Chapter 1

Introductory Chapter: Background on Composite Materials

Mohamed M. Dawoud and Hosam M. Saleh

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.80960

1. Overview

"Composite materials" also referred to as "composition materials" or briefly "composites," as the most frequently used term, display materials consisting of two or more components; these two components display considerably diverse physical and/or chemical characteristics. Merging the two or more basic materials creates a new material with features different from the single constituents. Because the individual components remain distinct and separate within the final material structure, composites have to be strictly differentiated from material mixtures and solutions of solids.

The new composite material often displays many beneficial characteristics; in many cases, composites are stronger, of lower density, or less costly in comparison to established materials. Commonly, composites consist of two or more different components forming regions sufficiently large to be considered as continua; the basic components are usually strongly fused at the interface. A variety of both natural and synthetic materials confirm to this picture, such as mortar and concrete, reinforced rubber, alloys, polymers containing fillers, aligned and chopped fiber composites, porous and cracked media, polycrystalline (metal) aggregates, and others [1].

Composite materials are composed of individual basic materials, which are referred to as so-called constituent materials. Two main categories of constituent materials are distinguished: the matrix (aka "binder") and the reinforcement. At least one representative from each category is needed to create a composite. The matrix phase embeds, surrounds, and supports the reinforcements by preserving their relative locations. The reinforcements contribute their specific physical and mechanical assets, thus enhancing the properties of the matrix. The achieved synergism between the two phases generates material properties not observed for the individual constituent materials, while the unlimited number of binders and reinforcements enables the designer to develop optimum combinations, thus creating tailor-made composites [2].

Well-known examples of composite materials are as follows:

- Lignocellulosic (straw) in sludge
- Wood (cellulose fibers embedded in hemicellulose and the binder lignin)
- Bones (soft protein collagen combined with the hard mineral apatite)
- Pearlite (ferrite combined with cementite) [3, 4]

Classification of composite materials occurs at two different levels:

- The first criterion of classification is based on the matrix (binder) constituent. The main composite families encompass organic matrix composites (OMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs). The term OMC generally refers to two classes of composites, namely, polymer matrix composites (PMCs) and carbon matrix composites, which are usually called carbon-carbon composites.
- The second classification criterion refers to the reinforcement phases; here, fiber-reinforced composites (FRCs), laminar composites, or particulate composites are distinguished. FRC can be further separated into those containing discontinuous or continuous fibers, respectively, as reinforcements.
- FRC consists of fibers surrounded by matrix materials. Such composites are considered as discontinuous fiber composites or short fiber composites, if the composite properties are dependent on the fiber length. However, when the fiber length is like that, that any further increase in length does not result in further increase in the composite's elastic modulus, the composite is regarded as "continuous fiber reinforced." Fibers are generally small in diameter, and, when pressed axially, they easily twist, although they normally have proficient tensile properties. Consequently, these fibers need to be reinforced to prevent bending and buckling of the individual fibers.
- Laminar composites consist of material layers stacked together by the matrix; sandwich structures are examples for this composite category.
- Particulate composites constitute particles distributed or embedded in a binding matrix; the particles can be flakes or in powdered. For this category, concrete and wood particle boards are well-known examples [5].

A range of other classifications of composite materials exist as follows:

1. Classification according to the type of matrix materials:
   - Metal matrix composites (MMCs)

http://dx.doi.org/10.5772/intechopen.80960

Metal fibers are generally of low costs but have a relatively high specific mass. They are applied for reinforcement of metal matrices. Because of their high density, they are not highly demanded. The main function in preparation of the metal-metal composite is enabled by the high fiber-matrix compatibility. Carbon steel fibers are used for reinforcement of metal matrices to resist temperatures up to 300°C. To reinforce metal matrices to withstand even higher temperatures, fibers made of heat resistant metals, such as tungsten or molybdenum, are applied. Some of the most commonly used fibers are listed below:

- Steel: often containing strengthening aluminum alloys.
- Tungsten: used to strengthen heat resistant materials; drawback: they are extremely heavy.
- Boric: very light, yet rigid and solid; the production is not trivial. As typical representative, boric fibers should be mentioned, in which a boron layer is attached on the surface of a thin tungsten wire by chemical deposition of BCl_3 vapor; its surface is first protected against oxidation and boron diffusion into the matrix by attaching a thin SiC layer.

