed by strength and tribological aspects (Jena et al., 2017). Newly established terms, such as "biotribology," "nanotribology," and "green tribology," have been used to investigate tribological phenomena, while adopting sustainable, green materials/biomaterials for ecological balance, economic stability, and energy savings (Luigi, 2017).

"Biomaterial" and "biocompatibility" are two keywords that show the biological performance of materials in an appropriate host, which simply implies the compatibility of the biomaterial with the living system. Wintermantel et al. (1994) extended this definition and distinguished between surface and structural compatibility of an implant. Surface compatibility was referred to as the chemical, biological, and physical (including surface morphology) suitability of an implant surface to the host tissues, whereas structural compatibility was defined as the optimal adaption to the mechanical behavior of the host tissues. However, both surface and structural compatibilities are required to meet optimal interaction between biomaterial and host (Ramakrishna et al., 2001).

The essential requirements for biomaterials are sterilization and meeting the desired characteristics. The sterilization of FRP materials, particularly polyetheretherketone (PEEK composites), alters the micromechanical properties to some extent as changes affect the in vivo behavior of the material. Therefore it is essential to analyze the changes in FRP material due to sterilization.

Besides this, biofunctionality, biocompatibility, bioadhesion, high strength, corrosion resistance, and low friction are needed (Patel and Gohil, 2012). Out of the above characteristics, mechanical properties have major impact on biocomposites, hence these are discussed here in detail.

### 12.3.1 Mechanical aspects of important implant materials

The mechanical properties of FRPs should be understood prior to discussing implant devices using these reinforcements in biomedical engineering. Metals, ceramics, and polymers are the three main groups of materials used in biomedical applications. Tantalum, gold, Co–Cr, NiTi (also known as shape memory alloy), and stainless steel are some important examples of metal and alloys used widely in biomedical applications. Zirconia, alumina, and bioglass (bioactive glass) are considered to be successful biocompatible ceramics. Although Co–Cr-based alloys show low levels of corrosion, but when implanted into the human body, the metal-in-metal joint experiences tribocorrosion, a form of metal degradation that may lead to the release of metal ions into the body (Bellefontaine, 2010). Commonly used polymer matrixes in conventional manufacturing processes include polypropylene (PP), PS, and polyurethane (PU) (Hofstatter et al., 2017). However, the most usable materials in the biomedical field are polylactic acid (PLA), polyamide (PA), silicone rubber (SR), polytetrafluoroethylene (PTFE), PEEK, polysulfone, polyethylene (PE) terephthalate (PET), polyglycolic acid (PGA), CF/ultrahigh-molecular-weight PE(UHMWPE), CF/epoxy, and hyaluronic acid (HA)/PE. Table 12.1 depicts such biomaterials.

**Table 12.1** List of some biomaterials currently used in biomedicine.

| | |
|---|---|
| Metallic | Cobalt (Co), nickel (N), tantalum (Ta), vanadium (V), iron (Fe) chromium (Cr), tungsten (W), and molybdenum (Mo) |
| Ceramic | Silicone nitrides, alumina, zirconia, glass ceramics, calcium aluminates, hydroxyapatites, and calcium phosphates |
| Polymeric | Polypropylene, polymethylmethacrylate, polyvinylchloride, polyethylene, polyethylenterephthalate, polytetrafluoroethylene, and polyamide |
| Biodegradable polymers and materials | Polyhydroxyvalerate, polyhydroxyalkanoates, polylactic, polybutylene succinate, polycaprolactone, polyanhydrides, polyvinyl alcohol, collagen, elastin, albumin, fibrin, and polysaccharides |

Structural or mechanical compatibility in biomaterials is the most important feature for their application in hard and soft tissues. On this basis, ceramics or metals are selected for hard tissue applications and polymers for soft tissue applications. Mechanical properties of hard and soft tissues are studied extensively by Black (1988). His results for hard tissues depicted that modulus of cancellous bone is very less (0.4 GPa) as compared to the modulus of enamel (84.3 GPa). Modulus of cortical bone on the other hand is 17.7 GPa in longitudinal direction, whereas 12.8 GPa in transverse direction. As regarding the tensile strength of cancellous bone, it is nearly 7.4 MPa, while cortical bone has a tensile strength of 133 MPa in longitudinal direction and 52 MPa in transverse direction. In case of soft tissues, the minimum modulus, 0.1–0.2 GPa is reported for skin, whereas modulus of Tendon and Ligament shows higher values, 401.5 GPa and 303.1 GPa, respectively. It is observed that the elastic module as well as tensile strength of biomaterials is about 10–20 times greater than the hard tissues of the body. Modulus and tensile strength of Co–Cr alloy is reported as 210 GPa and 1085 MPa, respectively. Very low modulus is reported for polymeric biomaterials. Polyurethane shows modulus nearly 0.02 GPa and for silicone rubber, modulus is least, that is, 0.008 GPa.

It is observed that the elastic module of biomaterials is about 10−20 times greater than the hard tissues of body. In the case of orthopedic surgery a congenial combination is required between bone and implant. However, the degree of stiffness mismatch is always proportional to the degree of stress protection.

Low modulus materials, such as polymer composite materials, appear to be efficacious for orthopedic applications (Hastings, 1993). There are certain advantages of polymer composites that make them superior than metals and ceramics. Moreover, mechanical as well as physiological conditions of the host tissues can be enhanced by varying the properties or design of any implant combined with control in volume fraction, structural integrity, and global mechanical response.

Therefore, composite materials show better potential for structural biocompatibilities than homogenous traditional materials. Human tissues are essentially composite materials with anisotropic properties, which depend on the roles and structural arrangements of various components, such as collagen, elastin, and hydroxyapatite, of the tissue.

The use of FRP composites are increasing in the field of orthopedics. Hard tissues show good mechanical properties, such as tensile strength and elastic modulus, which enable them to provide high strength and stiffness and to improve their functionality for use in bone fracture repair, dental application, and replacements of total hip, knee, ankle, and other joints. Metals and ceramics are selected for hard tissue applications considering their structural and mechanical compatibility with tissues.

Researchers have found that ceramic-filled metal alloy matrix showed better corrosion and mechanical properties as biocomposites (Razavi et al., 2010). In addition, it was also observed that ceramic as an additive provided protection to metal-based alloy matrix by rapidly forming an apatite layer on the surface (Adzali et al., 2012). Human joint implants should possess mechanical properties, such as Young's modulus, yield stress, plasticity, hardness, and tensile strength. All these are described in the following sections.

#### 12.3.1.1 Young's modulus (modulus of elasticity)

In the geometry and design of material the elastic modulus is a critical variable (Haneef et al., 2013). The Young's modulus or modulus of elasticity may be considered the most critical design variable. It is observed that the tensile strength, hardness, bending strength and density of fiber reinforced polymer increases with the increase in percentage of reinforcement. Elastic modulus is simply defined as the ratio of stress to strain within the proportional limit. Physically, it represents the stiffness of a material within the elastic range when tensile or compressive load is applied. It is clinically important because it indicates that the selected biomaterial has similar deformable properties as the tissue to be replaced. These force-bearing materials require high elastic modulus with low deflection. As the elastic modulus of a material increases, the fracture resistance decreases. It is desirable that the biomaterial elastic modulus be similar to bone. If the biomaterial elastic modulus is more than bone elastic modulus, then load is borne by material only, otherwise it is borne by bone only.

#### 12.3.1.2 Hardness

Hardness is one of the most important parameters for comparing properties of materials. It is used for finding the suitability of biomaterials for clinical use. Biomaterial hardness should be equal to bone hardness, if it is higher than the biomaterial, it will penetrate the bone.

#### 12.3.1.3 Fracture strength

The strength of materials is defined as the maximum stress that can be endured before fracture occurs. The strength of biomaterials is an important mechanical property because they are brittle. In brittle materials such as bioceramics, cracks easily propagate when the material is subjected to tensile loading, unlike with compressive loading. The strength of material and the reliability are important parameters, which influence flaws in bioceramics. Flaws can be produced either by heating or thermal sintering.

#### 12.3.1.4 Fracture toughness

Fracture toughness is required to alter the crack propagation in ceramics. It helps to evaluate the serviceability, performance, and long-term clinical success of biomaterial. It is reported that high fracture toughness material shows improved clinical performance and reliability as compared to low fracture toughness materials.

#### 12.3.1.5 Fatigue

Failure of any material by repeated loading or unloading is known as fatigue. During loading, microcracks or flaws may be initiated at the interface of the matrix and the filler, which further propagate large cracks, leading to material failure. High resistance to fatigue failure is required to stop any implant failure as reported in the case of hip prostheses (Teoh et al., 2010).

