CHAPTER 10

COMPOSITES

INTRODUCTION

A composite, is a multiphase material that is *artificially made,* as opposed to one that occurs or forms naturally.

The constituent phases must be chemically dissimilar and separated by a distinct interface.

In designing composite materials, combined various metals, ceramics, and polymers Are used to produce a new generation of extraordinary materials.

Most composites have been created to improve combinations of mechanical characteristics such as stiffness, toughness, and ambient and high temperature strength.

COMPOSITION OF COMPOSITE MATERIALS

Many composite materials are composed of just two phases;

a- one is termed the **matrix,** which is continuous and surrounds the other phase, often called
b- The **dispersed phase.**

The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase.

Dispersed phase geometry in this context means the shape of the particles and the particle size, distribution, and orientation; these characteristics are represented in Figure 16.1.

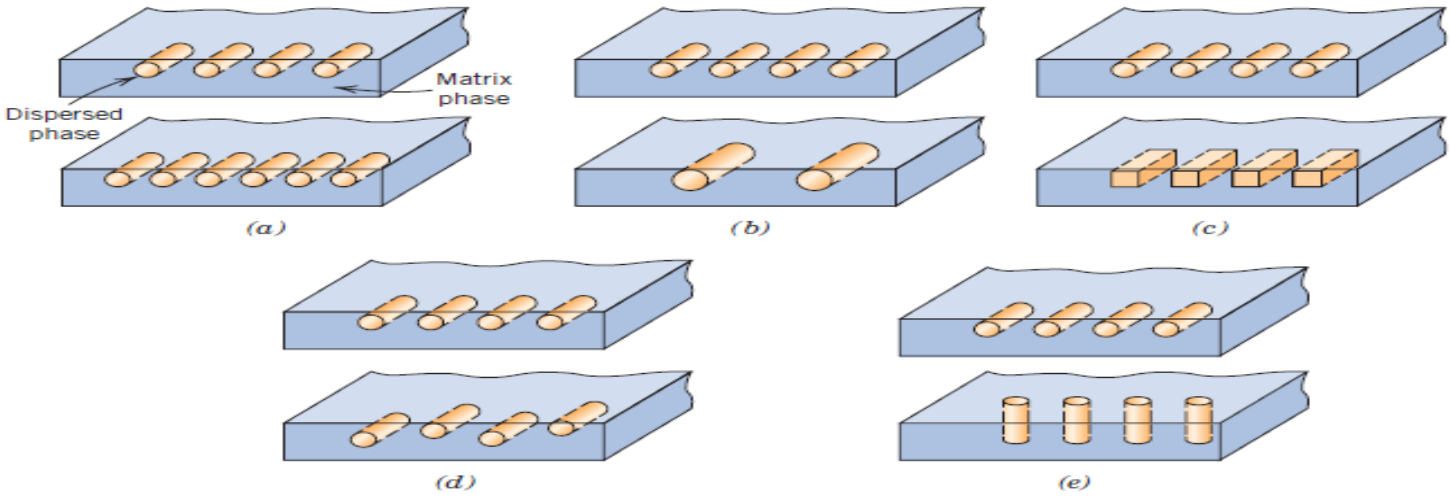


Figure 16.1 Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (*a*) concentration, (*b*) size, (*c*) shape, (*d*) distribution, and (*e*) orientation. (From Richard A. Flinn and Paul K. Trojan, *Engineering Materials and Their Applications*, 4th edition. Copyright © 1990 by John Wiley & Sons, Inc. Adapted by permission of John Wiley & Sons, Inc.)

One simple scheme for the classification of composite materials is shown in Figure 16.2, which consists of three main divisions: **particle-reinforced**, **fiber-reinforced**, and **structural composites**; also, at least two subdivisions exist for each.