◦ Inorganic nonmetallic matrix composite materials.

◦ Polymer matrix composites (PMCs).

These polymers display ideal matrix materials, because they are conveniently processed, are of low density, and display desirable mechanical features. Consequently, high-temperature-resistant polymeric resins are widely used in aeronautics [6].

Thermosets and thermoplastics are two major types of polymers. Thermosets are characterized by a well-bonded 3D-molecular structure built up after curing. These materials decompose instead of melting at elevated temperature. Simply altering the resin's basic composition is sufficient to change the conditions appropriate for curing and to determine other properties. In addition, they can be retained in a partially cured condition over extended periods. Moreover, thermosets are of high flexibility. Thus, they are highly suitable as matrix bases for FRC used for advanced applications. Thermosets are widely used to generate chopped fiber composites, especially when using a premixed or molding compound with fibers of specific quality and aspect ratio as starting material, as it is the case for epoxy, polymer, and phenolic polyamide resins. Thermoplastics have one- or two-dimensional molecular structure; they melt at elevated temperature and typically exhibit exaggerated melting points. As an additional advantage, their softening at elevated temperature is reversible; hence, their original properties can be restored by cooling; this facilitates applications of established compression techniques used to produce molded compounds. Currently, resins reinforced with thermoplastics constitute a steadily emerging class of composites. A lot of R&D efforts in this area nowadays are dedicated toward improving the basic properties of the resins and toward extracting the highest possible functional advantages from them for defined applications. This includes endeavors to substitute precarious metals in die-casting processes. In crystalline thermoplastics, the reinforcement considerably changes the morphology, stimulating the reinforcement to allow nucleation.

Whether crystalline or amorphous, these resins are able to change their creep properties over an extensive temperature range. However, this temperature range includes the point where usage of resins is impaired, and reinforcement in such systems can rise the failure load and their creep resistance.

Ceramic matrix composites (CMCs) and carbon-based composite materials like C/C composite materials are the best described representatives of inorganic nonmetallic matrix composites. Polymer matrix composite materials are divided into thermosetting resin-based composite materials and thermoplastic resin-based composite materials; moreover, they encompass one component polymer matrix composites and polymer blends matrix composites [7, 8].

2. Classification according to the nature of the dispersed phase:

- Continuous fiber-reinforced composites
- Fibrous fabric (textile), woven-reinforced composites
- Sheet-reinforced composites
- Very short fiber (“whiskers”)-reinforced composites
- Particle-reinforced composites
- Nanoparticle-reinforced composites

3. Classification according to the type of reinforcing fibers:

- Carbon and graphite fiber composites: typical characteristics of these carbon and graphite fibers:
  - Ten times more rigid and only half the density (1.8–2 g cm^{-3}, comprises 90–95% pure carbon) in comparison to glass fibers.
  - Elongation at break is lower than observed for glass fibers.
  - Lower tensile strength at room temperature than for glass or aramid fibers; tensile strength does not decrease with temperature up to 1000°C.
  - Excellent thermal performance if oxidation-protected, stable and chemically inert up to 1000°C and when oxidation-protected: stability even up to 2000°C.
  - Minimal thermal expansion, sometimes even thermal contraction.
  - Drastically higher fatigue resistance than glass.
  - Electrical conductive.
  - A hundred times more expensive than glass.
  - High anisotropy.
  - Frequently poor adhesion to the matrix; therefore, surface modification is needed. The fibers can contain amounts of graphite, which differentiates them into carbon fiber composites, which contain predominantly amorphous carbon, and graphite fiber composites, which are characterized by a predominance of crystalline graphite.

http://dx.doi.org/10.5772/intechopen.80960

- Preparation modes:
- Polymer pyrolysis: the currently most frequently used method; resorts to synthetic polymers like polyacrylonitrile (PAN) or to natural polymers.
- Hydrocarbon pyrolysis: even production of nanofibers is possible.
- Evaporation from the arc discharge between carbon electrodes; one resorts to the positive pressure of argon. Whiskers can be produced.
- Glass fiber composites.
- Organic fiber composites.
- Boron fiber or SiC fiber composites.