#### 12.3.1.6 Tensile properties

Fibers have very high tensile strength as well as good flexural strength but usually have terrible compression strength. Some polymers are tough, while others are strong. The design may have to sacrifice strength for toughness, but sometimes two polymers with different properties can be combined to get a new material with some of the properties of both. There are three main ways of doing this: (1) copolymerization, (2) blending, and (3) making composite materials. High-impact PS (HIPS) is an immiscible blend that combines the properties of two polymers: styrene and polybutadiene. PS is a rigid plastic that when mixed with polybutadiene, an elastomer, forms a phase-separated mixture with the strength of PS along with the toughness supplied by the polybutadiene. For this reason, HIPS is far less brittle than regular PS (Hashim et al., 2011).

### 12.3.2 Important factors in material selection for biomedical application

The materials formed by various combinations of metals, ceramics, and polymers are used in biomedical applications. There are various important factors to be considered for these biomaterials. FRP composites have been included in new reconstruction and rehabilitation of damaged tissues due to its ability to fulfill the essential requirements as cited in Fig. 12.3 and Table 12.2. The advantages and disadvantages of all groups of biomaterials (i.e., polymers, metals, and ceramics) are given in Table 12.3.

A biomaterial should satisfy the following essential requirements:

1. Mechanical properties: Stress shielding occurs due to variation of the Young's modulus of any biomaterial to that of bone. By stopping this variation, which

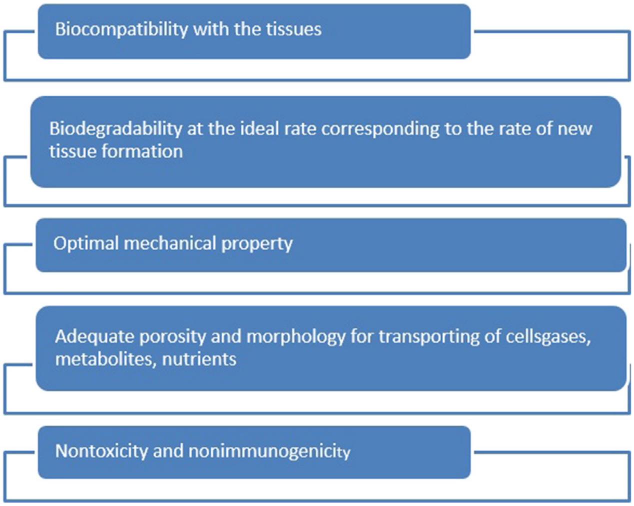



**FIGURE 12.3**

Essential requirements fulfilled by optimal fiber-reinforced polymer materials used in biomedical engineering.

**Table 12.2** Characteristics of fiber-reinforced polymer for biomedical applications (Ramakrishna et al., 2001).

| Factors | Description | | |
|---|---|---|---|
| | **Chemical/biological characteristics** | **Physical characteristics** | **Mechanical/ structural characteristics** |
| First-level materials properties | Chemical composition (bulk and surface) | Density | Elastic modulus, yield strength, tensile strength, compressive strength, and Poisson's ratio |
| Second-level materials properties | Adhesion | Surface topology (texture and roughness) | Hardness, shear modulus, shear strength, flexural modulus, and flexural strength |
| Specific functional requirements (based on application) | Biofunctionality (nonthrombogenic, cell adhesion, etc.), bioinert (nontoxic, nonirritant, nonallergic, noncarcinogenic, etc.), bioactive, bio stability (resistant to corrosion, hydrolysis, oxidation, etc.), biodegradation | Form (solid, porous, coating, film, fiber, mesh, powder), geometry, coefficient of thermal expansion, electrical conductivity, refractive index, opacity, or translucency | Stiffness or rigidity, fracture toughness, fatigue strength, creep resistance, friction and wear resistance, adhesion strength, impact strength, proof stress, and abrasion resistance |
| Characteristics of host | Tissue, organ, age, sex, health condition, systemic response, activity, medical/surgical procedure, and period of application/usage | | |

**Table 12.3** Advantages and disadvantages of all groups of biomaterials.

| Biomaterials | | Polymers | Metals | Ceramics |
|---|---|---|---|---|
| | Advantages | Easily fabricate into complex shapes and structure, large availability in a wide variety of properties, composition and forms | High strength, ductility and resistance to wear | Good biocompatibility, corrosion, resistance, high compression and strength |
| | Disadvantages | Extremely weak and flexible to meet the mechanical demands of certain applications | Low biocompatibility and extremely high stiffness as compared to tissues | Brittleness, low mechanical reliability, high density, lack of resilience, difficult to fabricate and low fracture strength |

is about 4–30 GPa, stress shielding may be prevented (Lawrence, 1980). Problems of revision surgery may be narrowed by using material of high strength and low modulus to extend the functionality of the implant (Hussein et al., 2015).

2. Biocompatibility: According to Walowit (1997), the developed material should be compatible with living systems and not cause any bodily harm, which includes all of the negative effects a material can have on the components of a biological system (bone, extra- and intracellular tissues, and ionic composition of plasma).
   a. High wear resistance: The material should have a high wear resistance and exhibit a low friction coefficient when sliding against body tissues. It was noticed that an increase in the friction coefficient or a decrease in the wear resistance can cause the implant to loosen (Alvarado et al., 2003).
   b. High corrosion resistance: An implant that is made up of a biomaterial with low corrosion resistance can release metal ions into the body, which in turn can produce toxic reactions. Therefore high corrosion resistance is a desirable quality of biomaterials (Hallab et al., 2005).
   c. Osseointegration: This was initially defined as a direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant. The roughness, chemistry, and topography of the surface play a major role in good osseointegration (Geetha et al., 2009). Implant loosening resulting from the nonintegration of the implant surface into the adjacent bone has also been seen (Viceconti et al., 2000).

Wennerberg et al. (2016) noted that it was undesirable due to the risk of not being able to remove the implant after use. However, recently Barfeie et al. (2015) considered osseointegration as a desirable property for a biomaterial for implants so that it can integrate properly with the bone and other tissues.

**d.** Long fatigue life: To extend the fatigue life, material should show high resistance to fatigue failure as well as stress shielding from fatigue fracture.

**e.** Cytotoxicity (that leads to individual cell damage) as well as genotoxicity (that alters the DNA of the genome) should not be in the material (Hussein et al., 2015).

## 12.4 Applications of fiber-reinforced polymer in biomedical engineering

The unlimited bioengineered resources to replace defective or missing parts has increasingly been challenged due to clinical problems. Advancement in the research of bioimplants has seen the innate regenerative capacity of the human body (Arvidson et al., 2011; Ripamonti et al., 2010; Wong et al., 2010).

The application of FRPs in biomedicine can be broadly grouped into hard tissue and soft tissue applications. Hard tissue applications comprised bone fracture repair, dental applications, and total hip, knee, ankle, and other joint replacements, whereas soft tissue applications cover connective as well as nonconnective tissue repair. Currently, single- and multiphase materials (composites) have been designed as scaffolds to support cell growth and then are used for in vivo replacement or reconstruction of hard and soft tissues. New additive manufacturing technologies can be applied for the development of innovative bioactive porous scaffold. Senatov et al. (2016) have investigated the low-cycle fatigue behavior of three-dimensional (3D)-printed PLA-based porous scaffolds.

FRP composites are currently being developed as alternatives to metals for bone repair, dental applications, and orthopedic implants, and their demand is increasing day by day. For resetting of damaged hard and soft tissues, different biomaterials are used. Silicon carbide (SiC), alumina ($Al_2O_3$), UHMWPE, Co−Cr alloy, hydroxyl apatite, stainless steel 316L, and Ti−6AL−4V alloy are the most common replacement materials in dental applications as well as bone fractures, such as hip, knee, or ankle joints (Tathe et al., 2010). Each material has properties of resorption, reactivity, and biocompatibility (Chen et al., 2010). Bioceramics also provide similar results, given a correct therapeutical indication and clinical application (Mardas et al., 2010). The biomedical applications of FRPs are summarized in Fig. 12.4.

