Introduction to Composite Materials

LECTURE : 2: CHAPTER ONE

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1.1 Introduction to Composite Materials

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.

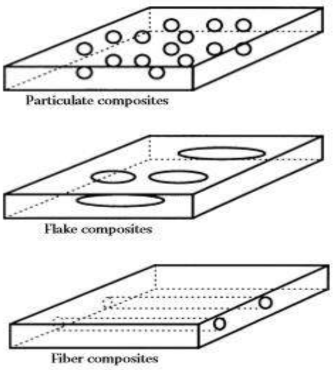

FIGURE 1.8
Types of composites based on reinforcement shape.

- **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–alumino silicate. Continuous fiber composites are emphasized in this lecture 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 olefinbased nanocomposites.9 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
System of units: USCS					
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
System of units: SI					
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
System of units: USCS						
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	μin./in./°F	−0.722	−2.778	2.778	6.5	12.8
System of units: SI						
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	μm/m/°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

	% Weight	
Material	**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).

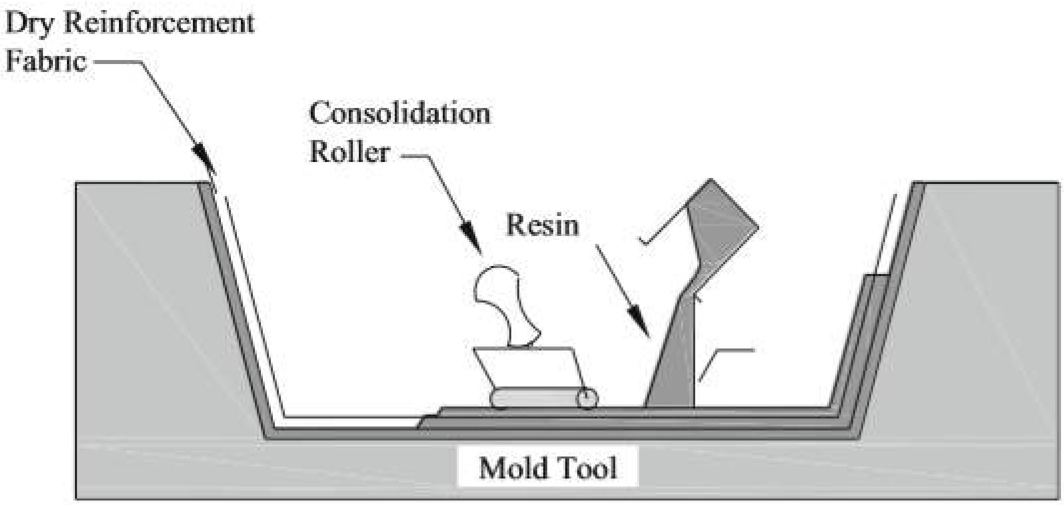

Fig. 1.3 Schematic of hand layup

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.

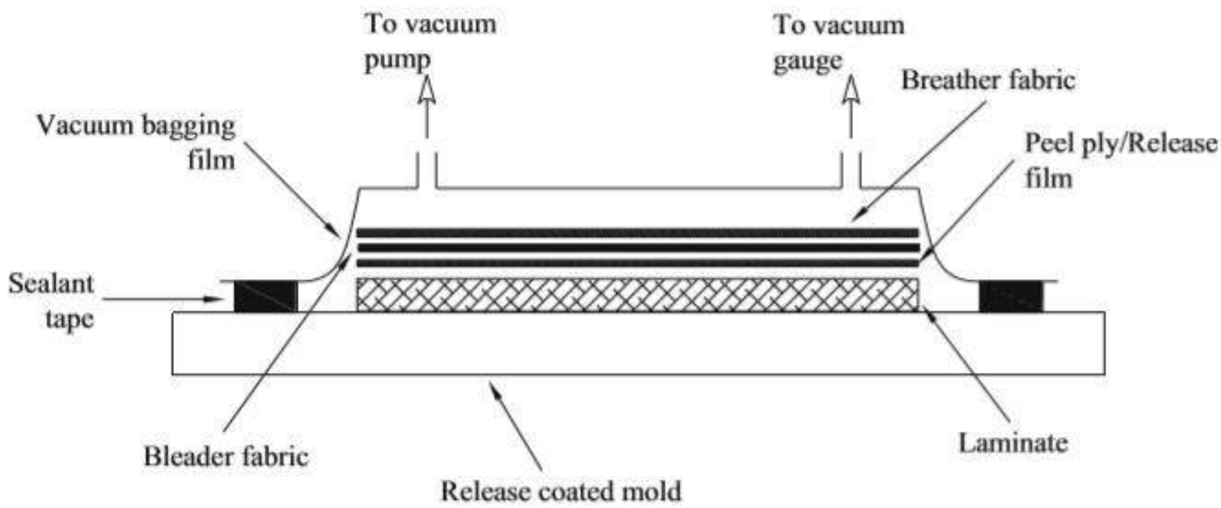

Fig. 1.4 Schematic of vacuum bag molding

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.