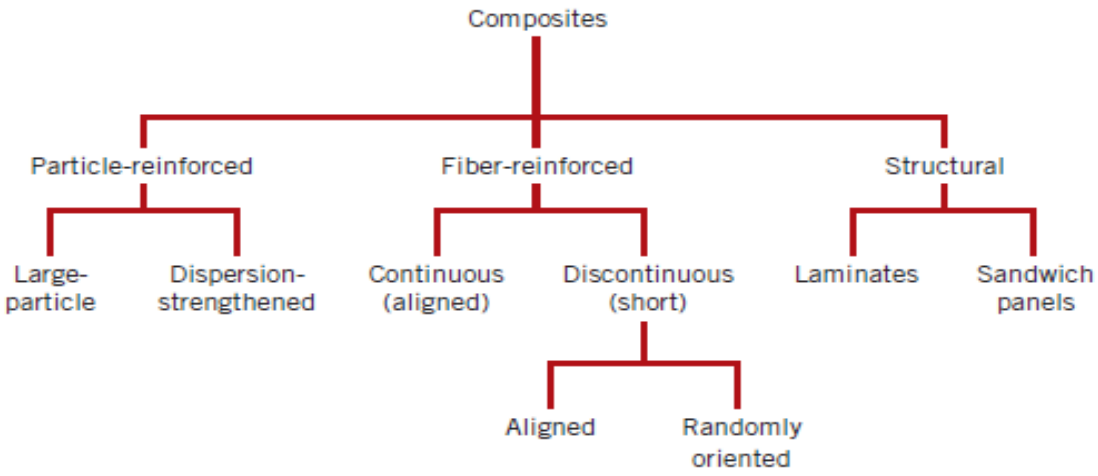


Figure 16.2 A classification scheme for the various composite types discussed in this chapter.

The dispersed phase for particle-reinforced composites is equiaxed (i.e., particle dimensions are approximately the same in all directions);

For fiber-reinforced composites, the dispersed phase has the geometry of a fiber (i.e., a large length-to-diameter ratio).

Structural composites are combinations of composites and homogeneous materials.

Particle-Reinforced Composites

As in Figure 16.2, **large-particle** and **dispersion-strengthened composites** are the two subclassifications of particle-reinforced composites.

The distinction between these is based on reinforcement or strengthening mechanism.

a-The term *large* is used to indicate that particle–matrix interactions cannot be treated on the atomic or molecular level rather continuum mechanics is used.

For most of these composites, the particulate phase is harder and stiffer than the matrix. These reinforcing particles tend to restrain movement of the matrix phase in the vicinity of each particle.

The matrix transfers some of the applied stress to the particles, which bear a fraction of the load.

The degree of reinforcement or improvement of mechanical behavior depends on strong bonding at the matrix–particle interface.

b- For dispersion-strengthened composites, particles are normally much smaller, with diameters between 0.01 and 0.1 μm (10 and 100 nm).

Particle–matrix interactions that lead to strengthening occur on the atomic or molecular level.

The matrix bears the major portion of an applied load; the small dispersed particles hinder or impede the motion of dislocations. Thus, plastic deformation is restricted such that yield and tensile strengths, as well as hardness, improve.

Examples

Some **polymeric materials** to which fillers have been added are large-particle composites. the fillers modify or improve the properties of the material and/or replace some of the polymer volume with a less expensive material—the filler.
Another familiar large-particle composite is **concrete**, which is composed of **cement** (the matrix) and **sand and gravel** (the particulates).

Particles can have quite a variety of geometries, but they should be of approximately the same dimension in all directions (equiaxed).

For effective reinforcement, the particles should be small and evenly distributed throughout the matrix.

The volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.

Two mathematical expressions have been formulated for the dependence of the elastic modulus on the volume fraction of the constituent phases for a two-phase composite. These **rule-of mixtures** equations predict that the elastic modulus should fall between an upper bound represented by

$$E_c(u) = E_m V_m + E_p V_p \qquad (16.1)$$

and a lower bound, or limit,

$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m} \qquad (16.2)$$

Where
E and V denote the elastic modulus and volume fraction, respectively,
The subscripts c, m, and p represent composite, matrix, and particulate phases.

Figure 16.3 plots upper- and lower-bound *Ec*-versus-*Vp* curves for a copper–tungsten composite, in which tungsten is the particulate phase; experimental data points fall between the two curves.

