

# **MECHANICS OF COMPOSITE MATERIALS**

**(ME 4306E)**

**College of Engineering**

**Mechanical Department**

**(Stage 4)**



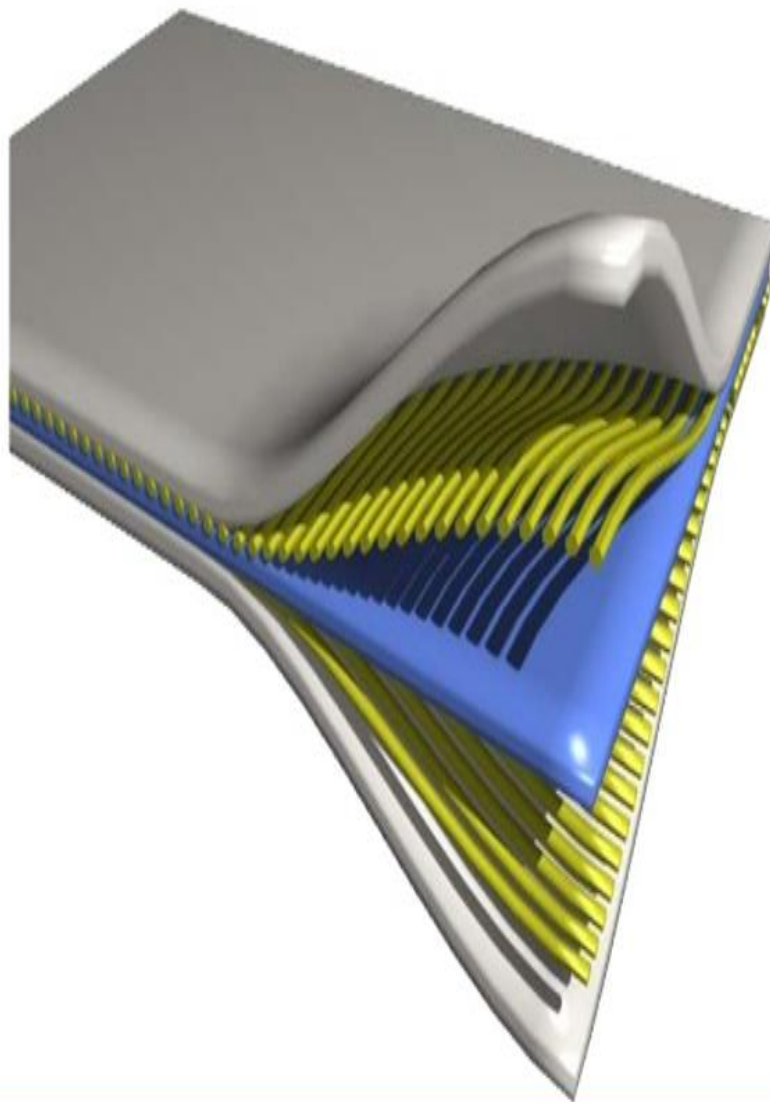
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# *Introduction to Composite Materials*



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LECTURE : 1: CHAPTER ONE

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## 1.1 Introduction to Composite Materials

### Chapter One: Objectives

- Define a composite, enumerate advantages and drawbacks of composites over monolithic materials, and discuss factors that influence mechanical properties of a composite.
- Classify composites, introduce common types of fibers and matrices, and manufacturing, mechanical properties, and applications of composites.
- Discuss recycling of composites.
- Introduce terminology used for studying mechanics of composites.

### What is a composite?

A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. The reinforcing phase material may be in the form of fibers, particles, or flakes. The matrix phase materials are generally continuous. Examples of composite systems include concrete reinforced with steel and epoxy reinforced with graphite fibers, etc.

### Give some examples of naturally found composites:

Examples include wood, where the lignin matrix is reinforced with cellulose fibers and bones in which the bone-salt plates made of calcium and phosphate ions reinforce soft collagen.

### **What are advanced composites?**

Advanced composites are composite materials that are traditionally used in the aerospace industries. These composites have high performance reinforcements of a thin diameter in a matrix material such as epoxy and aluminum. Examples are graphite/epoxy, Kevlar/epoxy, and boron/ aluminum composites. These materials have now found applications in commercial industries as well.

### **Combining two or more materials together to make a composite is more work than just using traditional monolithic metals such as steel and aluminum. What are the advantages of using composites over metals?**

Monolithic metals and their alloys cannot always meet the demands of today's advanced technologies. Only by combining several materials can one meet the performance requirements. For example, trusses and benches used in satellites need to be dimensionally stable in space during temperature changes between  $-256^{\circ}\text{F}$  ( $-160^{\circ}\text{C}$ ) and  $200^{\circ}\text{F}$  ( $93.3^{\circ}\text{C}$ ). Limitations on coefficient of thermal expansion $\ddagger$  thus are low and may be of the order of  $\pm 1 \times 10^{-7}$  in./in./ $^{\circ}\text{F}$  ( $\pm 1.8 \times 10^{-7}$  m/m/ $^{\circ}\text{C}$ ). Monolithic materials cannot meet these requirements; this leaves composites, such as graphite/epoxy, as the only materials to satisfy them.

In many cases, using composites is more efficient. For example, in the highly competitive airline market, one is continuously looking for ways to lower the overall mass of the aircraft without decreasing the stiffness and strength of its components. This is possible by replacing conventional metal alloys with composite materials. Even if the composite material costs may be higher, the reduction in the number of parts in an assembly and the savings in fuel costs make them more profitable. Also, composites offer several other advantages over conventional materials. These may include

improved strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance, etc.

\* **Stiffness** is defined as the resistance of a material to deflection.

† **Strength** is defined as the stress at which a material fails.

‡ **Fatigue resistance** is the resistance to the lowering of mechanical properties such as strength and stiffness due to cyclic loading, such as due to take-off and landing of a plane, vibrating a plate, etc.

\*\* **Impact resistance** is the resistance to damage and to reduction in residual strength to impact loads, such as a bird hitting an airplane or a hammer falling on a car body.

†† **Thermal conductivity** is the rate of heat flow across a unit area of a material in a unit time, when the temperature gradient is unity in the direction perpendicular to the area.

††† **Electrical conductivity** is the ability of electric current to flow through a material.

‡‡ **Corrosion resistance** is the resistance to corrosion, such as pitting, erosion, galvanic, etc.

\* **Young's modulus of an elastic material** is the initial slope of the stress–strain curve.

† **Density** is the mass of a substance per unit volume.

‡ **A unidirectional composite** is a composite lamina or rod in which the fibers reinforcing the matrix are oriented in the same direction.

### How is the mechanical advantage of composite measured?

For example, the axial deflection,  $u$ , of a prismatic rod under an axial load,  $P$ , is given by

$$u = \frac{PL}{AE} , \quad (1.1)$$

where

$L$  = length of the rod

$E$  = Young's modulus of elasticity of the material of the rod

Because the mass,  $M$ , of the rod is given by

$$M = \rho AL , \quad (1.2)$$

where  $\rho$  = density of the material of the rod, we have

$$M = \frac{PL^2}{4} \frac{1}{E/\rho} . \quad (1.3)$$

This implies that the lightest beam for specified deflection under a specified load is one with the highest  $(E/\rho)$  value. Thus, to measure the mechanical advantage, the  $(E/\rho)$  ratio is calculated and is called the **specific modulus** (ratio between the Young's modulus ( $E$ ) and the density ( $\rho$ ) of the material). The other parameter is called the specific strength and is defined as the ratio between the strength ( $\sigma_{ult}$ ) and the density of the material ( $\rho$ ), that is