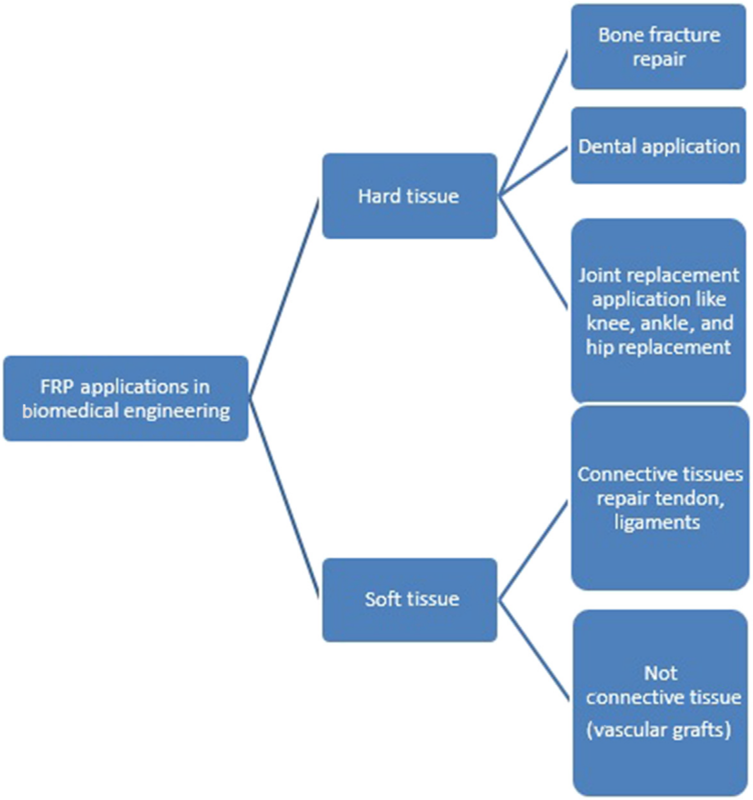



**FIGURE 12.4**

Applications of FRP in biomedical engineering. *FRP*, Fiber-reinforced polymer.

### 12.4.1 Hard tissue applications

In the last few decades, bone grafting procedures have become important for addressing bone deficiency in oral surgery and periodontology. Grafts may be derived in three ways: (1) autograft (from the patient's own body), (2) allograft (from human donors), and (3) xenograft (from animals) and sometimes from engineered materials. The main goal of bone tissue engineering is to maximize the resources from biological sciences as well as material engineering to optimize new bone regeneration. Bone morphogenetic protein combined with suitable biomaterials such as poly hydroxy acid polymers have been used for further application in bone tissue engineering (Yu et al., 2010). Composites, bioceramics, biopolymers, and metals are the most common engineered materials in hard tissue applications.

Chen et al. (2010) designed titanium mesh coral composite scaffolds for jaw reconstruction via engineered segmental bone grafts in a predetermined shape by seeding osteoblast precursor cells. Earlier, Ryan et al. (2008) used the same alloy to form porous titanium scaffolds with reproducible porosity, pore size, and interconnected pore networks. The scaffolds' porous characteristics were governed by a sacrificial wax template, fabricated using a commercial 3D printer. Powder metallurgy processes were employed to generate the titanium scaffolds by filling around the wax template with titanium slurry. 3D reconstruction enabled the main architectural parameters, such as pore size, interconnecting porosity, level of anisotropy, and level of structural disorder to be determined. Highly biocompatible bioceramics are formed by calcium sulfates or phosphates. It was found that the mineral component of mammalian teeth and bones is quite similar to a biomaterial called calcium orthophosphate, which is mostly applied in hard tissue engineering (Dorozhkin, 2010). They are nontoxic, biocompatible, and, most importantly, integrate into living tissue using the same processes as healthy bone. Moreover, calcium orthophosphates support osteoblast adhesion and proliferation. The use of FRP in biomedical implants and devices is illustrated by the following examples of structural applications.

#### *12.4.1.1 Bone fracture repair*

Bone fracture repair is used when a broken bone does not heal properly with casting or splinting alone. The skeletal system is made up of bones and teeth. Different bone types and shapes in the human body are illustrated in Figs. 12.5 and 12.6. One of the most important functions of bones in our body is to provide support and structure. Bones form a mechanism consisting of skeletal muscles, tendons, ligaments, and joints that function together to produce and transmit

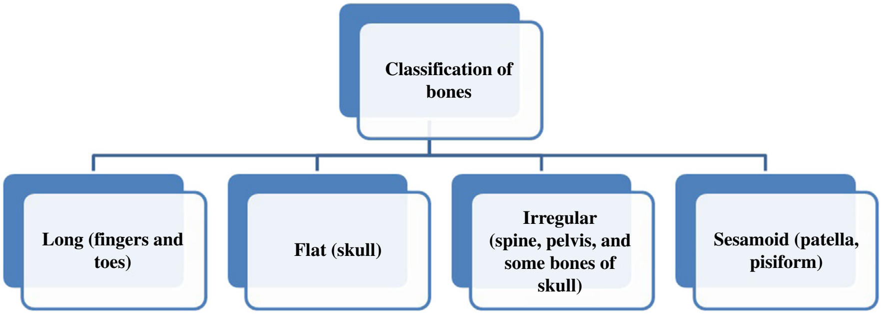



**FIGURE 12.5**

Various bones possessed by human body.

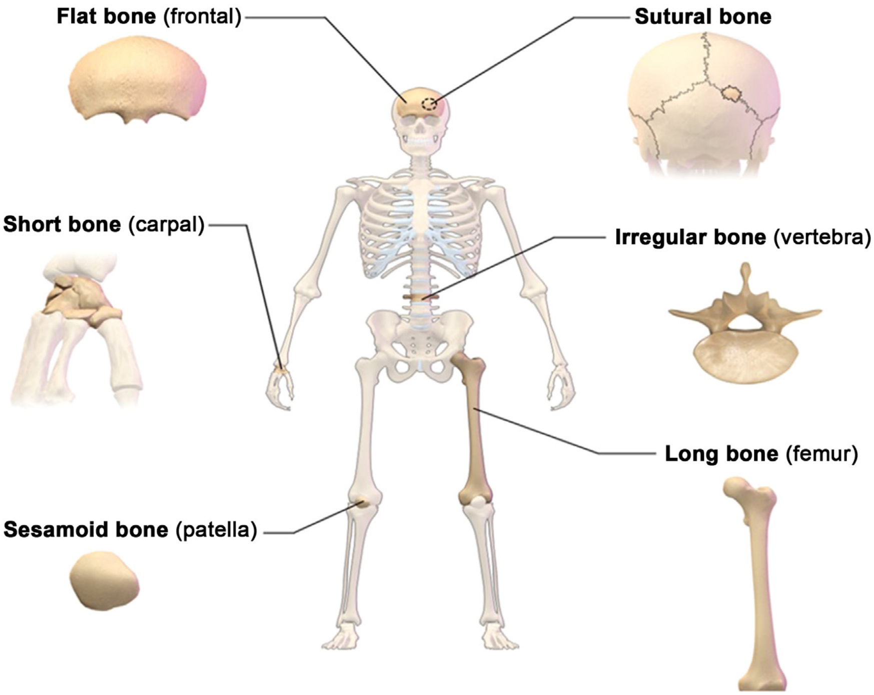



**FIGURE 12.6**

Classification of bones by shape.

forces, thus enabling the whole body to move in 3D space. The important properties of bone in human body include the following:

1. Bone is an anisotropic material and its properties, such as Young's modulus and modulus of rigidity change with direction along the object.
2. Density of bone is affected by the intensity of load applied to bone. High magnitude applied stress results in denser bone. However, density decrease leads to bone weakening if the applied stress is lower than the physiological load.
3. Mechanical strength such as tensile and shear strength of bone is poor specifically along longitudinal planes. Therefore bone may undergo different types of fractures depending on the crack size, morphology, position, and orientation when subjected to excessive loading condition.

Seventy percent of dry bone mass comprises high elastic modulus and hydroxyapatite and consequently is responsible for high stiffness of bones. The composition of bones is shown in Fig. 12.7. Low elastic modulus collagen is directed along the main stress direction. A very important characteristic of bone is remodeling in response to mechanical environment, thus causing the new structure to become appropriately adapted to the load condition. This can be explained

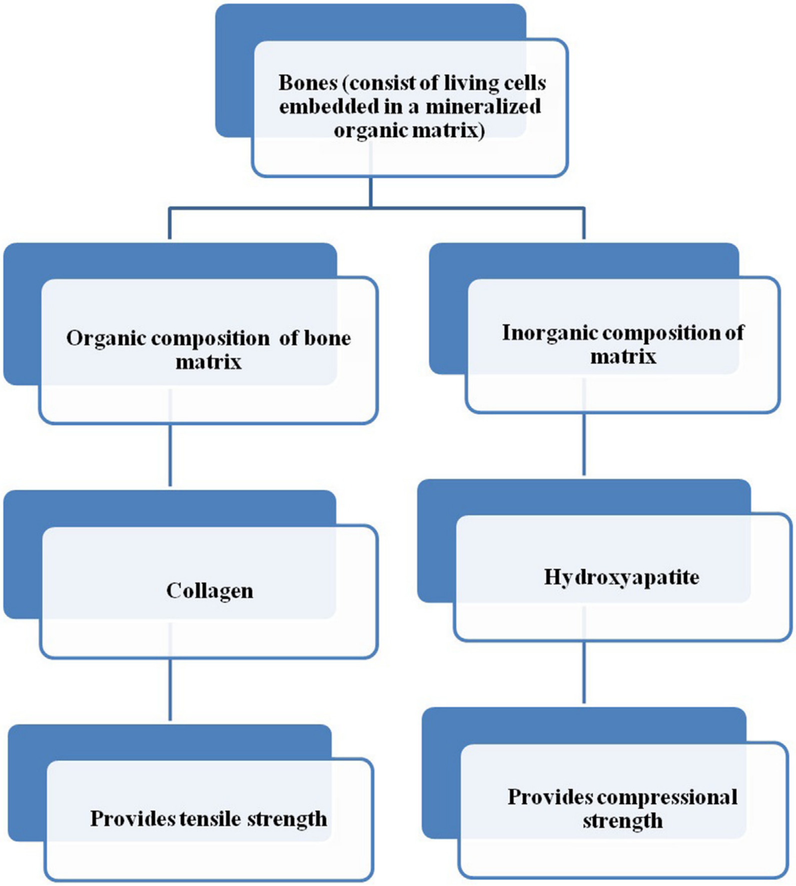



**FIGURE 12.7**

Bone composition.

by Wolf's law, which relates the internal structure and architecture of bones to external mechanical stimuli.