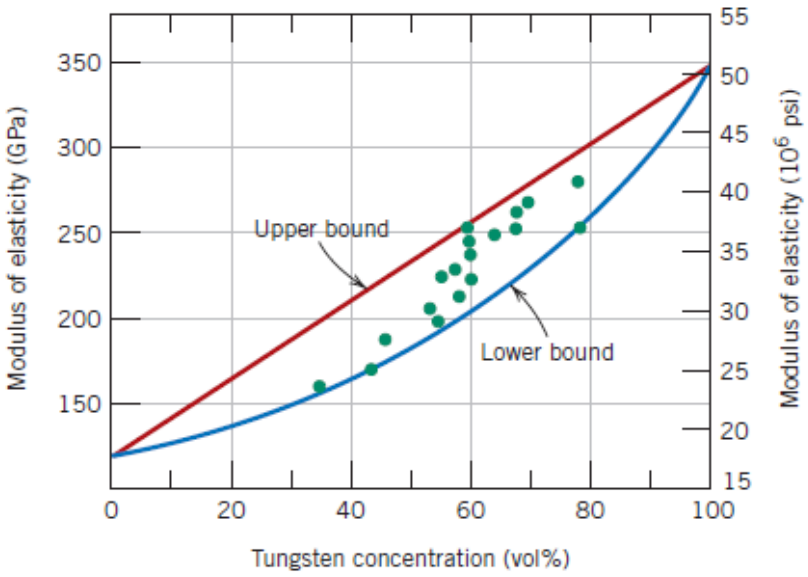


Figure 16.3 Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations 16.1 and 16.2; experimental data points are included. (From R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.)

Large-particle composites are used with all three material types (metals, polymers, and ceramics).

The **cermets** are examples of ceramic–metal composites.

The most common cermet is cemented carbide, which is composed of extremely hard particles of a refractory carbide ceramic such as tungsten carbide (WC) or titanium carbide (TiC), embedded in a matrix of a metal such as cobalt or nickel.

These composites are used extensively as cutting tools for hardened steels.

Elastomers and plastics are frequently reinforced with various particulate materials.

Our use of many of the modern rubbers would be severely restricted without reinforcing particulate materials such as *carbon black*. Carbon when added to rubber, this extremely inexpensive material enhances tensile strength, toughness, and tear and abrasion resistance.

Automobile tires contain on the order of 15 to 30 vol% carbon black.

Concrete is a common large-particle composite in which both matrix and dispersed phases are ceramic materials
Concrete implies a composite material consisting of an aggregate of particles that are bound together in a solid body by some type of binding medium, that is, a cement.

Fiber-Reinforced Composites

The dispersed phase is in the form of a fiber.

Design goals of **fiber-reinforced composites** often include high strength and/or stiffness on a weight basis.

These characteristics are expressed in terms of **specific strength** and **specific modulus** parameters, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity.

Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that use low-density fiber and matrix materials.

As noted in Figure 16.2, fiber-reinforced composites are subclassified by fiber length. For short fiber, the fibers are too short to produce a significant improvement in strength.

Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length l_c is dependent on the fiber diameter d and its ultimate (or tensile) strength σ_f^*, and on the fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) τ_c according to

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \qquad (16.3)$$

Fibers for which $l \gg l_c$ (normally $l > 15 l_c$) are termed *continuous*;

Discontinuous or short fibers have lengths shorter than this ($l < l_c$)

To effect a significant improvement in strength of the composite, the fibers must be continuous as in Figure (16.8).