$$\text{Specific modulus} = \frac{E}{\rho},$$

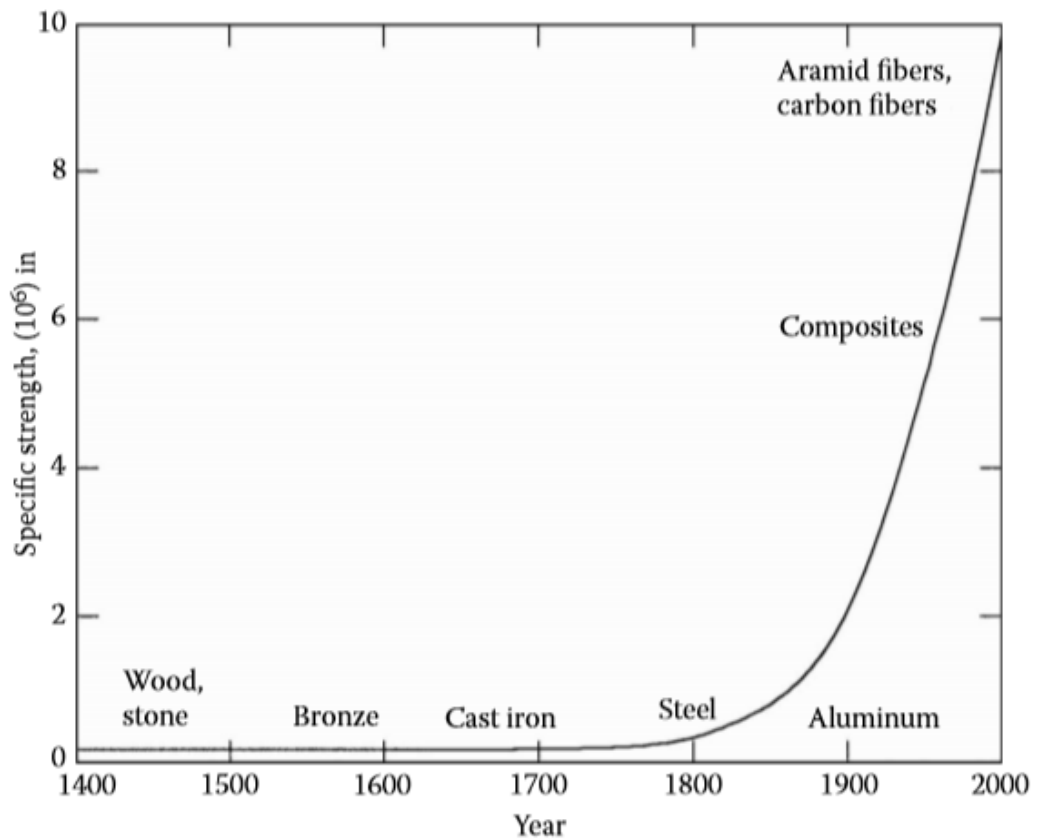
$$\text{Specific strength} = \frac{\sigma_{ult}}{\rho}.$$

The two ratios are high in composite materials. For example, the strength of a graphite/epoxy unidirectional composite could be the same as steel, but the specific strength is three times that of steel. **What does this mean to a designer?** Take the simple case of a rod designed to take a fixed axial load. The rod cross section of graphite/epoxy would be same as that of the steel, but the mass of graphite/epoxy rod would be one third of the steel rod. This reduction in mass translates to reduced material and energy costs. **Figure 1.1** shows how composites and fibers rate with other traditional materials in terms of specific strength.<sup>3</sup> Note that the unit of specific strength is inches in **Figure 1.1** because specific strength and specific modulus are also defined in some texts as

$$\text{Specific modulus} = \frac{E}{\rho g},$$

$$\text{Specific strength} = \frac{\sigma_{ult}}{\rho g}.$$

where  $g$  is the acceleration due to gravity (32.2 ft/s<sup>2</sup> or 9.81 m/s<sup>2</sup>).



**FIGURE 1.1** Specific strength as a function of time of use of materials. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

Values of specific modulus and strength are given in [Table 1.1](#) for typical composite fibers, unidirectional composites,\* cross-ply† and quasi-isotropic‡ laminated composites, and monolithic metals. On a first look, fibers such as graphite, aramid, and glass have a specific modulus several times that of metals, such as steel and aluminum. This gives a false impression about the mechanical advantages of composites because they are made not only of fibers, but also of fibers and matrix combined; matrices generally have lower modulus and strength than fibers. **Is the comparison of the specific modulus and specific strength parameters of unidirectional composites to metals now fair?** The answer is no for two reasons. First, unidirectional composite structures are acceptable only for carrying simple loads such as uniaxial tension or pure bending. In structures with complex requirements of loading and stiffness,



composite structures including angle plies will be necessary. Second, the strengths and elastic moduli of unidirectional composites given in [Table 1.1](#) are those in the direction of the fiber. The strength and elastic moduli perpendicular to the fibers are far less.

\* **A unidirectional laminate** is a laminate in which all fibers are oriented in the same direction.

† **A cross-ply laminate** is a laminate in which the layers of unidirectional lamina are oriented at right angles to each other.

‡ **Quasi-isotropic laminate** , it behaves similarly to an isotropic material; that is, the elastic properties are the same in all directions.

**TABLE 1.1**

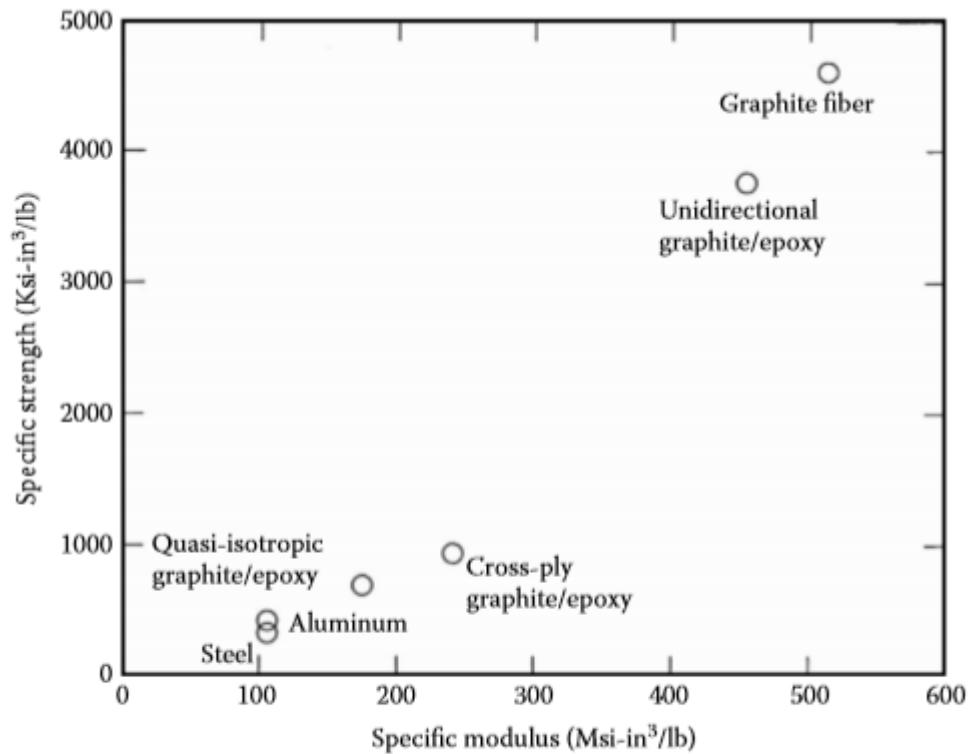
Specific Modulus and Specific Strength of Typical Fibers, Composites, and Bulk Metals

Material Units	Specific gravity <sup>a</sup>	Young's modulus (Msi)	Ultimate strength (ksi)	Specific modulus (Msi-in. <sup>3</sup> /lb)	Specific strength (ksi-in. <sup>3</sup> /lb)
<i>System of Units: USCS</i>					
Graphite fiber	1.8	33.35	299.8	512.9	4610
Aramid fiber	1.4	17.98	200.0	355.5	3959
Glass fiber	2.5	12.33	224.8	136.5	2489
Unidirectional graphite/epoxy	1.6	26.25	217.6	454.1	3764
Unidirectional glass/epoxy	1.8	5.598	154.0	86.09	2368
Cross-ply graphite/epoxy	1.6	13.92	54.10	240.8	935.9
Cross-ply glass/epoxy	1.8	3.420	12.80	52.59	196.8
Quasi-isotropic graphite/epoxy	1.6	10.10	40.10	174.7	693.7
Quasi-isotropic glass/epoxy	1.8	2.750	10.60	42.29	163.0
Steel	7.8	30.00	94.00	106.5	333.6
Aluminum	2.6	10.00	40.00	106.5	425.8

Material Units	Specific gravity	Young's modulus (GPa)	Ultimate strength (MPa)	Specific modulus (GPa-m <sup>3</sup> /kg)	Specific strength (MPa-m <sup>3</sup> /kg)
<i>System of Units: SI</i>					
Graphite fiber	1.8	230.00	2067	0.1278	1.148
Aramid fiber	1.4	124.00	1379	0.08857	0.9850
Glass fiber	2.5	85.00	1550	0.0340	0.6200
Unidirectional graphite/epoxy	1.6	181.00	1500	0.1131	0.9377
Unidirectional glass/epoxy	1.8	38.60	1062	0.02144	0.5900
Cross-ply graphite/epoxy	1.6	95.98	373.0	0.06000	0.2331
Cross-ply glass/epoxy	1.8	23.58	88.25	0.01310	0.0490
Quasi-isotropic graphite/epoxy	1.6	69.64	276.48	0.04353	0.1728
Quasi-isotropic glass/epoxy	1.8	18.96	73.08	0.01053	0.0406
Steel	7.8	206.84	648.1	0.02652	0.08309
Aluminum	2.6	68.95	275.8	0.02652	0.1061

<sup>a</sup> Specific gravity of a material is the ratio between its density and the density of water.