Bone fracture repair can be understood by grouping it into two types, external and internal fixation. In this section, some important aspects of both fixations are summarized. The fundamental necessity of fracture fixation is given in Fig. 12.8. Opening of fracture location in the case of external fixation is not required, whereas internal fixation requires opening of fracture location. To set a fracture the bone fragments are repositioned into their normal alignment. Bone fragments are held together splints, casts, braces, and external fixator system in external fixation, whereas wires, pins, screws, plates, and intramedullary nails are used in internal fixation. The most common parts in internal fixation are bone plates and screws. The implants used in internal and external fracture fixation are illustrated in Fig. 12.9.

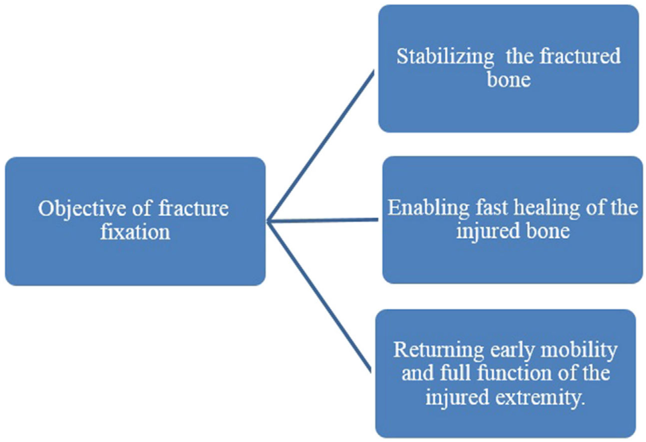



**FIGURE 12.8**

Main aspect of fracture fixation.

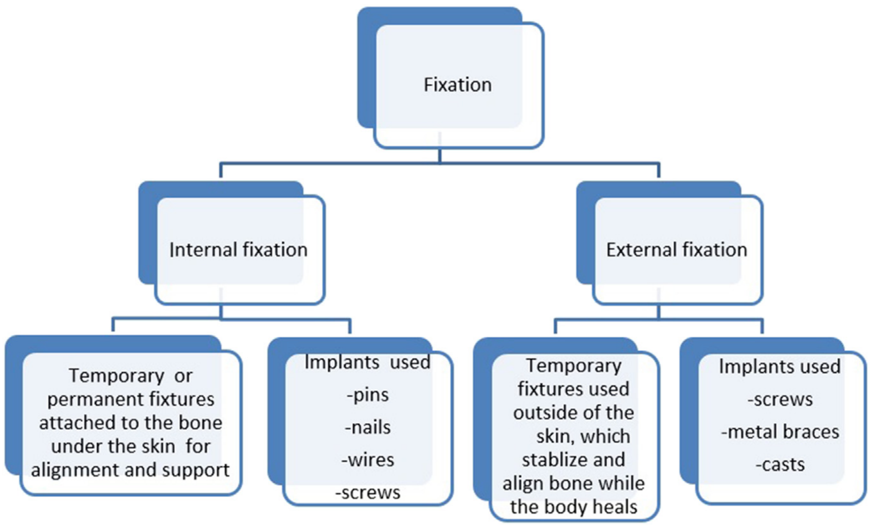
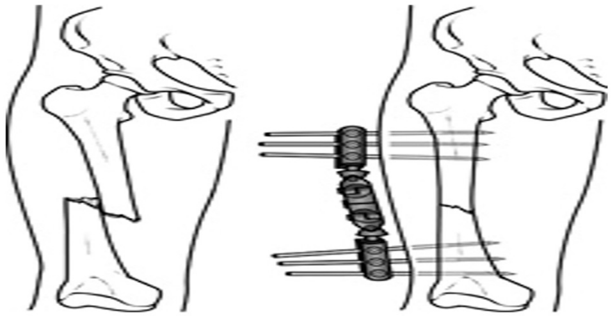



**FIGURE 12.9**

Implants used in internal and external fracture fixation.

## External fixation

Surgical treatment to fix bone and soft tissue at a distance from the injured or operative area is defined by external fixation. This type of fixation offers unhindered accessibility to appropriate soft tissue and relevant structures for initial assessment. Secondary intervention is also required to restore bone continuity.



(A) (B)

**FIGURE 12.10**

(A and B) External fixation holding the injured skin and muscles.

External fixation is often used to hold the bones together temporarily when the skin and muscles have been injured (Fig. 12.10A and B).

Various composite materials are applied for external applications. Composite materials such as cast materials and plaster bandages consisting of woven cotton fabrics and plaster of Paris matrix are used successfully to form splints, casts, and braces. In addition, cast materials, such as glass fibers, polyesters fibers, and water-activated PUs, are reinforcement materials used in external fixation. The use of metals such as stainless and titanium in bone repairing due to its biocompatibility properties is very common, but it causes unnecessary pain and inconveniences due to several surgeries required to remove these metals over time (Ho et al., 2011). Traditional materials such as stainless steel are also used for designing wires, but their heavy weight makes them less effective. CF or epoxy composite materials, on the other hand, possess characteristics such as lightweight, mechanical strength, and stiffness, which help in external fixation (Baidya et al., 2001).

### Internal fixation

During a surgical treatment, in the case of internal fixation, the bone fragments are first repositioned into their normal alignment and then held together using special implants, such as plates, screws, nails, wires, and intramedullary nails. These implants must be compatible with the human body and should not cause undesirable effects. The implants used for conventional internal fixation are made from stainless steel and titanium. Internal fixation allows shorter hospital stays, enables patients to return to function earlier, and reduces the incidence of nonunion (improper healing) and malunion (healing in improper position) of broken bones. These implants are fixed inside the body for a limited time only and removed after satisfactory healing of bone fracture. Detailed descriptions of internal fixation are given as follows.

*Bone plates*

The widely used method for rigid internal fixation of the fractured bone is plate and screw fixation as shown in Fig. 12.11A and B. Bone plates are also known as osteosynthesis plates. Traditional materials used for the construction of these plates are stainless steel, Cr–Co, and Ti alloy. The purpose of rigid fixation is to heal primary bone without the formation of external callus by providing high axial pressure, also called dynamic compressive, in the fragments of the bone. Certain difficulties were registered in rigid fixation, for example, it caused bone atrophy beneath the plate and produced a chance of refracture of bone after the removal of the plates. However, these problems can be minimized by using less rigid fixation plates whose mechanical properties are similar to those of bones. Polymers, such as PA and PTFE, and polyester were used in some cases but subsequently found unsuccessful because of low stiffness.

Several polymer composite materials grouped into different categories, such as nonresorbable, partially resorbable, and fully resorbable bone plates, have also been proposed (Hastings, 1993). Nonresorbable thermoset composites such as PEEK,CF,epoxy, and glass filled (GF) possessed high biocompatibility, radiation degradation, and hydrolysis resistance for implantation (Morrison et al., 1995). During the healing process the stress on the plate should decrease with time. This requirement can be met by using resorbable materials such as PLA and PGA as they resorb or degrade upon implantation into the body. Fully resorbable composites, that is, PLA fibers and calcium phosphate–based glass fibers have one advantage in that they eliminate the need for secondary surgery to remove the plate after healing. However, this type of surgery is necessary with metallic or nonresorbable composite implants. Further, the mechanical properties of resorbable materials

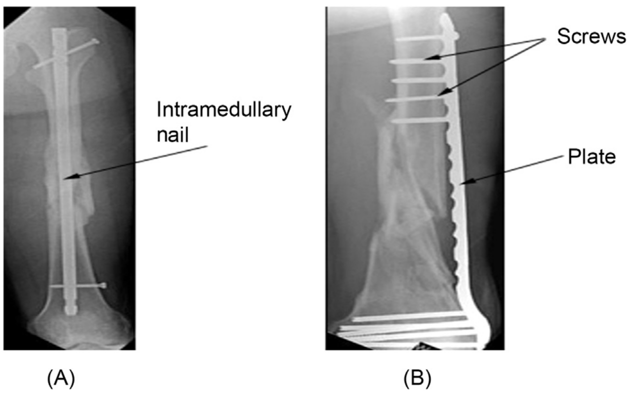



**FIGURE 12.11**

(A and B) Some important internal fixation.

could be improved by reinforcing them with a variety of nonresorbable materials including CFs. In this direction, one group of researchers developed unidirectional bioglass fiber-reinforced PLA composites with improved mechanical properties for a bone plate to heal weight-bearing long-bone fractures (Mehboob et al., 2016).