Boron is among the materials that are very challenging to make ductile, and it is highly reactive. Therefore, for use in a metal matrix, a thin layer of SiC is attached onto the fibers.

- Hybrid fiber composites [9].

2. Characteristics of composites

Based on the classification of composites, we are already familiar with the fact that there exists a myriad of different types of these materials. It is a common saying that different types of composites differ in their performance. Yet, composites also have some characteristics in common. Grace to their inherent beneficial characteristics, polymer matrix composites have developed to the fastest emergent and most extensively used composites. Compared with well-established materials like metals, polymer matrix composites display particular characteristics as follows:

1. High specific strength and high specific modulus

The most important benefits of polymer matrix composites are their high specific strength and high specific modulus. Specific strength is defined as the ratio of strength to density, while the specific modulus is the ratio of modulus to density; in both cases, length is the corresponding dimension/unit. Under the premise of equal mass, these parameters are tools to quantify the material's bearing capacity and stiffness properties, which are very significant for aerospace structural materials. **Table 1** provides an overview of values for specific strength and specific modulus of several common structural materials; it is shown that carbon fiber resin matrix composites generally show higher specific modulus and specific strength. The high specific strength and high specific modulus of composites can be explained by the high performance and low density of reinforcing fibers. As a result of relatively low modulus and high density of glass fibers, the specific modulus of the glass fiber resin matrix composites is slightly lower than measured for metallic materials.

2. Expedient fatigue resistance and high damage resistance

The fatigue failure of metallic materials is frequently of no apparent warning to the strikingness of damage. The fiber/matrix interface in composites can avoid crack propagation. The fatigue failure always starts from those links of fibers prone to break. Crack growth or destruction propagates gradually for a long time; hence, there is a substantial forerun before

Materials	Density (g/cm^3)	Tensile strength (GPa)	Elastic modulus (10^2GPa)	Specific strength (10^6cm)	Specific modulus (10^8cm)
Steel	7.8	1.03	2.1	1.3	2.7
Aluminum alloy	2.8	0.47	0.75	1.7	2.6
Titanium alloy	4.5	0.96	1.14	2.1	2.5
Glass fiber composite materials	2.0	1.06	0.4	5.3	2.0
Carbon fiber II/epoxy composite materials	1.45	1.50	1.4	10.3	9.7
Carbon fiber I/epoxy composite materials	1.6	1.07	2.4	6.7	15
Organic fiber/epoxy composites	1.4	1.40	0.8	1.0	5.7
Boron fiber/epoxy composites	2.1	1.38	2.1	6.6	10
Boron fiber/aluminum matrix composites	2.65	1.0	2.0	3.8	7.5

Table 1. Specific strength and specific modulus of some commonly used materials and fiber composites [10].

the onset of the final destruction. As it is visible from the S-N curve of fatigue properties, fatigue strength of the majority of metallic materials amounts to only 30–50% of tensile strength, while this value increases to 70–80% for carbon fiber/polyester composites; for glass fiber composites, the percentage is between these two examples.

3. Good damping characteristics

The natural vibration frequency of forced structures relates to the structure shape itself and is also proportional to the square root of the specific modulus of structural materials. Consequently, composites have a high natural frequency, and generation of a resonance in general is not easy. In parallel, the fiber/matrix interface in composites very easily absorbs vibrational energy, which results in a high vibration damping of these materials. In case vibrations occur, they can easily be stopped [10].

4. Useful processing techniques

- Fiber matrix and other raw materials can be selected according to the utilization conditions and performance requirements of the product; hence, tailor-made material can be designed on demand.
- Molding processing techniques can be applied according to the size, shape, and number of the product.
- Integrated molding can decrease the number of individual parts, which saves time and material and reduces weight.

3. Principle approach for material selection

The proper material choice for an envisaged application is of outstanding importance and key in the development of a new product. Selecting the most suitable material determines the performance of the final product—whether it will meet the designated function and performance requirements. Inappropriate, less suitable materials can cause the following impairments:

- Technological problems occurring during the production process
- Increase of production costs, consequently higher price of the final product
- Negative ecological impact
- ○ Selection of material

Material selection is a multifaceted, complex process, which needs to address various factors such as:

- Material expenses
- Production cost
- Demand for energy and raw materials (material intensity of the process)
- The possible environmental impact of material selection, which depends on the production and consumer cycle (cradle-to-grave life cycle)
- Accessibility to material recycling:
- ○ The interrelations of material, technology, and product:

The functionality of the product (based on its individual components), structure (its shape), material, and technology closely interacts and cannot be regarded independently from each other; consequently, the selection of material cannot be done independently of the technology.