A comparison is now made between popular types of laminates such as cross-ply and quasi-isotropic laminates. Figure 1.2 shows the specific strength plotted as a function of specific modulus for various fibers, metals, and composites.



**FIGURE 1.2**  
Specific strength as a function of specific modulus for metals, fibers, and composites.

**Are specific modulus and specific strength the only mechanical parameters used for measuring the relative advantage of composites over metals?**

No, it depends on the application. Consider compression of a column, where it may fail due to buckling. The Euler buckling formula gives the critical load at which a long column buckles as:

$$P_{cr} = \frac{\pi^2 EI}{L^2}, \quad (1.4)$$

where

- $P_{cr}$  = critical buckling load (lb or N)
- $E$  = Young's modulus of column (lb/in.<sup>2</sup> or N/m<sup>2</sup>)
- $I$  = second moment of area (in.<sup>4</sup> or m<sup>4</sup>)
- $L$  = length of beam (in. or m)

If the column has a circular cross section, the second moment of area is

$$I = \pi \frac{d^4}{64} \quad (1.5)$$

and the mass of the rod is

$$M = \rho \frac{\pi d^2 L}{4}, \quad (1.6)$$

where

$$\begin{aligned} M &= \text{mass of the beam (lb or kg)} \\ \rho &= \text{density of beam (lb/in.}^3 \text{ or kg/m}^3\text{)} \\ d &= \text{diameter of beam (in. or m)} \end{aligned}$$

Because the length,  $L$ , and the load,  $P$ , are constant, we find the mass of the beam by substituting Equation (1.5) and Equation (1.6) in Equation (1.4) as

$$M = \frac{2L^2 \sqrt{P_\sigma}}{\sqrt{\pi}} \frac{1}{E^{1/2} / \rho} . \quad (1.7)$$

This means that the lightest beam for specified stiffness is one with the highest value of  $E^{1/2} / \rho$ .

Similarly, we can prove that, for achieving the minimum deflection in a beam under a load along its length, the lightest beam is one with the highest value of  $E^{1/3} / \rho$ . Typical values of these two parameters,  $E^{1/2} / \rho$  and  $E^{1/3} / \rho$  for typical fibers, unidirectional composites, cross-ply and quasi-isotropic laminates, steel, and aluminum are given in [Table 1.2](#). Comparing these numbers with metals shows composites drawing a better advantage for these two parameters. Other mechanical parameters for comparing the performance of composites to metals include resistance to fracture, fatigue, impact, and creep.

**TABLE 1.2**

Specific Modulus Parameters  $E/\rho$ ,  $E^{1/2}/\rho$ , and  $E^{1/3}/\rho$  for Typical Materials

Material Units	Specific gravity	Young's modulus (Msi)	$E/\rho$ (Msi-in. <sup>3</sup> /lb)	$E^{1/2}/\rho$ (psi <sup>1/2</sup> -in. <sup>3</sup> /lb)	$E^{1/3}/\rho$ (psi <sup>1/3</sup> -in. <sup>3</sup> /lb)
<i>System of Units: USCS</i>					
Graphite fiber	1.8	33.35	512.8	88,806	4,950
Kevlar fiber	1.4	17.98	355.5	83,836	5,180
Glass fiber	2.5	12.33	136.5	38,878	2,558
Unidirectional graphite/epoxy	1.6	26.25	454.1	88,636	5,141
Unidirectional glass/epoxy	1.8	5.60	86.09	36,384	2,730
Cross-ply graphite/epoxy	1.6	13.92	240.8	64,545	4,162
Cross-ply glass/epoxy	1.8	3.42	52.59	28,438	2,317
Quasi-isotropic graphite/epoxy	1.6	10.10	174.7	54,980	3,740
Quasi-isotropic glass/epoxy	1.8	2.75	42.29	25,501	2,154
Steel	7.8	30.00	106.5	19,437	1,103
Aluminum	2.6	10.00	106.5	33,666	2,294

Material Units	Specific gravity	Young's modulus (GPa)	$E/\rho$ (GPa-m <sup>3</sup> /kg)	$E^{1/2}/\rho$ (Pa-m <sup>3</sup> /kg)	$E^{1/3}/\rho$ (Pa <sup>1/3</sup> -m <sup>3</sup> /kg)
<i>System of Units: SI</i>					
Graphite fiber	1.8	230.00	0.1278	266.4	3.404
Kevlar fiber	1.4	124.00	0.08857	251.5	3.562
Glass fiber	2.5	85.00	0.034	116.6	1.759
Unidirectional graphite/epoxy	1.6	181.00	0.1131	265.9	3.535
Unidirectional glass/epoxy	1.8	38.60	0.02144	109.1	1.878
Cross-ply graphite/epoxy	1.6	95.98	0.060	193.6	2.862
Cross-ply glass/epoxy	1.8	23.58	0.0131	85.31	1.593
Quasi-isotropic graphite/epoxy	1.6	69.64	0.04353	164.9	2.571
Quasi-isotropic glass/epoxy	1.8	18.96	0.01053	76.50	1.481
Steel	7.8	206.84	0.02652	58.3	0.7582
Aluminum	2.6	68.95	0.02662	101.0	1.577

**The Well-Known, composites have distinct advantages over metals. Are there any drawbacks or limitations in using them?**

Yes, drawbacks and limitations in use of composites include:

- High cost of fabrication of composites is a critical issue. For example, a part made of graphite/epoxy composite may cost up to 10 to 15 times the material costs. A finished graphite/epoxy composite part may cost as much as \$300 to \$400 per pound (\$650 to \$900 per kilogram). Improvements in processing and manufacturing techniques will lower these costs in the future. Already, manufacturing techniques such as SMC (sheet molding compound) and SRIM (structural reinforcement injection molding) are lowering the cost and production time in manufacturing automobile parts.

- Mechanical characterization of a composite structure is more complex than that of a metal structure. Unlike metals, composite materials are not isotropic, that is, their properties are not the same in all directions. Therefore, they require more material parameters. For example, a single layer of a graphite/epoxy composite requires nine stiffness and strength constants for conducting mechanical analysis. In the case of a monolithic material such as steel, one requires only four stiffness and strength constants. Such complexity makes structural analysis computationally and experimentally more complicated and intensive. In addition, evaluation and measurement techniques of some composite properties, such as compressive strengths, are still being debated.
- Repair of composites is not a simple process compared to that for metals. Sometimes critical flaws and cracks in composite structures may go undetected.

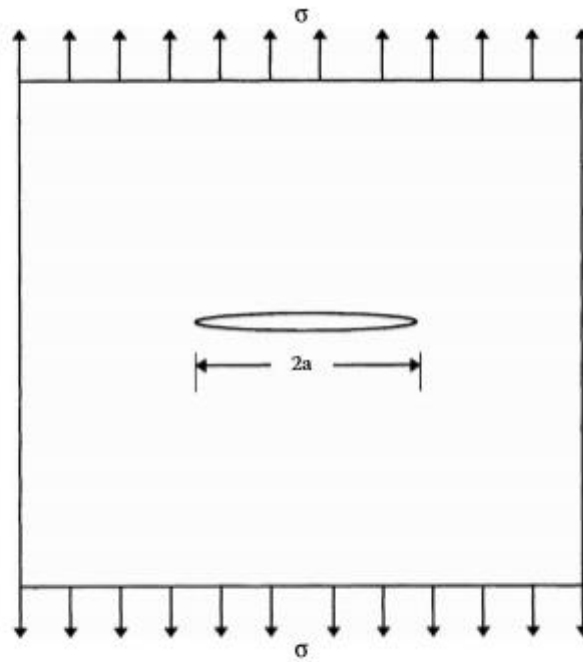
**Note:**

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\* In a material with a crack, the value of the stress intensity factor gives the measure of stresses in the crack tip region. For example, for an infinite plate with a crack of length  $2a$  under a uniaxial load  $\sigma$  (Figure 1.3), the stress intensity factor is