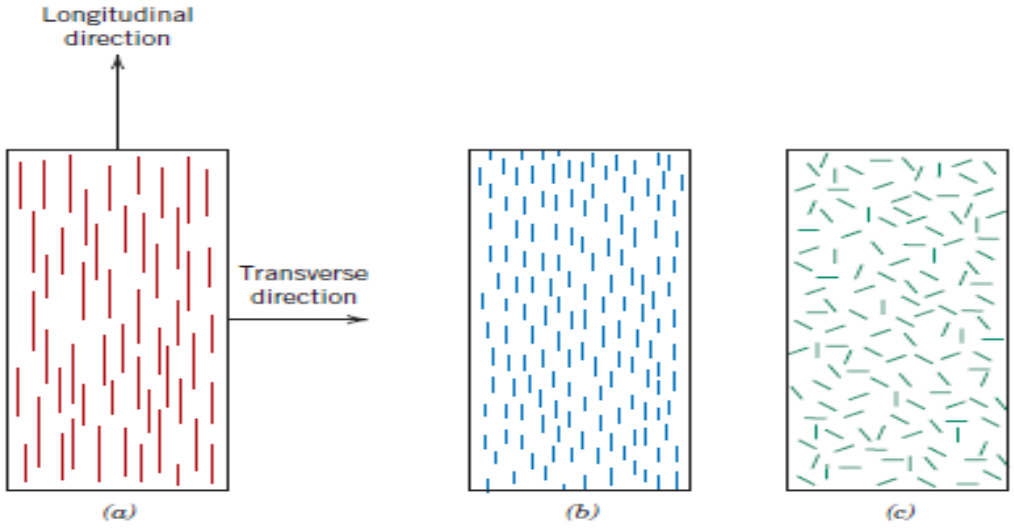


Figure 16.8 Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiber–reinforced composites.

Structural Composites

A **structural composite** is normally composed of both homogeneous and composite materials.

the properties depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements.

Laminar composites and **sandwich panels** are two of the most common structural composites.

LAMINAR COMPOSITES

A **laminar composite** is composed of two-dimensional sheets or panels that have a preferred high-strength direction, such as is found in wood and continuous and aligned fiber–reinforced plastics.

The layers are stacked and subsequently cemented together such that the orientation of the high-strength direction varies with each successive layer (Figure 16.16).

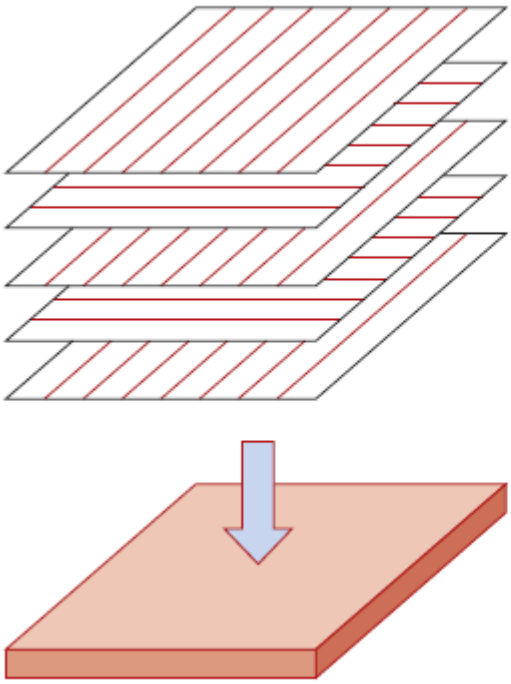


Figure 16.16 The stacking of successive oriented fiber–reinforced layers for a laminar composite.

SANDWICH PANELS

Sandwich panels, considered to be a class of structural composites, are designed to be lightweight beams or panels having relatively high stiffnesses and strengths.

A sandwich panel consists of two outer sheets, or faces, that are separated by and adhesively bonded to a thicker core (Figure 16.17).