*Intramedullary nails*

The main use of intramedullary nails or rods is to fix long bones such as fracture of femoral neck or intertrochanteric bone fracture. A screw or friction fit approach is used to insert nails into the intramedullary cavity of the bone (Fig. 12.11A). Nails can be inserted through a small skin incision without opening the fracture site. The nail must be strong enough to bear the weight of the body without undergoing any bending in either flexural or torsion. Stainless steel and composite materials, for example, GF and PEEK are widely used for this purpose. These biocomposites possess good biocompatibility, high flexural strength, and elastic modulus close to bone.

#### 12.4.1.2 Dental applications

A dental subgingival implant is a fixture, surgically placed into the alveolar bone, which functions as an artificial root that can stabilize and support a fixed or removable prosthesis (Awad et al., 2014). The tooth (hardest substance in the human body) has two anatomical parts, crown and root, disarticulated by the gingival (gum). The crown is the visible part and covered with enamel, whereas the root is normally invisible and embedded in the jaw. The parts of the tooth and their specific characteristics are illustrated in Fig. 12.12. The tooth is nonhomogenous, unsymmetrical, and anisotropic in structure (Fig. 12.13) and may undergo varied amounts and types of forces during crushing and grinding during the chewing process (Darendeliler et al., 1992). Many dental treatments, such as cavity filling, bridges, crowns, root canal treatment, braces, dental implants, broken or knocked out tooth and teeth whitening, are mostly performed on human beings.

##### Dental restorative materials

Dental restorative materials are used to fill tooth cavities (carriers), mass discoloration (veneering), and sometimes to correct contour and alignment deficiencies. A large variety of biomaterials are used for these dental treatments. Two important categories of dental materials are direct and indirect (Table 12.4). Direct materials can be directly placed in the tooth cavity during a single appointment, while indirect materials are those that can be placed in or on the tooth after being used to fabricate restorations in the dental laboratory. Restorative materials should have the following characteristics for successful dental treatments:

1. It must have low viscosity that enables it to fill the cavity completely.
2. The thermal expansion coefficient must be similar to the dentine/enamel; otherwise, the stress produced due to mismatch may lead to leakage of saliva and bacteria at the interface margins.

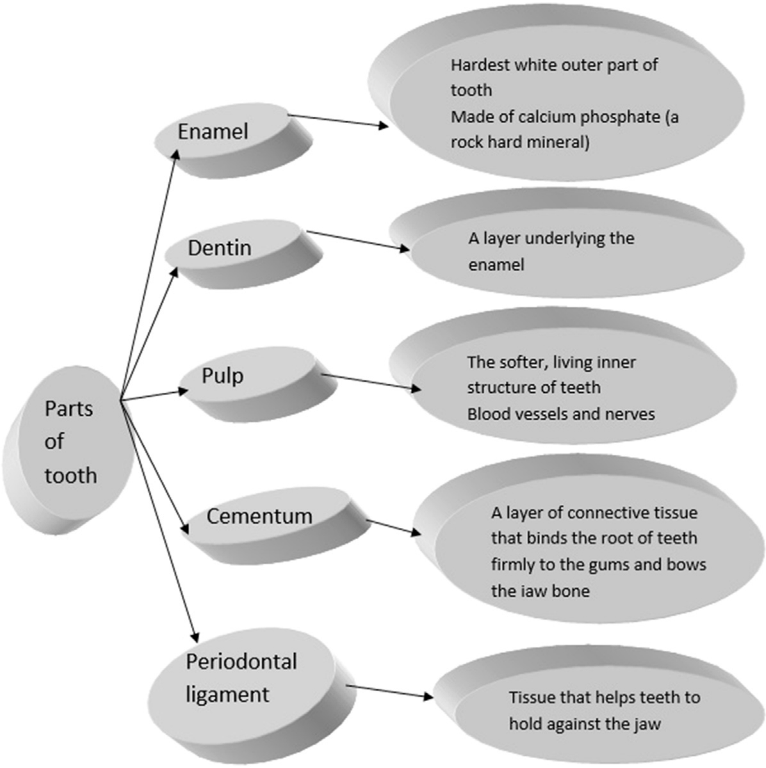



**FIGURE 12.12**

Parts of teeth along with their specific characteristics.

3. It should possess good resistance to creep wear and water absorption.
4. It must have controllable polymerization.
5. The radio opacity of the dental composite serve as posterior restorative material, hence should be radio opaque as the enamel.

## Fiber-reinforced polymer composite materials used in various dental applications

The implant materials, usually titanium and its alloys (Guo et al., 2012), zirconia (Liu et al., 2012), or FRCs (Zhang and Matinlinna, 2012), should be biocompatible (Mallineni et al., 2013) and possess suitable surface properties that induce bone formation around the implant. It should also have a suitable design, high hydrophilicity, and appropriate surface roughness.

Besides these materials, amalgam, gold, alumina, silicate cements, and acrylic resins are generally used for restoring decayed teeth in most dental treatments. Amalgam and gold are particularly suitable for the restoration of posterior teeth

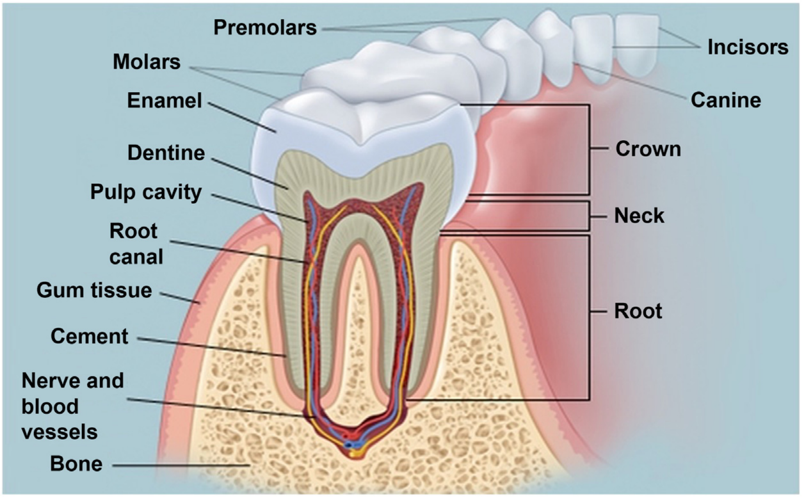



**FIGURE 12.13**

Teeth structure.

**Table 12.4** Main categories of restorative materials.

| Direct | Indirect |
|---|---|
| Amalgam | All ceramic (porcelain) |
| Resin-based composites (direct and indirect) | Metal ceramic |
| Glass ionomers | Cast gold (high noble) alloys |
| Resin-modified ionomers | Base metal (nonnoble) alloys |

but not suitable for anterior ones due to cosmetic issues and long-term toxicity of silver mercury amalgam. Acrylic resins and silicate cements are preferred for anterior teeth treatment purposes. However, they have short service life and tend to have clinical damage due to their weak mechanical properties. These materials are being replaced by dental composite resins to restore posterior and anterior teeth.

Dental composite resin consists of BIS–GIM [derived from the reaction of bis (4-hydroxyphenl) and glycidyl methacrylate] as the matrix polymer and quartz, barium glass, and colloidal silica as fillers. Inhibitors, such as butylated trioxytoluene, or 2,4,6-tri-*tert*-butylhenol, are used to prevent premature polymerization and low-viscosity liquids such as triethylene glycol dimethacrylate are used to lower the viscosity. Urethane dimethacrylate resin is also a commonly used dental composite resin. Similarly, glass fiber is extensively used as filler material due to its efficacy to impart high stiffness, strength, and good wear resistance to the dental composite resins (Kennedy et al., 1998). Moreover, the glass fibers minimize shrinkage during polymerization of the resin as well as variation between thermal expansion coefficients of the composite resin and the teeth. Silane-coupling agents are used to establish strong bonding between fillers and resin.