$$K = \sigma\sqrt{\pi a} .$$

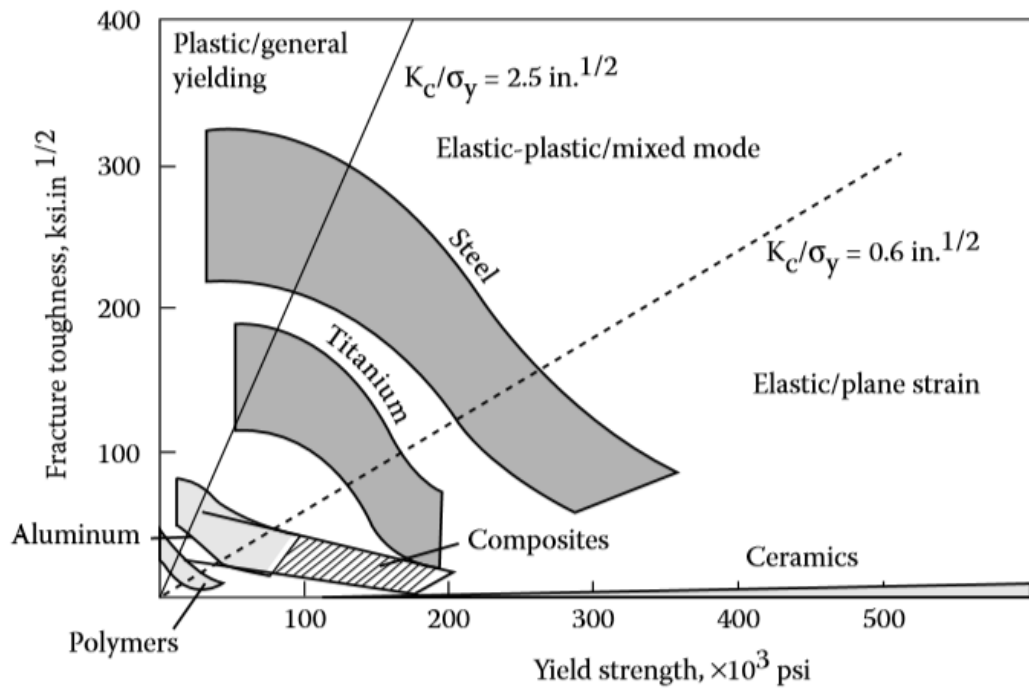
If the stress intensity factor at the crack tip is greater than the critical stress intensity factor of the material, the crack will grow. The greater the value of the critical stress intensity factor is, the tougher the material is. The critical stress intensity factor is called the fracture toughness of the material. Typical values of fracture toughness are  $23.66 \text{ ksi}\sqrt{\text{in.}}$  ( $26 \text{ MPa}\sqrt{\text{m}}$ ) for aluminum and  $25.48 \text{ ksi}\sqrt{\text{in.}}$  ( $28 \text{ MPa}\sqrt{\text{m}}$ ) for steel.



**FIGURE 1.3**  
A uniformly loaded plate with a crack.

- Composites do not have a high combination of strength and fracture toughness\* compared to metals. In [Figure 1.4](#), a plot is shown for fracture toughness vs. yield strength for a 1-in. (25-mm) thick material. Metals show an excellent combination of strength and fracture toughness compared to composites. (Note: The transition areas in [Figure 1.4](#) will change with change in the thickness of the specimen.)

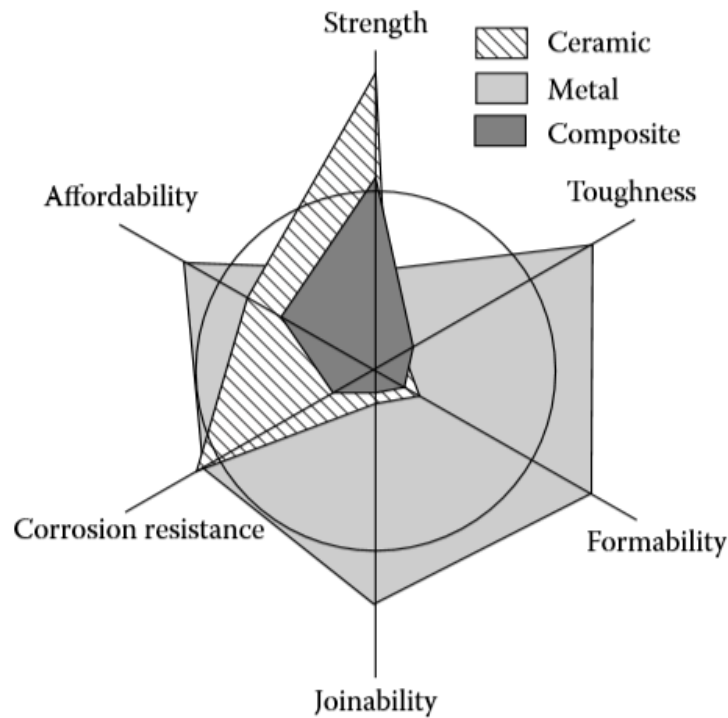




**FIGURE 1.4**

Fracture toughness as a function of yield strength for monolithic metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

- Composites do not necessarily give higher performance in all the properties used for material selection. In Figure 1.5, six primary material selection parameters — strength, toughness, formability, joinability, corrosion resistance, and affordability — are plotted. If the values at the circumference are considered as the normalized required property level for a particular application, the shaded areas show values provided by ceramics, metals, and metal–ceramic composites. Clearly, composites show better strength than metals, but lower values for other material selection parameters.



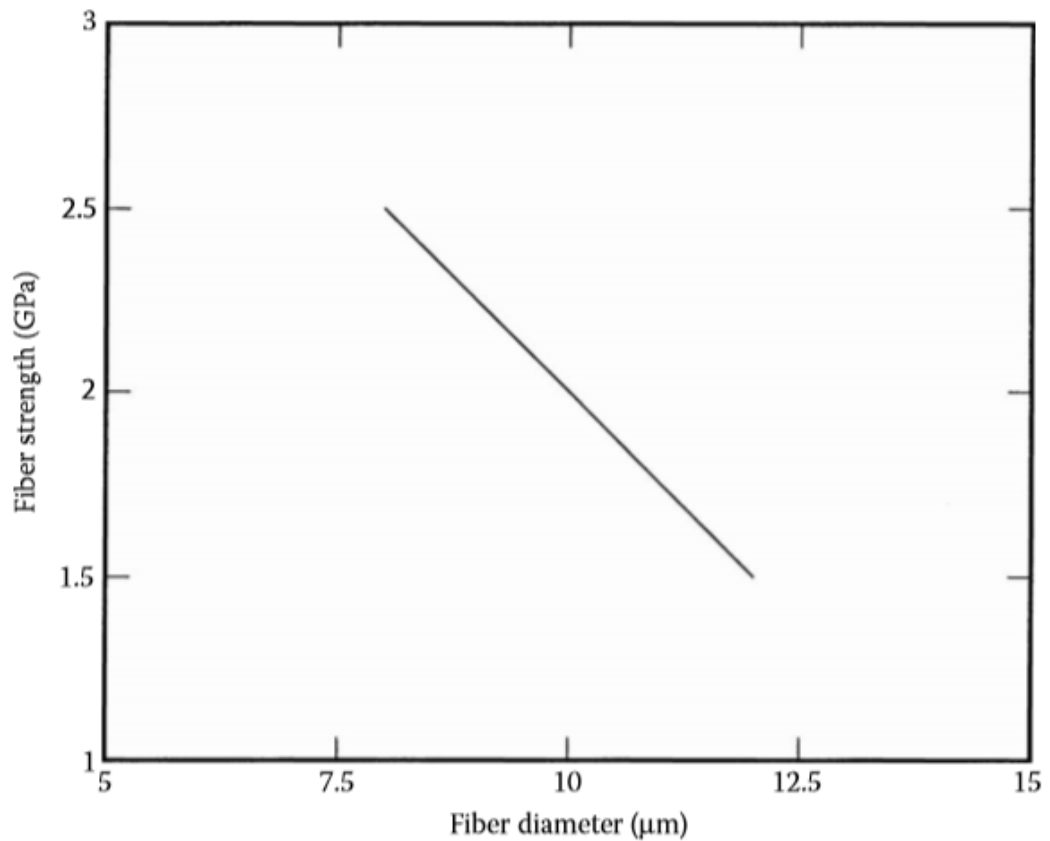
**FIGURE 1.5**

Primary material selection parameters for a hypothetical situation for metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

### Why are fiber reinforcements of a thin diameter?

The main reasons for using fibers of thin diameter are the following:

- Actual strength of materials is several magnitudes lower than the theoretical strength. This difference is due to the inherent flaws in the material. Removing these flaws can increase the strength of the material. As the fibers become smaller in diameter, the chances of an inherent flaw in the material are reduced. A steel plate may have strength of 100 ksi (689 MPa), while a wire made from this steel plate can have strength of 600 ksi (4100 MPa). [Figure 1.6](#) shows how the strength of a carbon fiber increases with the decrease in its diameter.