- ○ Parameters and needs during product design/development:
- The choice of most suitable, individual components regarding their future performance.
- Assessment of the compatibility of components—each phase of the composite material has to preserve its beneficial features; the individual components must not have a negative effect/damage on each other.
- Determining an applicable geometrical form for each phase—while the stronger parts (fibers, strips, belts, etc.) need to be elongated, the weaker phase should wrap the stronger one and bring individual fibers closely in contact within a single structure.
- Composite phases should be distributed in a way which enables them to function in a synergistic way.
- Knowledge on the conditions in which the future composite will function in praxi, such as temperature, humidity, pressure, abrasion, etc.

4. Applications

- Space crafts: antenna structures, radar, rocket engines, satellite structures, solar reflectors, etc.
- Aircrafts: airfoil surfaces, compressor blades, engine bay doors, fan blades, flywheels, helicopter transmission structures, jet engines, rotor shafts in helicopters, turbine blades, turbine shafts, wing box structures, etc.
- Automobiles: abrasive materials, bearing materials, electrical machinery, engine parts (bearing materials, connecting rod, crankshafts, cylinder, piston, etc.), pressure vessels, truss members, cutting tools, electrical brushes, etc.
- Wind turbine blades: wind turbine blades of carbon-wood epoxy composites.
- Cemented carbide: usual cemented carbides are based on tungsten carbide (WC), titanium carbide (TiC), and chromium carbide (Cr_3C_2).

*Tungsten carbide cermets (Co-binder): cutting tools are most frequently used; others: dies for powder metallurgy, indenters for hardness testers, wire drawing dies, rock drilling bits, other mining tools.

*Titanium carbide cermets (Ni-binder): high-temperature applications such as gas turbine nozzle vanes, cutting tools for steels, valve seats, thermocouple protection tubes, torch tips, etc.

*Chromium carbides cermets (Ni-binder): gage blocks, bearing seal rings, valve liners, spray nozzles, etc. [11].

Author details

Mohamed M. Dawoud and Hosam M. Saleh*

*Address all correspondence to: hosamsaleh70@yahoo.com

Radioisotope Department, Nuclear Research Center, Atomic Energy Authority, Egypt

References

[1] Hashin Z. Analysis of composite materials—A survey. Journal of Applied Mechanics. 1983;**50**(3):481-505

[2] Hon D, Shiraishi N, editors. Wood and Cellulose Chemistry. 2nd ed. New York: Marcel Dekker; 2001. p. 5

[3] Ibrahim ID, Jamiru T, Sadiku RE, Kupolati WK, Agwuncha SC, Ekundayo G. The use of polypropylene in bamboo fibre composite and their mechanical properties—A review. Journal of Reinforced Plastics and Composites. 2015;**34**(16):1347-1356

[4] Altenbach H et al. Mechanics of Composite Structural Elements. Berlin: Springer-Verlag; 2004

[5] Miracle DB, Donaldson SL. Introduction to composites. ASM Handbook. 2001;**21**:3-17

[6] Wang R-M, Zheng S-R, Zheng Y-P. Polymer Matrix Composites and Technology. WP, Woodhead Publishing, Oxford; 2011

[7] Thostenson ET, Ren Z, Chou T-W. Advances in the science and technology of carbon nanotubes and their composites: A review. Composites Science and Technology. 2001;**61**(13):1899-1912

[8] Das B et al. Nano-indentation studies on polymer matrix composites reinforced by few-layer graphene. Nanotechnology. 2009;**20**(12):125705

[9] Berthelot J-M. Composite Materials: Mechanical Behavior and Structural Analysis. New York, NY, USA: Springer; 1999

[10] Christensen RM. 2005. Mechanics of Composite Materials. Mineola, New York; 2012

[11] Gay D, Hoa SV, Tsai SW. Composite Materials: Design and Applications. Fl USA: CRC Press; 2003

IntechOpen