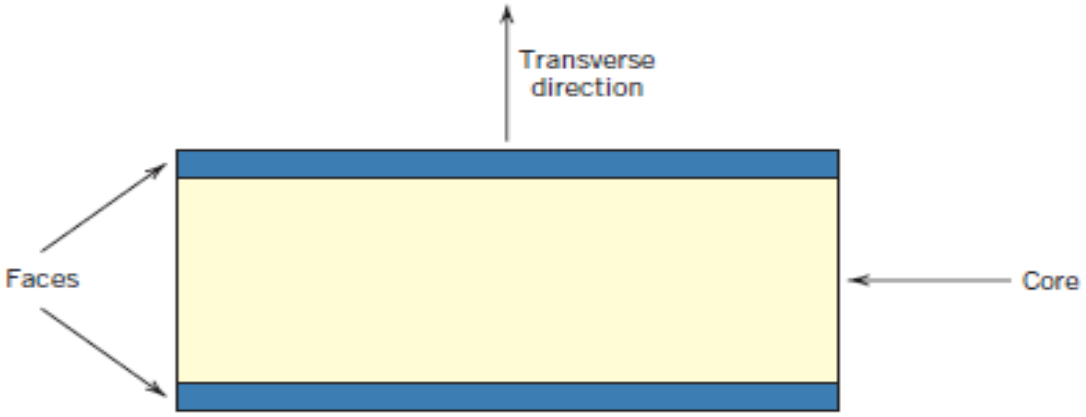


Figure 16.17 Schematic diagram showing the cross section of a sandwich panel.

The outer sheets are made of a relatively stiff and strong material, typically aluminum alloys, fiber-reinforced plastics, titanium, steel, or plywood; they impart high stiffness and strength to the structure and must be thick enough to withstand tensile and compressive stresses that result from loading.

The core material is lightweight and normally has a low modulus of elasticity.

Core materials typically fall within three categories: rigid polymeric foams (i.e., phenolics, epoxy, polyurethanes), wood (i.e., balsa wood), and honeycombs.

Structurally, the core serves several functions. First of all, it provides continuous support for the faces. It must have sufficient shear strength to withstand transverse shear stresses and also be thick enough to provide high shear stiffness (to resist buckling of the panel). (Tensile and compressive stresses on the core are much lower than on the faces.)

Another popular core consists of a "honeycomb" structure—thin foils that have been formed into interlocking hexagonal cells, with axes oriented perpendicular to the face planes (Figure 16.18).

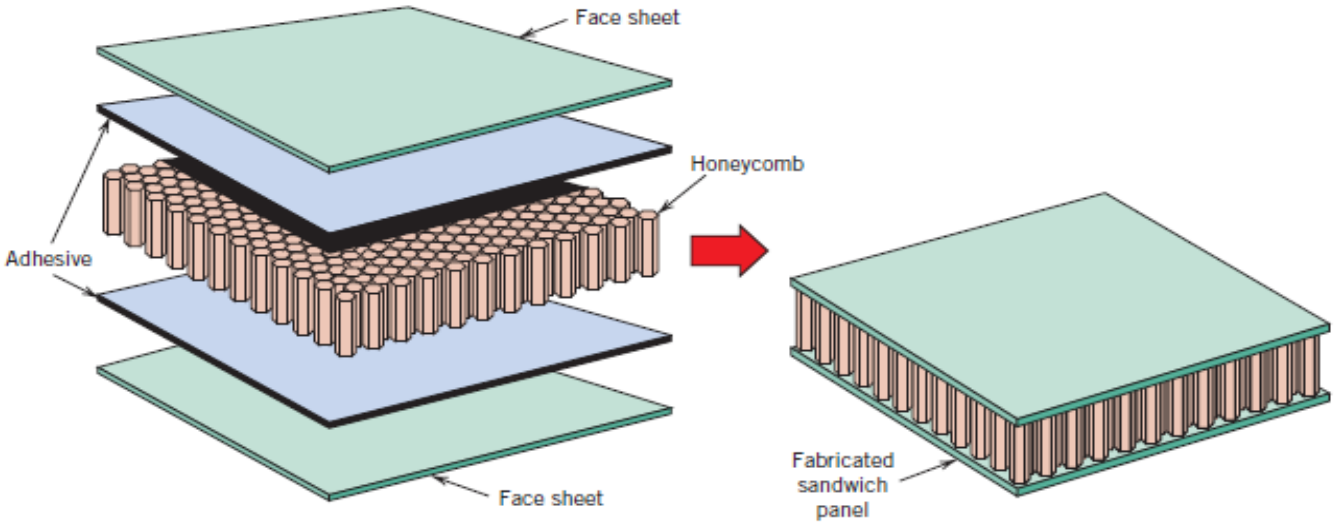


Figure 16.18 Schematic diagram showing the construction of a honeycomb core sandwich panel. (Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Metals Park, OH, 1987.)