Dental implant surgery is a procedure that replaces damaged or missing teeth with artificial teeth that resemble and function like real ones. Rehabilitation of severely damaged or decayed teeth is possible with dental implants. A wide range of materials, such as metals (Co−Cr−Mo alloys, stainless steel, silver, Ti alloy, and platinum), ceramics (zirconia, alumina, glass, and carbon), polymers [UHMWPE, poly(methyl methacrylate) (PMMA), PTFE, PS, and PE PET], and composites (SiC/carbon and CF/carbon) are being used in various types of dental implants (Ratnev et al., 1996). The high biocompatibility of Ti and its alloys has resulted in their preferential use over other alloy systems in the medical and dentistry fields (Henriques, 2010). Dental implants must be able to withstand significant and varying amounts of force applied during mastication. Compared to metals and ceramics, these composite materials in the desired requirements to be used as dental implant materials by offering high or sufficient and superior fatigue properties (Jancar et al., 1993). GF/polycarbonates, GF/nylon/GF/PP, and GF/PMMA are used to fabricate arch wires due to their certain specific properties such as aesthetics, easy forming in the clinic, and the possibility of varying stiffness without component dimensions (Zufall et al., 1998). Some composite materials, such as CF/PMMA, polyvinylidene fluoride resin/PMMA, UHMWPE/PMMA (Davy et al., 1998), and GF/PMMA (Miettinen and Vallittu, 1997), are used for bridge, which is a partial denture (false teeth) used to replace one or more damaged teeth completely.

#### 12.4.1.3 Joint replacement applications

Joint replacement is a common orthopedic surgery used to improve the quality of life of patients suffering from arthritis. Joints usually undergo osteoarthritis, which is one of the most common joint diseases in the world and may lead to degeneration of joints and adjacent structures. The disease adversely affects the performance of joints' ability to function and move. Moreover, osteoarthritis results in worn-out surfaces that cause joint pain and stiffness. Joint replacement surgery is considered to be very effective for the treatment of damaged joints in which the damaged surface is replaced with artificial joints. Artificial joints are permanently fixed within the body. There are many joints in the human body, such as hip, elbow, shoulder, and knee (called synovial joints), which allow free movement and enable the body to do various daily life activities. The structure of a synovial joint shows two opposing articulating bones surrounded by a very thin protecting layer known as cartilage and lubricated by elastic−viscous synovial fluid. The fluid mainly consists of water HA and high-molecular-weight mucopolysaccharides.

A number of artificial joints have been designed and used to replace damaged joints in the body. The two most common types of artificial joints are total hip replacement (THR) and total knee replacement (TKR). The hip and knee joint structures are reinforced and stabilized with ligaments and tendons (Vrahas et al., 2004; Vanputte et al., 2010).

#### 12.4.1.4 Total hip replacement

THR is a very common surgical procedure performed to replace the damaged part of the hip joint with an artificial joint. The weight of the body, both in dynamic and static condition, is supported by the hip joint, which is the largest weight-bearing joint in the body (Vanputte et al., 2010). The hip joint mainly consists of three components: (1) femoral stem, (2) femoral head, and (3) acetabular component. The femoral head is designed to provide joint articulation as it fits into the acetabular cup and femoral stem (also called the femoral shaft) and tapered shape is to be fixed into a reamed medullary canal of the femur geometry of acetabular cups.

Osteoarthritis is the most common cause of arthroplasty or total joint replacement. Developments in biomaterials and implant design technology have offered better joint replacement options for patients suffering from osteoarthritis. Women are the most likely to suffer from osteoarthritis of all joints (Sun, 2010; Zhang and Jordan, 2010).

##### Total hip joint replacement materials

To be used for hip joint replacement, materials must possess important mechanical properties, such as high compression, bending and tensile strength, fracture toughness, wear resistance at sliding surface, and fatigue resistance under cycle loading. Co−Cr alloy has been used to design acetabular cups, but due to the friction and wear associated with it, polymers are now preferred. PTFE has also been used to fabricate acetabular components due to its high thermal and chemical stability, lowest coefficient of friction, and the quality of being inert in the body, but investigations have shown that it suffers excessively high wear and distortion caused by its poor mechanical properties, such as low compressive stiffness and strength. Acetabular cup components made of UHMWPE may also undergo creep deformation, plastic distortion, and high wear or erosion though satisfactory results were obtained for short-term applications. A modification of UHMWPE with CFs provides improved creep resistance, stiffness, and strength, and has been proposed by researchers for long-term applications.

The mismatch of stiffness of the femur bone and the prosthesis is one important issue with THR applications. Artificial hip stems made of metal alloys are at least five to six times stiffer than bone (Vanputte et al., 2010), hence cause disadvantages due to stiffness mismatch. First, the remodeling process of bones is affected by unphysiological stress caused by stiffness mismatch and second, bone resorption, and eventual aseptic loosening of the prosthesis.

It has been acknowledged that these problems can be overcome by proper prosthesis design and selecting a proper material with low stiffness and mechanical properties similar to that of bones. In this regard, composite polymer materials have been found to be more suitable than metals for implants. Composites provide certain advantages over conventional implants such as better strength and more flexibility than metals. In addition, in such composites, prosthesis mechanical properties such as strength and modulus can be altered without affecting stiffness.

Fixation between the bone and the components of the total hip arthroplasty can be achieved with cemented or cementless fixation methods. Cemented fixation, that is, mechanical interlocking, is achieved by press-fitting the implant using bone cement as a grouting agent. Cementless fixation may be achieved either by biological fixation (i.e., bone growth into the rough or porous surface structure) or by direct chemical bonding (e.g., using hydroxyapatite coating) between implant and bone. It was observed that in 83%–97% cases, the survival rate of metallic femoral stem is minimum 15 years by cementless press-fit fixation.

Materials used in joint replacement must fulfill strict requirements for biocompatibility and mechanical properties under the corrosive environment of the human body. Implant materials must be nontoxic, nonirritant, nonallergenic, and noncarcinogenic. Moreover, an integrated approach of osteoconduction, osteoinduction, and osseointegration is beneficial to improve the functionality of implants due to positive reactions between host bone and biomaterials.

Panayotov et al. (2016) used CF/PEEK as implant material for hip joint applications (Fig. 12.14).

CF/UHMWPE, CF/epoxy, and CF/PEEK are some examples of composite polymers. These biomaterials are discussed in detail as follows:

1. *Metallic components*

   The major weight-bearing components in joint replacements are titanium–aluminum–vanadium (Ti–6Al–4V), titanium (Ti) and its alloys, cobalt–chromium (Co–Cr) and its alloys, and cobalt–chromium–molybdenum (Co–Cr–Mo).

**FIGURE 12.14**

Carbon fiber/polyetheretherketone composite stem for total hip replacement.

As joint replacement implants, metallic implants possess high strength, high fracture toughness, hardness, corrosion resistance, and biocompatibility. However, the elastic modulus of the conventional metallic implant materials is very high compared with the elastic modulus of bone. Cobalt alloys are suitable materials for artificial articulation surfaces due to their better wear resistance compared with titanium-based alloys. However, the foremost limitation with cobalt- and chromium-based implants is toxicity by ions released from these metals that further lead to allergic reactions (Revell, 2008).

2. *Hydroxyapatite coatings*

   Hydroxyapatite is a naturally occurring mineral, and its chemical composition is similar to the inorganic component of bone that is formed from carbonated hydroxyapatite. It is a reactive and osteoconductive ceramic with excellent biocompatibility. Hydroxyapatite coating of metallic implants in cementless joint arthroplasty allows a direct, strong chemical bonding between the implant and bone in order to enhance proper fixation.

3. *Bearing couples*

   Recent research has been focusing on use of alternative bearing couples for knee replacement which demonstrate lesser friction rate as well as lower wear rates. In knee arthroplasty, metalon—PE-bearing couple is the most dominant option, although ceramicon—PE option is under reevaluation (Heimke et al., 2002). The main bearing couples used in knee arthroplasty are ceramicon—PE and metalon—PE, which show low friction and wear rates as well as good biocompatibility (Heimke et al., 2002).

4. *Polyethylene*

   UHMWPE is commonly used for orthopedic implants due to high mechanical strength and biocompatibility with improved sliding properties of PE. However, these implants have problems, such as loosening of the implant, osteolysis, and foreign body reactions. A few researchers have reported that some factors such as, malalignment of joint replacement components, high physical activity, obesity, and probability for fractures on PE surface, have an effect on increased probability for fractures and stress—strain distribution (Revell, 2008; Oral and Muratoglu et al., 2010).