**FIGURE 1.6**

Fiber strength as a function of fiber diameter for carbon fibers. (Reprinted from Lamotte, E. De, and Perry, A.J., *Fibre Sci. Technol.*, 3, 159, 1970. With permission from Elsevier.)

- For higher ductility\* and toughness, and better transfer of loads from the matrix to fiber, composites require larger surface area of the fiber–matrix interface. For the same volume fraction of fibers in a composite, the area of the fiber–matrix interface is inversely proportional to the diameter of the fiber and is proved as follows.

Assume a lamina consisting of  $N$  fibers of diameter  $D$ . The fiber–matrix interface area in this lamina is

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$$A_l = N \pi D L. \quad (1.8)$$

If one replaces the fibers of diameter,  $D$ , by fibers of diameter,  $d$ , then the number of fibers,  $n$ , to keep the fiber volume the same would be

$$n = N \left( \frac{D}{d} \right)^2. \quad (1.9)$$

Then, the fiber–matrix interface area in the resulting lamina would be

$$\begin{aligned} A_{ll} &= n \pi d L. \\ &= \frac{N \pi D^2 L}{d} \\ &= \frac{4 (\text{Volume of fibers})}{d}. \end{aligned} \quad (1.10)$$

This implies that, for a fixed fiber volume in a given volume of composite, the area of the fiber–matrix interface is inversely proportional to the diameter of the fiber.

**Note:**

\* **Ductility** is the ability of a material to deform without fracturing. It is measured by extending a rod until fracture and measuring the initial ( $A_i$ ) and final ( $A_f$ ) cross-sectional area. Then ductility is defined as,

$$R = l - (A_f/A_i).$$

- Fibers able to bend without breaking are required in manufacturing of composite materials, especially for woven fabric composites. Ability to bend increases with a decrease in the fiber diameter and is measured as flexibility. Flexibility is defined as the inverse of bending stiffness and is proportional to the inverse of the product of the elastic modulus of the fiber and the fourth power of its diameter; it can be proved as follows.

**Bending stiffness** is the resistance to bending moments. According to the Strength of Materials course, if a beam is subjected to a pure bending moment,  $M$ ,

$$\frac{d^2v}{dx^2} = \frac{M}{EI}, \quad (1.11)$$

where

$v$  = deflection of the centroidal line (in. or m)

$E$  = Young's modulus of the beam (psi or Pa)

$I$  = second moment of area (in.<sup>4</sup> or m<sup>4</sup>)

$x$  = coordinate along the length of beam (in. or m)

The bending stiffness, then, is  $EI$  and the flexibility is simply the inverse of  $EI$ . Because the second moment of area of a cylindrical beam of diameter  $d$  is

$$I = \frac{\pi d^4}{64}, \quad (1.12)$$

then

$$\text{Flexibility} \propto \frac{1}{Ed^4}. \quad (1.13)$$

For a particular material, unlike strength, the Young's modulus does not change appreciably as a function of its diameter. Therefore, the flexibility for a particular material is inversely proportional to the fourth power of the diameter.

### **What fiber factors contribute to the mechanical performance of a composite?**

Four fiber factors contribute to the mechanical performance of a composite are :

- **Length:** The fibers can be long or short. Long, continuous fibers are easy to orient and process, but short fibers cannot be controlled fully for proper orientation. Long fibers provide many benefits over short fibers. These include impact resistance, low shrinkage, improved surface finish, and dimensional stability. However, short fibers provide low cost, are easy to work with, and have fast cycle time fabrication procedures. Short fibers have fewer flaws and therefore have higher strength.

- **Orientation:** Fibers oriented in one direction give very high stiffness and strength in that direction. If the fibers are oriented in more than one direction, such as in a mat, there will be high stiffness and strength in the directions of the fiber orientations. However, for the same volume of fibers per unit volume of the composite, it cannot match the stiffness and strength of unidirectional composites.
- **Shape:** The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and squareshaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.
- **Material:** The material of the fiber directly influences the mechanical performance of a composite. Fibers are generally expected to have high elastic moduli and strengths. This expectation and cost have been key factors in the graphite, aramids, and glass dominating the fiber market for composites.

### **What are the matrix factors that contribute to the mechanical performance of composites?**

Use of fibers by themselves is limited, with the exceptions of ropes and cables. Therefore, fibers are used as reinforcement to matrices. The matrix functions include binding the fibers together, protecting fibers from the environment, shielding from damage due to handling, and distributing the load to fibers. Although matrices by themselves generally have low mechanical properties compared to those of fibers, the matrix influences many mechanical properties of the composite. These properties include transverse modulus and strength, shear modulus and strength, compressive strength, interlaminar shear strength, thermal expansion coefficient, thermal resistance, and fatigue strength.

### **Other than the fiber and the matrix, what other factors influence the mechanical performance of a composite?**

Other factors include the fiber–matrix interface. It determines how well the matrix transfers the load to the fibers. Chemical, mechanical, and reaction bonding may form the interface. In most cases, more than one type of bonding occurs.

- Chemical bonding is formed between the fiber surface and the matrix. Some fibers bond naturally to the matrix and others do not. Coupling agents\* are often added to form a chemical bond.

- The natural roughness or etching of the fiber surface causing interlocking may form a mechanical bond between the fiber and matrix.

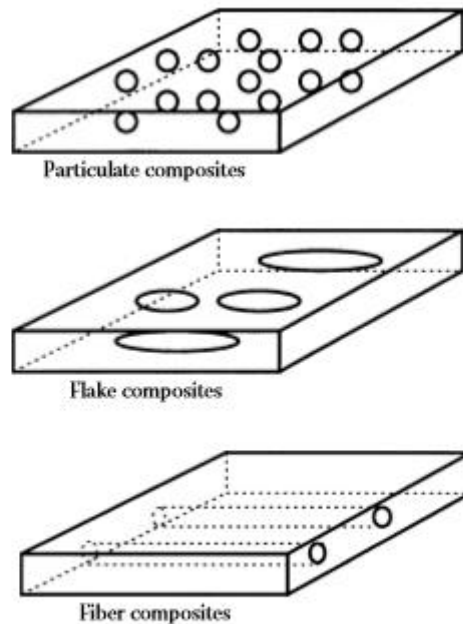
**Note:** \* Coupling agents are compounds applied to fiber surfaces to improve the bond between the fiber and matrix. For example, silane finish is applied to glass fibers to increase adhesion with epoxy matrix.

- If the thermal expansion coefficient of the matrix is higher than that of the fiber, and the manufacturing temperatures are higher than the operating temperatures, the matrix will radially shrink more than the fiber. This causes the matrix to compress around the fiber.

## 1.2 Classification

### How are composites classified?

Composites are classified by the geometry of the reinforcement, such as particulate, flake, and fibers (Figure 1.8) — or by the type of matrix, such as polymer, metal, ceramic, and carbon.



**FIGURE 1.8**  
Types of composites based on reinforcement shape.

- **Particulate composites** consist of particles immersed in matrices such as alloys and ceramics. They are usually isotropic because the particles are added randomly. Particulate composites have advantages such as improved strength, increased operating temperature, oxidation resistance, etc. Typical examples include use of aluminum particles in rubber; silicon carbide particles in aluminum; and gravel, sand, and cement to make concrete.
- **Flake composites** consist of flat reinforcements of matrices. Typical flake materials are glass, mica, aluminum, and silver. Flake composites provide advantages such as high out-of-plane flexural modulus,\* higher strength, and low cost. However, flakes cannot be oriented easily and only a limited number of materials are available for use.