The honeycomb material is normally either an aluminum alloy or aramid polymer.

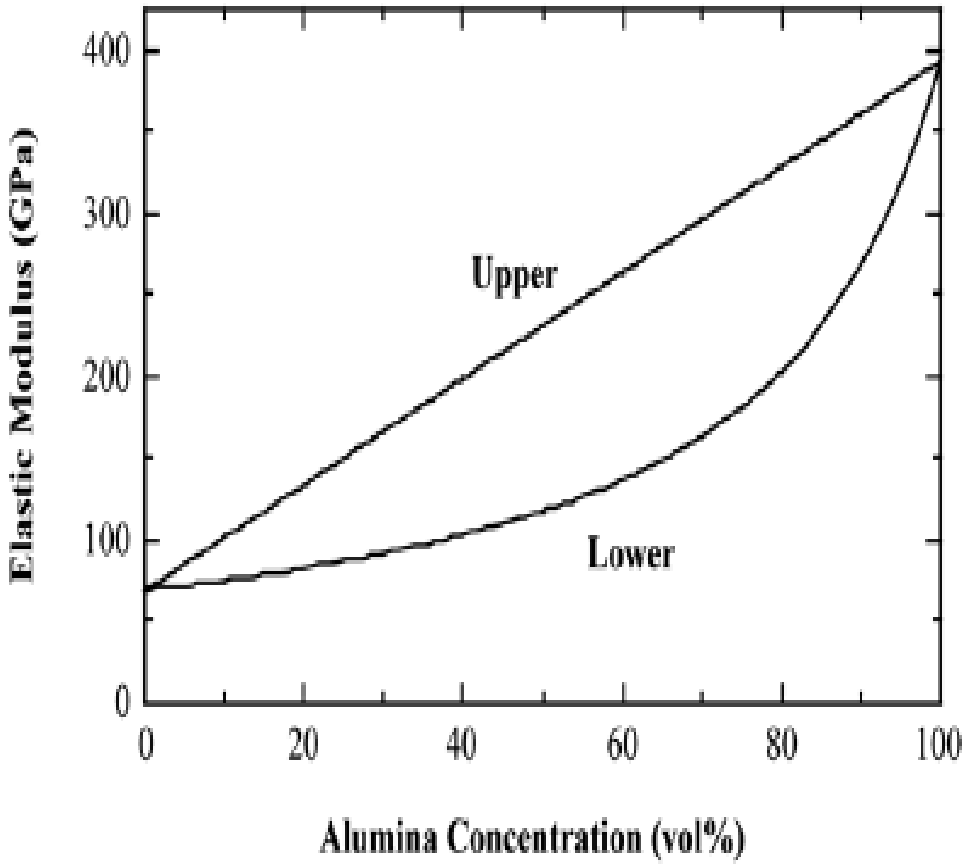
Strength and stiffness of honeycomb structures depend on cell size, cell wall thickness, and the material from which the honeycomb is made.

QUESTIONS and ANSWERS

Q1- The mechanical properties of aluminum may be improved by incorporating fine particles of aluminum oxide (Al_2O_3). Given that the moduli of elasticity of these materials are, respectively, 69 GPa (10×10^6 psi) and 393 GPa (57×10^6 psi), plot modulus of elasticity versus the volume percent of Al_2O_3 in Al from 0 to 100 vol%, using both upper- and lower-bound expressions.

Solution

The elastic modulus versus the volume percent of Al_2O_3 is shown below, on which is included both upper and lower bound curves; these curves were generated using Equations 16.1 and 16.2, respectively, and using the moduli of elasticity for aluminum and Al_2O_3 that were given in the problem statement.



Q2- A large-particle composite consisting of tungsten particles within a copper matrix is to be prepared. If the volume fractions of tungsten and copper are 0.60 and 0.40, respectively, estimate the upper limit for the specific stiffness of this composite given the data that follow.