5. *Metal-on-metal*

   All metal-on-metal joints are cobalt-based alloys and are preferred over conventional metal-on-PE bearing surfaces for designing a hip prosthesis matching the normal dimensions of the hip (Revell, 2008). Metal-on-metal bearing surface may be an option for young and active patients with hip osteoarthritis. However, these potentially toxic metal ions, released by corrosion, are eliminated from the body by the kidneys, and it has been recommended that patients with chronic renal failure should not have metal-on-metal bearing surfaces in their total hip prosthesis. However, the toxic effect of chromium can be reduced by applying ceramic-on-metal rather than metal-on-metal bearing surfaces (Triclot, 2011).

6. *Ceramic-on-ceramic*

   Aluminum oxide ($Al_2O_3$) and zirconium oxide ($ZrO_2$) are the most widely used ceramics on bearing surfaces. Ceramic-on-ceramic bearing couples may be an option especially for young and active patients. The complete catastrophic failure of the implant is one critical limitation of bearing couples due to one single flaw in the structure (Hannouche et al., 2011).

#### 12.4.1.5 Total knee replacement

The knee joint has a more complicated structure than a hip joint. The basic structure of TKR is made up of the femoral and tibial components. Two articulations are found in TKR: one is in between the femur and the tibia and the other between the femur and the patella. The knee joint has a pivotal joint that supports flexion and extension as well as slight medial and lateral rotation.

There are two types of the knee joint replacement, total and unicondylar or half replacement. The types of TKRs are nonconstrained, semiconstrained, and constrained knee replacements.

##### Total knee joint replacement materials

Co–Cr and Ti alloys are generally used to design femoral components (Walker and Blumm, 1997). The material used for the tibial component is normally UHMWPE polymer with a metallic tibial tray. UHMWPE tends to cold deformation and causes sinking of prosthesis. To overcome this problem, CFs have been used to reinforce UHMWPE, which reduced cold flow (creep deformation) considerably and improved its mechanical properties such as stiffness, tensile yield strength, creep resistance, and fatigue strength (Silverton et al., 1996).

### 12.4.2 Soft tissue applications

Soft tissues connect, support, or surround other structures and organs of the body, unlike hard tissue such as bone. Soft tissue includes tendons, ligaments, fascia, skin, fibrous tissues, fat, and synovial membranes (which are connective tissue), and muscles, nerves, and blood vessels (which are not connective tissue).

Soft tissue reconstruction based on autologous tissue grafts and synthetic implants has many problems due to implant rupture or contracture and tissue resorption. Therefore natural biomaterials by using cells loaded in biocompatible scaffolds, mesenchyme stem cells (adult stem cells) or fibroblasts, adipocytes, and keratinocytes (adult cells) with combination of synthetic materials are mostly applied for soft tissue reconstruction.

Congenital, developmental, or acquired defects are usually found in soft tissues, and different types of implants are used in the surgery to save tissue from these defects. There are various types of functions performed by soft tissue implants such as to fill the space from some defects and enclose, store, isolate, or transport fluids in the body. They also give mechanical support and serve as a scaffold for tissue growth (Ramakrishna et al., 2001).

#### 12.4.2.1 Single-component scaffolds

Collagen is a family of extracellular matrix (ECM) proteins occurring as a major constituent of connective tissue, giving it strength and flexibility. Currently, collagen-based scaffolds are predominantly used as dermal substitutes in the form of hydrogels due to physiological interactions with cells as well as their biocompatible nature (Hekary et al., 2010).

Fibrin is a protein involved in the clotting of blood and formed by polymerization of fibrinogen in the presence of thrombin. In the field of regenerative medicine, fibrin glue has been widely used as a biological tissue adhesive. Fibrin glue was used as an alternative to staples in burn patients requiring wound excision and skin grafting (Foster et al., 2008). As a main constituent of ECM, HA is widely used in clinical application as its less antigenic nature helps cell proliferation and differentiation in different in vivo and in vitro studies (Solchaga et al., 1999).

#### 12.4.2.2 Composite scaffolds

As a replacement of single-component scaffolds, Judith et al. (2010) developed biocomposites in tissue engineering. He designed acellular provisional matrix aimed to copy the ECM of a wound site and studied in vivo dermal regeneration. He prepared excisions of $1.5 \times 1.5$ cm on the back of female albino rats and further cured the wounds by platelet-derived growth factor (PDGF)-incorporated collagen-chitosan or PDGF-incorporated chitosan. Chitosan composed of *N*-acetyl glucosamine and glucosamine is the structural element in the exoskeleton of crustaceans (Weinstein-Oppenheimer et al., 2010). Some of the important implants used in soft tissue surgery are discussed in the following sections.

#### 12.4.2.3 Bulk space fillers

Bulk space fillers are used for the treatment of cosmetic defects, atrophy, or hypoplasty, particularly in the head and neck regions (McGranth, 1992). Some of the materials used in these applications are SR and PE. In addition, bulk space fillers are also used for the replacement of articular cartilage damaged by osteoarthritis. Subsequently, it has been reported that composite materials made of PET or PTFE and PU are more suitable for this type of treatment. Moreover, they may reduce the cartilage degeneration. Woven CF fabrics and their composites were also found useful for the treatment of cartilage defects (Pongor et al., 1992).

#### 12.4.2.4 Encapsulates and carriers

Wound dressing is one of the important treatments as it prevents loss of electrolyte, fluids and other biomolecules. Wound dressing must be permeable so that passage of discharge through the pores or cuts can take place, and it must have ability to adhere to the wound surface and to peel from the skin without affecting the new tissues.

Materials used in various types of skin dressing are woven fabrics or porous layers of resorbable polymer such as collagen, chitin, and PLLA. Synthetic polymers and cultured cells are combined to form composites to be used in hybrid skin dressing.

#### 12.4.2.5 Ureter prosthesis

Materials, such as polyvinylchloride, PE, nylon, and PTFE, can be used to design ureter prosthesis. They are suitable only for short-term applications due to the difficulty of joining a fluid-tight prosthesis to the living system, problem of microbial infections, and blockage of passage by calcification deposits from urine.

Prosthesis made of polyester fiber-reinforced glycol methacrylate gel with a fabric backing is considered suitable. Fabric backing has certain advantages and provides easy attachment of a prosthesis fixed on to the mucous membrane without causing any irritation. In addition to this, it has hydrophilic nature, which facilitates the establishment of a clear inner space.

#### 12.4.2.6 Catheters

Catheters (tubes) are predominantly used to control fluids, such as nutrients, isotonic, saline, glucose, medications, blood and blood products, and to obtain data artery pressure, gases, and for collecting blood samples for analysis in remote regions of the human body. The material used to fabricate catheter tubes is PU because of its flexibility and ability to easily fabricate into a wide range of sizes. Improved tear strength and decrease in wettability is achieved by reinforcing SR with silica particles.

#### 12.4.2.7 Functional load-carrying and supporting implants

##### Tendons and ligaments

Load-bearing soft tissues implants are artificial tendons and ligaments. Tendons are strong fibrous tissue that appear from a muscle to the periosteum of the bone. The main function of ligaments and tendons is to hold the bones of a joint thus maintaining their stability and movement. They are particularly composite materials made of undulated collagen fiber bundles oriented along the length and submerged in a complex base substance comprised elastic and mucopolysaccharide hydrogel (Pradas and Calleja, 1991). Ligament is a connective tissue that connects bones in the vicinity of very synovial joints, and tendons are strong fibrous tissues that appear from a muscle to the periosteum of the bone. Damaged tendons take a very long time to regenerate fully due to their poor regenerative capacity. The selection of biomaterials plays an important role in repair of tendons or ligaments. The selection depends on its flexibility as the natural tissue and regeneration of the same mechanical and damping properties and large extensibility without undergoing any permanent deformation.

There are various ways to use biomaterials in tendon healing such as to replace the tendon, to hold a damaged tendon in proper alignment, or to form a new sheath followed by two surgical treatments. First, the operation procedure includes the replacement of tendon by a gliding implant to facilitate the formation of a new tendon sheath. In the second operation, gliding implant is replaced by a tendon graft (Ramakrishna et al., 2001). Materials used to make synthetic implants are PP, UHMWPE, PET, PTFE, PU, Kelvar 49, carbon, and reconstituted collagen fibers or braided forms (Marois and Roy, 1993). These synthetic prostheses have some limitations as they are not suitable for long-term applications because their strength is degraded due to wear and abrasion. Second, abrasion particulate matter is generated against rough bony surface, which may lead to synovitis. These limitations can be overcome by polymer coating of the prosthesis. These polymers are SR, poly 2-hydroxyethyl methacrylate (PHEMA), and PLA. Combination of polymethylacrylate or polyethylacrylate with crimpled Kelvar-49 fibers was very effective at maintaining stress−strain behavior of natural ligaments (Iannace et al., 1995). Ligament prosthesis made by reinforcing a hydrogel matrix (PHEMA) with helically wound rigid PET fibers may reproduce both static and dynamic behavior of natural ligament.