- **Fiber composites** consist of matrices reinforced by short (discontinuous) or long (continuous) fibers. Fibers are generally anisotropic† and examples include carbon and aramids. Examples of matrices are resins such as epoxy, metals such as aluminum, and ceramics such as calcium–aluminum silicate. Continuous fiber composites are emphasized in this book and are further discussed in this chapter by the types of matrices: polymer, metal, ceramic, and carbon. The fundamental units of continuous fiber matrix composite are unidirectional or woven fiber laminas. Laminas are stacked on top of each other at various angles to form a multidirectional laminate.
- **Nanocomposites** consist of materials that are of the scale of nanometers ( $10^{-9}$  m). The accepted range to be classified as a nanocomposite is that one of the constituents is less than 100 nm. At this scale, the properties of materials are different from those of the bulk material. Generally, advanced composite materials have constituents on the microscale ( $10^{-6}$  m). By having materials at the nanometer scale, most of the properties of the resulting composite material are better than the ones at the microscale. Not all properties of nanocomposites are better; in some cases, toughness and impact strength can decrease. **Applications of nanocomposites** include packaging applications for the military in which nanocomposite films show improvement in properties such as elastic modulus, and transmission rates for water vapor, heat distortion, and oxygen.

*Body side molding of the 2004 Chevrolet Impala* is made of olefin-based nanocomposites.<sup>9</sup> This reduced the weight of the molding by 7% and improved its surface quality. General Motors™ currently uses 540,000 lb of nanocomposite materials per year.

**Rubber** containing just a few parts per million of metal conducts electricity in harsh conditions just like solid metal. Called Metal Rubber®, it is fabricated molecule by molecule by a process called electrostatic self-assembly. **Awaited applications of the Metal Rubber** include artificial muscles, smart clothes, flexible wires, and circuits for portable electronics.

## 1.2.1 Polymer Matrix Composites

### What are the most common advanced composites?

The most common advanced composites are polymer matrix composites (PMCs) consisting of a polymer (e.g., epoxy, polyester, urethane) reinforced by thin diameter fibers (e.g., graphite, aramids, boron). For example, graphite/ epoxy composites are approximately five times stronger than steel on a weight-for-weight basis. The reasons why they are the most common composites include their low cost, high strength, and simple manufacturing principles.

### What are the drawbacks of polymer matrix composites?

The main drawbacks of PMCs include low operating temperatures, high coefficients of thermal and moisture expansion,\* and low elastic properties in certain directions.

### What are the typical mechanical properties of some polymer matrix composites? Compare these properties with metals.

Table 1.4 gives typical mechanical properties of common polymer matrix composites.

**TABLE 1.4**

Typical Mechanical Properties of Polymer Matrix Composites and Monolithic Materials

Property	Units	Graphite/ epoxy	Glass/ epoxy	Steel	Aluminum
<i>System of units: USCS</i>					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	Msi	26.25	5.598	30.0	10.0
Ultimate tensile strength	ksi	217.6	154.0	94.0	40.0
Coefficient of thermal expansion	μin./in./°F	0.01111	4.778	6.5	12.8
<i>System of units: SI</i>					
Specific gravity	—	1.6	1.8	7.8	2.6
Young's modulus	GPa	181.0	38.6	206.8	68.95
Ultimate tensile strength	MPa	150.0	1062	648.1	275.8
Coefficient of thermal expansion	μm/m/°C	0.02	8.6	11.7	23

Give names of various fibers used in advanced polymer composites.

The most common fibers used are glass, graphite, and Kevlar. Typical properties of these fibers compared with bulk steel and aluminum are given in Table 1.5.

**TABLE 1.5**

Typical Mechanical Properties of Fibers Used in Polymer Matrix Composites

Property	Units	Graphite	Aramid	Glass	Steel	Aluminum
<i>System of units: USCS</i>						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	Msi	33.35	17.98	12.33	30	10.0
Ultimate tensile strength	ksi	299.8	200.0	224.8	94	40.0
Axial coefficient of thermal expansion	$\mu\text{in./in./}^\circ\text{F}$	-0.722	-2.778	2.778	6.5	12.8
<i>System of units: SI</i>						
Specific gravity	—	1.8	1.4	2.5	7.8	2.6
Young's modulus	GPa	230	124	85	206.8	68.95
Ultimate tensile strength	MPa	2067	1379	1550	648.1	275.8
Axial coefficient of thermal expansion	$\mu\text{m/m/}^\circ\text{C}$	-1.3	-5	5	11.7	23

Give a description of the glass fiber.

Glass is the most common fiber used in polymer matrix composites. Its advantages include its high strength, low cost, high chemical resistance, and good insulating properties. The drawbacks include low elastic modulus, poor adhesion to polymers, high specific gravity, sensitivity to abrasion (reduces tensile strength), and low fatigue strength.

The glass used for making fibers is classified into five major types, explain each one.

The letter designation is based on the characteristic property of the glass:

- (i) A-glass is a high-alkali glass; it has very good resistance to chemicals, but lower electrical properties.
- (ii) C-glass is a chemical grade, which offers extremely high chemical resistance.
- (iii) E-glass has low alkali content and it is electrical grade. It provides good insulation property and strong resistance to water.

- (iv) S-glass has 33 % higher tensile strength than E-glass.
- (v) D-glass has superior electrical properties with low dielectric constant.

**The difference in the properties** is due to the compositions of E-glass and S-glass fibers. The main elements in the two types of fibers are given in Table 1.7.

**TABLE 1.7**  
Chemical Composition of E-Glass  
and S-Glass Fibers

Material	% Weight	
	E-Glass	S-Glass
Silicon oxide	54	64
Aluminum oxide	15	25
Calcium oxide	17	0.01
Magnesium oxide	4.5	10
Boron oxide	8	0.01
Others	1.5	0.8

Give a description of graphite fibers.

Graphite fibers are very common in high-modulus and high-strength applications such as aircraft components, etc. The advantages of graphite fibers include high specific strength and modulus, low coefficient of thermal expansion, and high fatigue strength. The drawbacks include high cost, low impact resistance, and high electrical conductivity.

Are carbon and graphite the same?

No, they are different. Carbon fibers have 93 to 95% carbon content, but graphite has more than 99% carbon content. Also, carbon fibers are produced at 2400°F (1316°C), and graphite fibers are typically produced in excess of 3400°F (1900°C).

### Give a description of the aramid fiber.

An aramid fiber is an aromatic organic compound made of carbon, hydrogen, oxygen, and nitrogen. Its advantages are low density, high tensile strength, low cost, and high impact resistance. Its drawbacks include low compressive properties and degradation in sunlight.

**Types:** The two main types of aramid fibers are Kevlar 29®\* and Kevlar 49®†. Both types of Kevlar fibers have similar specific strengths, but Kevlar 49 has a higher specific stiffness. Kevlar 29 is mainly used in bulletproof vests, ropes, and cables. High performance applications in the aircraft industry use Kevlar 49.

### Give names of various polymers used in advanced polymer composites.

These polymers include epoxy, phenolics, acrylic, urethane, and polyamide.

### Why are there so many resin systems in advanced polymer composites?

Each polymer has its advantages and drawbacks in its use:

- **Polyesters:** The advantages are low cost and the ability to be made translucent; drawbacks include service temperatures below 170°F (77°C), brittleness, and high shrinkage\* of as much as 8% during curing.
- **Phenolics:** The advantages are low cost and high mechanical strength; drawbacks include high void content.
- **Epoxies:** The advantages are high mechanical strength and good adherence to metals and glasses; drawbacks are high cost and difficulty in processing.

As can be seen, each of the resin systems has its advantages and drawbacks. The use of a particular system depends on the application. These considerations include mechanical strength, cost, smoke emission, temperature excursions, etc.

### Epoxy is the most common type of matrix material. Why?

Although epoxy is costlier than other polymer matrices, it is the most popular PMC matrix. More than two-thirds of the polymer matrices used

in aerospace applications are epoxy based. The main reasons why epoxy is the most used polymer matrix material are

- High strength
- Low viscosity and low flow rates, which allow good wetting of fibers and prevent misalignment of fibers during processing
- Low volatility during cure
- Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement
- Available in more than 20 grades to meet specific property and processing requirements.

Polymers are classified as thermosets and thermoplastics. What is the difference between the two? Give some examples of both.

Thermoset polymers are insoluble and infusible after cure because the chains are rigidly joined with strong covalent bonds; thermoplastics are formable at high temperatures and pressure because the bonds are weak and of the van der Waals type.