	Specific Gravity	*Modulus of Elasticity (GPa)*
Copper	*8.9*	*110*
Tungsten	*19.3*	*407*

Solution

Given the elastic moduli and specific gravities for copper and tungsten we are asked to estimate the upper limit for specific stiffness when the volume fractions of tungsten and copper are 0.60 and 0.40, respectively. There are two approaches that may be applied to solve this problem. The first is to estimate both the upper limits of elastic modulus [$E_c(u)$] and specific gravity (ρ_c) for the composite, using expressions of the form of Equation 16.1, and then take their ratio. Using this approach

$$E_c(u) = E_{Cu}V_{Cu} + E_WV_W$$

$$= (110\ \text{GPa})(0.40) + (407\ \text{GPa})(0.60)$$

$$= 288\ \text{GPa}$$

And

$$\rho_c = \rho_{Cu}V_{Cu} + \rho_WV_W$$

$$= (8.9)(0.40) + (19.3)(0.60) = 15.14$$

Therefore

$$\text{Specific Stiffness} = \frac{E_c(u)}{\rho_c} = \frac{288\ \text{GPa}}{15.14} = 19.0\ \text{GPa}$$

With the alternate approach, the specific stiffness is calculated, again employing a modification of Equation 16.1, but using the specific stiffness-volume fraction product for both metals, as follows:

$$\text{Specific Stiffness} = \frac{E_{Cu}}{\rho_{Cu}} V_{Cu} + \frac{E_W}{\rho_W} V_W$$

$$= \frac{110 \text{ GPa}}{8.9}(0.40) + \frac{407 \text{ GPa}}{19.3}(0.60) = 17.6 \text{ GPa}$$

Q3- (a) What is the distinction between cement and concrete?
(b) Cite three important limitations that restrict the use of concrete as a structural material.
(c) Briefly explain three techniques that are utilized to strengthen concrete by reinforcement.

Solution

(a) Concrete consists of an aggregate of particles that are bonded together by a cement.

(b) Three limitations of concrete are: (1) it is a relatively weak and brittle material; (2) it experiences relatively large thermal expansions (contractions) with changes in temperature; and (3) it may crack when exposed to freeze-thaw cycles.

(c) Three reinforcement strengthening techniques are: (1) reinforcement with steel wires, rods, etc.; (2) reinforcement with fine fibers of a high modulus material; and (3) introduction of residual compressive stresses by prestressing or posttensioning.

Q4- For some glass fiber-epoxy matrix combination, the critical fiber length-fiber diameter ratio is 50. Using the data in Table 16.4, determine the fiber-matrix bond strength.

Table 16.4 Characteristics of Several Fiber–Reinforcement Materials

Material	*Specific Gravity*	*Tensile Strength [GPa (10^6 psi)]*	*Specific Strength (GPa)*	*Modulus of Elasticity [GPa (10^6 psi)]*	*Specific Modulus (GPa)*
		Whiskers			
Graphite	2.2	20 (3)	9.1	700 (100)	318
Silicon nitride	3.2	5–7 (0.75–1.0)	1.56–2.2	350–380 (50–55)	109–118
Aluminum oxide	4.0	10–20 (1–3)	2.5–5.0	700–1500 (100–220)	175–375
Silicon carbide	3.2	20 (3)	6.25	480 (70)	150
		Fibers			
Aluminum oxide	3.95	1.38 (0.2)	0.35	379 (55)	96
Aramid (Kevlar 49)	1.44	3.6–4.1 (0.525–0.600)	2.5–2.85	131 (19)	91
Carbon[a]	1.78–2.15	1.5–4.8 (0.22–0.70)	0.70–2.70	228–724 (32–100)	106–407
E-glass	2.58	3.45 (0.5)	1.34	72.5 (10.5)	28.1
Boron	2.57	3.6 (0.52)	1.40	400 (60)	156
Silicon carbide	3.0	3.9 (0.57)	1.30	400 (60)	133
UHMWPE (Spectra 900)	0.97	2.6 (0.38)	2.68	117 (17)	121
		Metallic Wires			
High-strength steel	7.9	2.39 (0.35)	0.30	210 (30)	26.6
Molybdenum	10.2	2.2 (0.32)	0.22	324 (47)	31.8
Tungsten	19.3	2.89 (0.42)	0.15	407 (59)	21.1

[a] The term *carbon* instead of *graphite* is used to denote these fibers, because they are composed of crystalline graphite regions, and also of noncrystalline material and areas of crystal misalignment.