### Vascular grafts

Vascular grafting is the use of transplanted or prosthesis blood vessels in surgical procedures to replace segments of the natural cardiovascular system, which are diseased or blocked. The structure of arterial blood vessels is very complex, consisting of collagen muscles, endothelium, and anisotropic in nature. Replacement of the aorta section infected by an aneurysm is an example of this.

Materials widely used for vascular grafts are woven or knitted fabric tubes of PET materials with extruded porous wall tubes of PTFE and PU (Ramakrishna et al., 2001). The most important property possessed by graft is porosity. A certain amount of porosity supports tissues to grow and to be accepted by host tissues, but the higher porosity may lead to leakage of blood. They must possess good dilation and creep resistance because they undergo static pressure and repeated stress of pulsation in applications. Vascular grafts made up of PET are effectively used to replace large diameter blood vessels (12−38 mm diameters), whereas PTFE is widely used for medium diameter (6−12 mm) vascular grafts. Some composite grafts made of PU fibers in a matrix of PU and PELA (block copolymer of lactic acid and PE glycol) have been developed for vascular graft applications (Gershon et al., 1992). Composite vascular grafts have many advantages such as prevention of the loss of blood, growth of granulation tissues, and generation of pores during healing (Ramakrishna, 1997).

As discussed earlier, all biomaterials used in various applications of biomedical engineering are summarized in Fig. 12.15 (Ramakrishna et al., 2001).

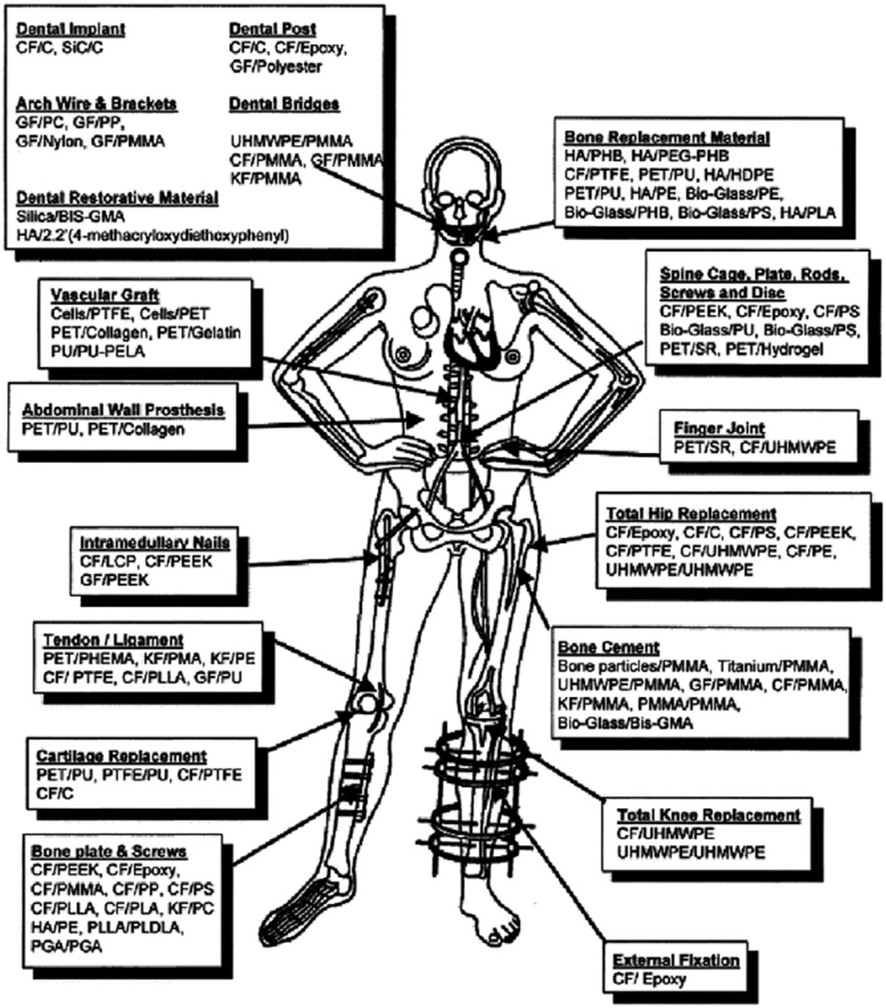



**FIGURE 12.15**

Various applications of biomedical engineering (Ramakrishna et al., 2001). *BIS-GMA*, Bis-phenol A glycidyl methacrylate; *C*, carbon; *CF*, carbon fibers; *HA*, hydroxyapatite; *KF*, Kevlar fibers; *LCP*, liquid crystalline polymer; *PC*, polycarbonate; *PEA*, polyethylacrylate; *PEEK*, polyetheretherketone; *PEG*, polyethylene glycol; *PELA*, block copolymer of lactic acid and PE glycol; *PET*, polyethyleneterephthalate; *PGA*, polyglycolica acid; *PHB*, polyhydroxybutyrate; *PHEMA*, poly 2-hydroxyethyl methacrylate; *PLDLA*, poly(L-DL-lactide); *PLLA*, poly(L-lactic acid); *PMA*, polymethylacrylate; *PMMA*, polymethyl methacrylate; *PP*, polypropylene; *PS*, polysulfone; *PTFE*, polytetrafluoroethylene; *PU*, polyurethane; *SR*, silicone rubber; *UHMWPE*, ultrahigh-molecular-weight polyethylene.

## 12.5 Limitations and future aspects of fiber-reinforced polymers in biomedical engineering

Biocomposites are used in many biomedical applications, such as tissue engineering, orthopedics, drug delivery, and gene delivery. FRPs offer low elastic modulus as well as high strength to be successfully used for several orthopedic and other applications. To advance the mechanical features and biological functions and to deliver special implants, researchers are trying to use many reinforcement components of composite materials. Although most biomaterials and medical devices perform satisfactorily, there is still probability of failure as man-made constructs are never perfect. Also, all humans differ in genetics, gender, body chemistry, living environment, and physical activity. Furthermore, physicians also differ in their "talent" for implanting devices. Researchers have reported many limitations regarding biomedical composites. The presence of elements, such as Ni, Cr, and Co in both stainless steel and Co−Cr alloys, has shown toxic effects (Yang et al., 2014). Ni toxicity leads to dermatitis, whereas Al and V ions in Ti alloys have been found to cause Alzheimer's disease, osteomalacia, and neuropathy. The presence of Co has also been reported to have carcinogenic effects (McGregor et al., 2000). Metallic implants, such as titanium, ceramics, medical-grade titanium, and other metal alloys have been used widely in a lot of orthopedic applications. However, the disadvantages of metal implants are corrosion and release of ions, so new orthopedic materials such as composites, which have a closer density to natural bone, are needed (Deshmukh and Kulkarni, 2015).

To overcome the problems as degradation, damage, and deformation of traditional materials, a new class of material with self-healing behavior (i.e., autonomic structure and functionality recovery) is needed in biomedical applications (Chen et al., 2018). Fiber tubes may be filled with a healing agent to prepare self-healing FRP-based composites (Hofstatter et al., 2017). Many challenges are involved with these self-healing strategies such as validation for application in real structures, methods of healing assessment, as well as values of healing quantification. Belli et al. (2014) articulated self cure or light activated polymerizable matrices, typically containing one or more monomers, such as bis-phenol-A-diglycidyl dimethacrylate, triethylene glycol dimethacrylate, and urethane dimethacrylate.

The use of FRPs in biomedical engineering can be improved by the selection of appropriate biocomposites, so that common problems of this technology such as implant mechanical failure, adverse effects in the organic system, stress shielding effect, loosening, releasing noncompatible metallic ions, allergic reactions, and revision surgery can be overcome. New methods and manufacturing processes are required to produce newer and better FRP composites for substituting diseased, damaged, or worn-out body parts. For composites to become competitive with metals, it is also important to reduce cost along with required guaranteed durability, maintainability, and reliability (Bhatt, 2018). The engineering of tissues and organs remains an exciting and dynamic field that requires a collaborative multidisciplinary approach (Wong et al., 2010).

## 12.6 Conclusion

With the advancement of composite science and technology, FRPs have been investigated for the implant devices in different areas of biomedical engineering, such as joint replacement, THR, bone plate and bone cement, dental implants for tooth fixation, heart valves, contact lenses, vascular grafts, dialysis membrane, catheters, pacemakers, leads, and blood vessel prosthesis. In addition, FRPs are considered new advanced materials to replace metal implants. Efforts have been put forth by researchers in developing specifically engineered polymer-based, high-strength FRCs to provide longer service to patients with improved light-weight performance.

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