**Typical examples of thermoset** include epoxies, polyesters, phenolics, and polyamide;

#### **Thermosetting Plastic Advantages:**

- More resistant to high temperatures
- Highly flexible design
- Thick to thin wall capabilities
- High levels of dimensional stability
- Cost-effective

#### **Thermosetting Plastics Disadvantages:**

- Can't be recycled
- More difficult to surface finish
- Can't be remolded or reshaped

**Typical examples of thermoplastics** include polyethylene, polystyrene, polyether–ether–ketone (PEEK), and polyphenylene sulfide (PPS).

**Thermoplastic Advantages:**

- Highly recyclable
- High-Impact resistance
- Reshaping capabilities
- Chemical resistant
- Aesthetically superior finishes
- Hard crystalline or rubbery surface options

**Thermoplastic Disadvantages:**

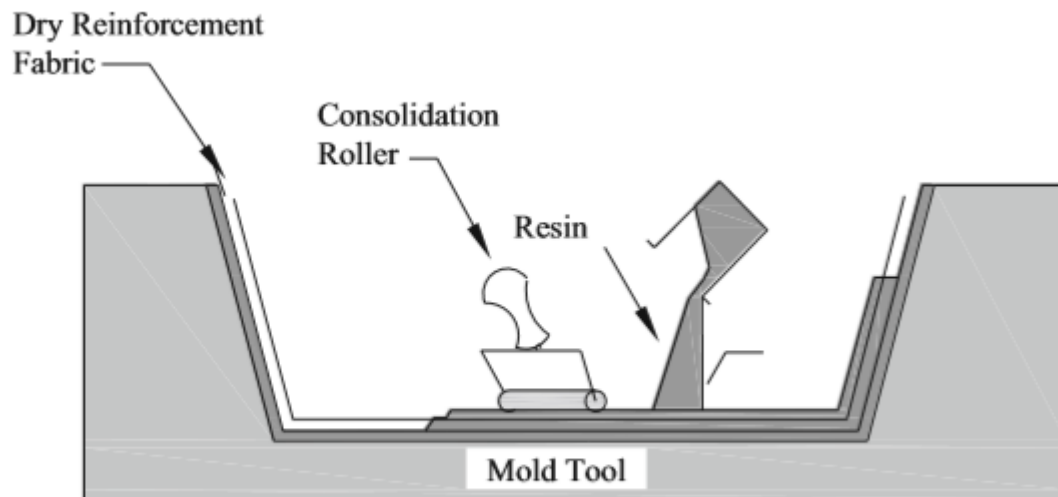
- Expensive
- Can melt if heated.

## **What are Current Manufacturing Methods of Polymer Matrix Composites?**

### **1) Hand Lay-up Technique:**

Hand layup is an oldest open-mold process used for the composite manufacturing. This process is simple, and it is a low-volume and labor-intensive process. Large components, such as boat hulls, can be prepared by this technique. Reinforcing mat or woven fabric or roving is placed manually in the open mold, and resin is poured, brushed, or sprayed over and into the glass plies. Squeegees or rollers are used to remove the entrapped air manually to complete the laminated structure as shown in Fig.1.3. The most commonly used matrixes are polyesters and epoxies that can be cured at room temperature. The time of curing depends on the type of polymer used for composite processing. For example, for epoxy-based system, normal curing time at room temperature is 24–48 h. A catalyst and accelerator are added to the resin, which enables room-temperature curing of the resin. In order to get high quality part surface, a pigmented gel layer is first applied on the mold surface. Hand layup is the most

commonly preferred process for the manufacture of polymeric composites. Composites were basically manufactured by hand lay-up process, using a fiber-to-resin ratio of 40:60 (w:w).

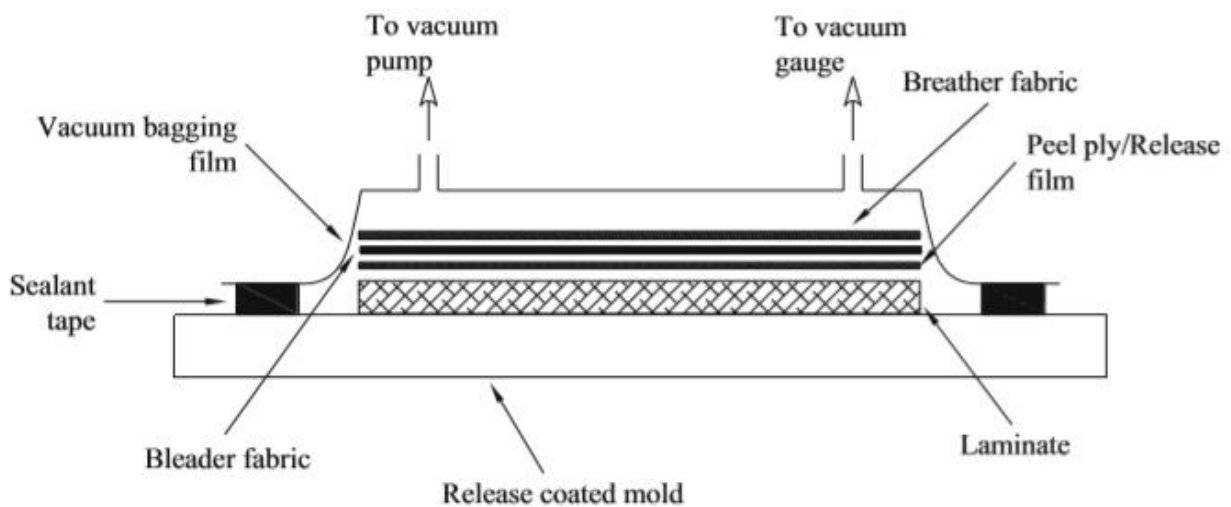


**Fig. 1.3** Schematic of hand layup



## 2) Vacuum Bag Molding

In vacuum bag molding, the entrapped air and excess resin are removed using vacuum. After fabrication of the lay-up, a perforated release film or peel ply is placed over the laminate. The bleeder ply, which is placed above the peel ply, is made of fiber glass cloth, nonwoven nylon, polyester cloth, or other material that absorbs excess resin from the laminate, followed by a breather ply of a nonwoven fabric. The vacuum bag is placed over the entire assembly and sealed at the mold flange as shown in Fig. 1.4.



**Fig. 1.4** Schematic of vacuum bag molding

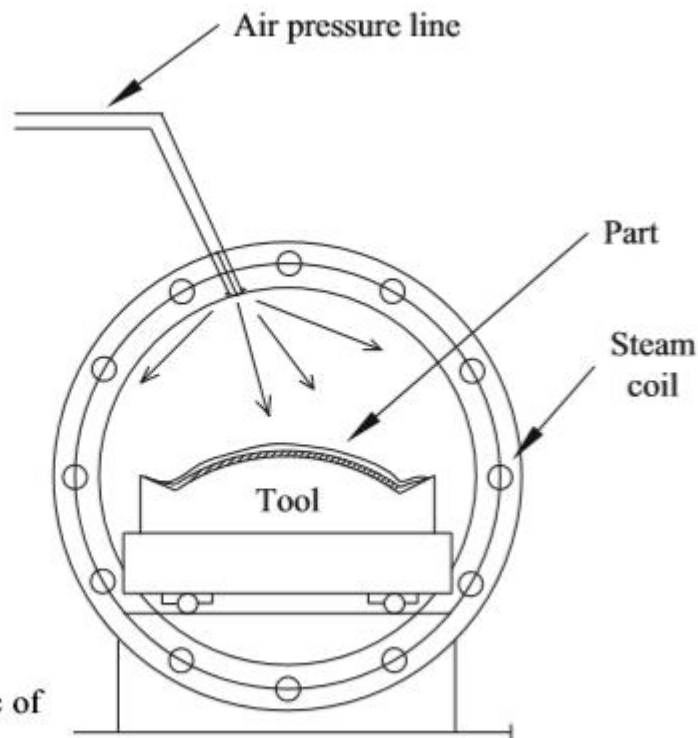
A vacuum is created under the bag, and thus the laminate can be merged by applying a pressure up to one atmosphere. This process provides a high reinforcement, improved adhesion between layers, and great control of fiber volume percent compared to the hand lay-up.

Major advantages of vacuum bag molding are higher fiber content in the laminate, lower void content, better fiber wet-out, and reduced volatile emissions as compared to the hand layup. Large cruising boats and racing car components can be manufactured by vacuum bag molding. Disadvantages of vacuum bag molding include expensive and disposable bagging materials, labor intensive, inconsistent performance, trapped air/volatiles, wrinkles, loss of seal, and requirement of higher level of operator skills.