Solution

This problem asks that, for a glass fiber-epoxy matrix combination, to determine the fiber-matrix bond strength if the critical fiber length-fiber diameter ratio is 50. Thus, we are to solve for τ_c in Equation 16.3. Since we are given that $\sigma_f^* = 3.45$ GPa from Table 16.4, and that $\frac{l_c}{d} = 50$, then

$$\tau_c = \sigma_f^* \left(\frac{d}{2l_c}\right) = (3.45 \times 10^3 \text{ MPa})\left(\frac{1}{2}\right)\left(\frac{1}{50}\right) = 34.5 \text{ MPa}$$

Q5- Compute the longitudinal strength of an aligned carbon fiber-epoxy matrix composite having a 0.25 volume fraction of fibers, assuming the following: (1) an average fiber diameter of 10×10^{-3} mm (3.94×10^{-4} in.), (2) an average fiber length of 5 mm (0.20 in.), (3) a fiber fracture strength of 2.5 GPa (3.625×10^{5} psi), (4) a fiber-matrix bond strength of 80 MPa (11,600 psi), Determine if the matrix is continuous or discontinuous?

Solution

It is first necessary to compute the value of the critical fiber length using Equation 16.3.

$$l_c = \frac{\sigma_f^* d}{2\tau_c} = \frac{(2.5 \times 10^3 \text{ MPa})(10 \times 10^{-3} \text{ mm})}{2(80 \text{ MPa})} = 0.16 \text{ mm}$$

Inasmuch as $l >> lc$ (5.0 mm >> 0.16 mm), then the fiber is **continues.**

Q6- For a polymer-matrix fiber-reinforced composite,

(a) List three functions of the matrix phase.

(b) Compare the desired mechanical characteristics of matrix and fiber phases.

(c) Cite two reasons why there must be a strong bond between fiber and matrix at their interface.

Solution

(a) For polymer-matrix fiber-reinforced composites, three functions of the polymer-matrix phase are: (1) to bind the fibers together so that the applied stress is distributed among the fibers; (2) to protect the surface of the fibers from being damaged; and (3) to separate the fibers and inhibit crack propagation.

(b) The matrix phase must be ductile and is usually relatively soft, whereas the fiber phase must be stiff and strong.

(c) There must be a strong interfacial bond between fiber and matrix in order to: (1) maximize the stress transmittance between matrix and fiber phases; and (2) minimize fiber pull-out, and the probability of failure.

Q7- (a) What is the distinction between matrix and dispersed phases in a composite material?
(b) Contrast the mechanical characteristics of matrix and dispersed phases for fiber-reinforced composites.

Solution

(a) The matrix phase is a continuous phase that surrounds the noncontinuous dispersed phase.

(b) In general, the matrix phase is relatively weak, has a low elastic modulus, but is quite ductile. On the other hand, the fiber phase is normally quite strong, stiff, and brittle.

Q8- Briefly describe laminar composites. What is the prime reason for fabricating these materials?

Solution

Laminar composites are a series of sheets or panels, each of which has a preferred high-strength direction. These sheets are stacked and then cemented together such that the orientation of the high-strength direction varies from layer to layer.

These composites are constructed in order to have a relatively high strength in virtually all directions within the plane of the laminate.

Q9- (a) Briefly describe sandwich panels.
(b) What is the prime reason for fabricating these structural composites?
(c) What are the functions of the faces and the core?

Solution

(a) Sandwich panels consist of two outer face sheets of a high-strength material that are separated by a layer of a less-dense and lower-strength core material.

(b) The prime reason for fabricating these composites is to produce structures having high in-plane strengths, high shear rigidities, and low densities.

(c) The faces function so as to bear the majority of in-plane tensile and compressive stresses. On the other hand, the core separates and provides continuous support for the faces, and also resists shear deformations perpendicular to the faces.