### 3) Pressure Bag Molding (or Autoclave )

Pressure bag molding or autoclave is identical to the vacuum bag molding except that the pressure, usually provided by compressed air or water, is applied to the flexible bag that covers the prepreg composite. The application of pressure forces out the entrapped air, vapors, and excess resin. It also facilitates better wetting of fibers.

Autoclaves are basically heated pressure vessels. These are usually provided with the vacuum systems. The bagged lay-up is cured inside the autoclave as shown in Fig.1.5.

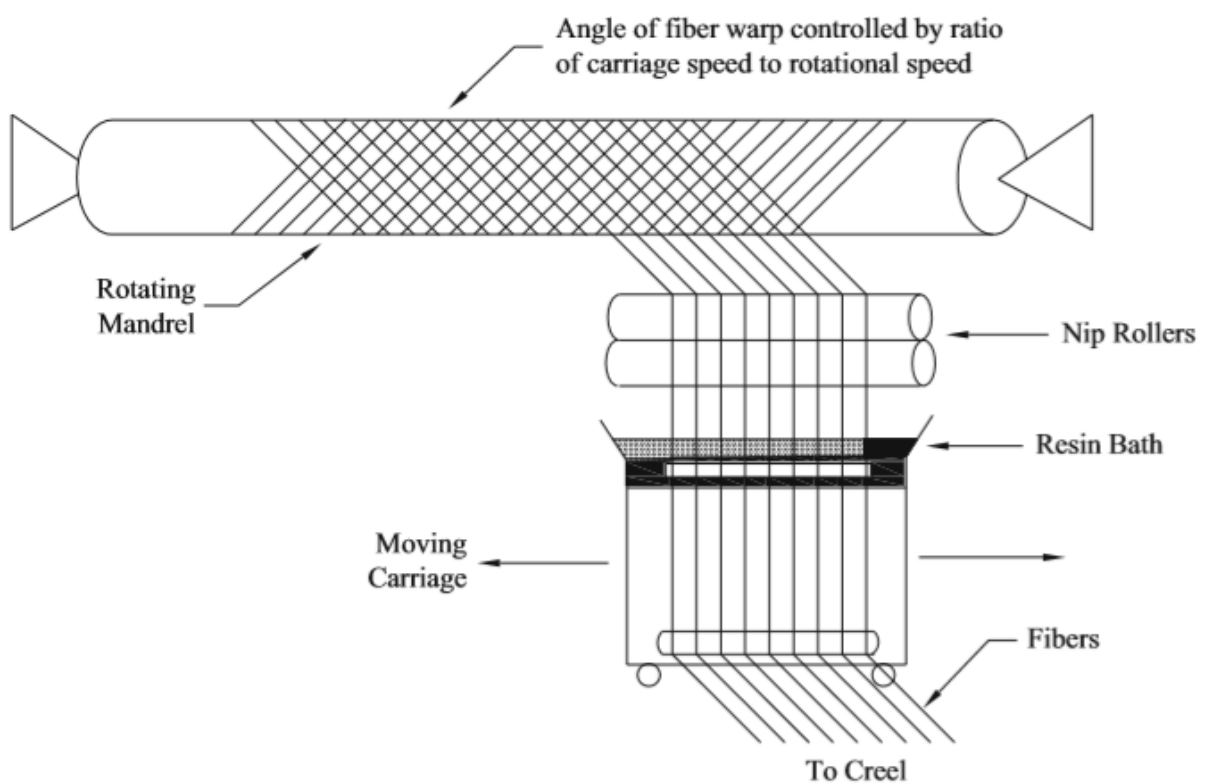


**Fig. 1.5** Schematic of autoclave

The process of autoclave involves application of higher heat and uniform pressure on the component during curing, which results in a denser and low void percentage product. The autoclave equipment and tooling are expensive and it is only suitable for high-end applications. The pressures required for curing are typically in the range of one to six bars and takes several hours to complete the curing. This method accommodates higher temperature matrix resins having properties higher than the conventional resins, such as epoxies. Component size is limited by the autoclave size. It is mostly used in the aerospace industry to manufacture high-strength/weight ratio parts from pre-impregnated high-strength fibers for aircraft, spacecraft, and missiles.

#### 4) Filament Winding

This process consists of a rotating mandrel on which pre-impregnated fibers or reinforcement is wound in the preset patterns. The method provides the best control of fiber placement. The wet method is shown in Fig. 1.6. Here, the fiber is allowed to pass through a bath containing low-viscosity resin. In the dry method, the pre-impregnated reinforcing layers are wound on the mandrel, and then the component is removed and postcured.



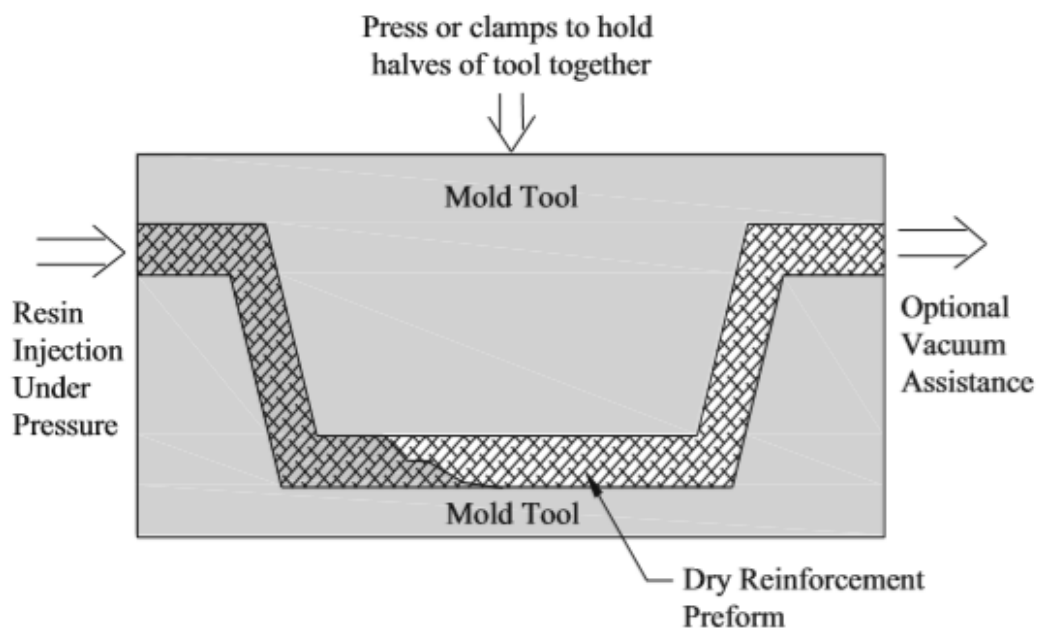
**Fig. 1.6** Schematic of filament winding

Conventionally, this process is used to make pressure vessels, rocket motor cases, tanks, ducting, golf club shafts, and fishing rods. Recently, non-cylindrical and nonspherical composite parts are also produced by filament winding technology. Polyesters, vinyl esters, epoxies, and phenolics are the typical thermoset resins used in the filament wound parts. This process is best suited for parts with rotational symmetry, but it is possible to wind odd-shaped parts using a robotized winding. It requires special

equipment and may result in variation in the part thickness in case of tapered parts. The tooling and setup cost is high and it is only suitable for a limited variety of components.

### 5) Resin Transfer Molding

Resin transfer molding (RTM) is a low-pressure closed molding process for moderate- and high-volume production. This process basically involves placement of the dry stack of reinforcement in the bottom part of the mold, and then the other half is clamped over the bottom mold. For complex shapes, preforms are used. After closing the mold, a low-viscosity resin containing catalyst is pumped in, which displace the air through strategically located vents. The resin/catalyst ratios are controlled by metered mixing equipment and injected into the mold port as shown in Fig. 1.8.



**Fig. 1.8** Schematic of resin transfer molding

The commonly used matrix resins include polyester, vinyl ester, epoxy, and phenolics. Both injection and curing can take place at either ambient or elevated temperature. In order to have optimum surface finish, a gel coat is applied to the mold surface prior to molding. High-quality parts such as automotive body parts, bathtubs, and containers are produced by this method. The variation in injection pressure has no effect on the

quality of moldings. A wide range of resin viscosities has been successfully molded by this technique (RTM). It can produce laminates having high fiber volume with very low void contents. It is safe for the health and environment due to the enveloping of resin. Component prepared by RTM has molded surface on both sides. The disadvantages of RTM process are need of heavy and expensive tooling to withstand pressures, limitation in size of the components, and very expensive scrap parts due to un-impregnated areas.