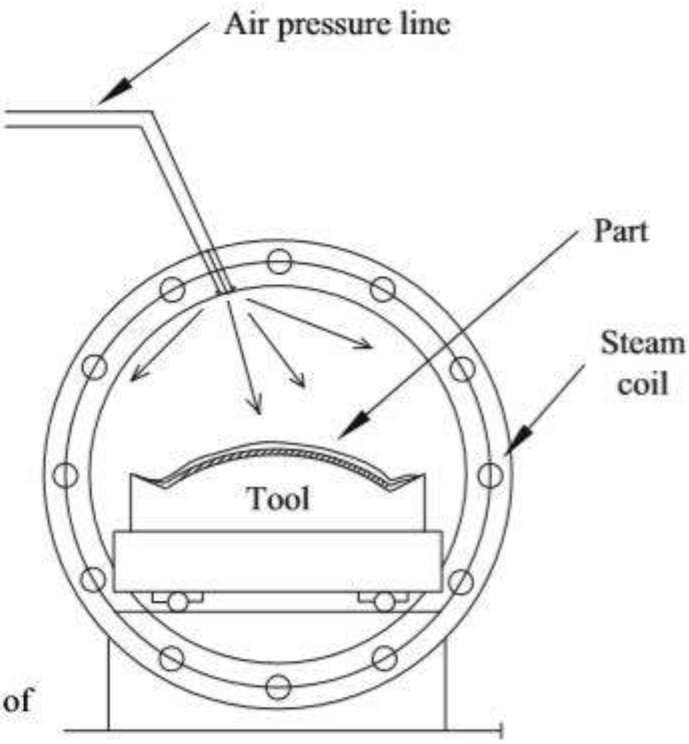

Fig. 1.5 Schematic of autoclave

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 <u>one to six bars</u> 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.

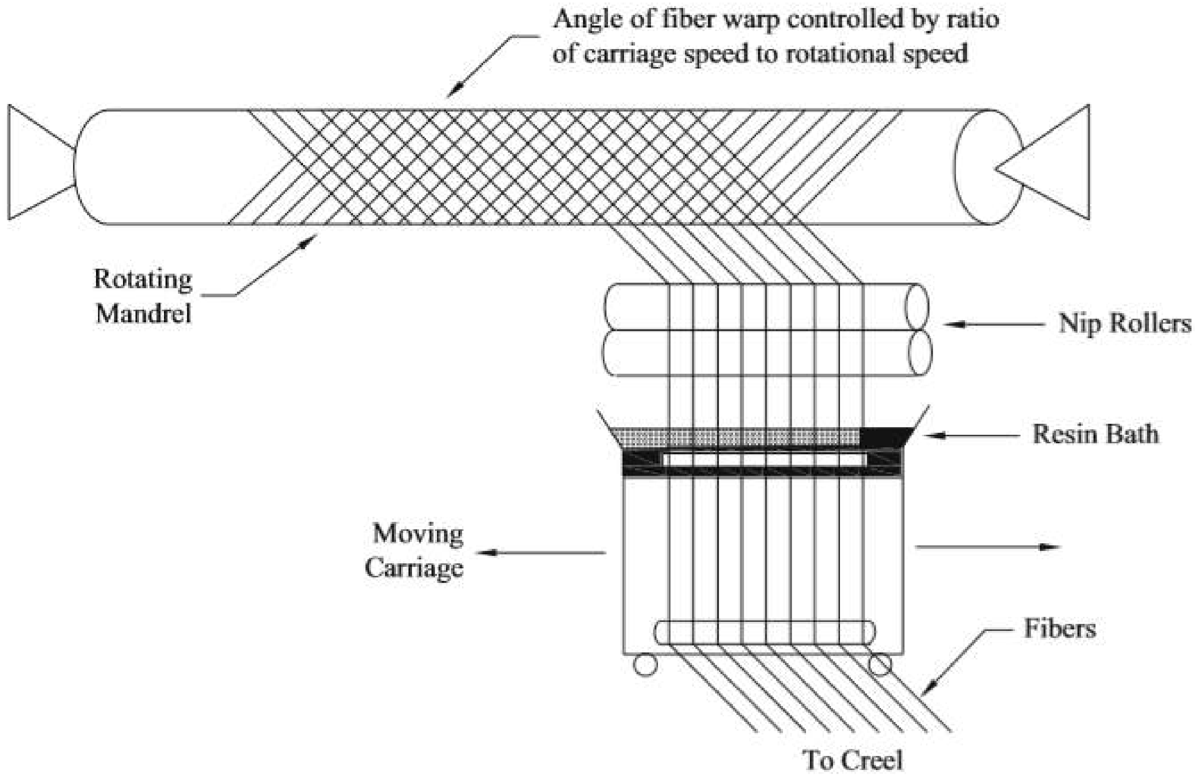

Fig. 1.6 Schematic of filament winding

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.

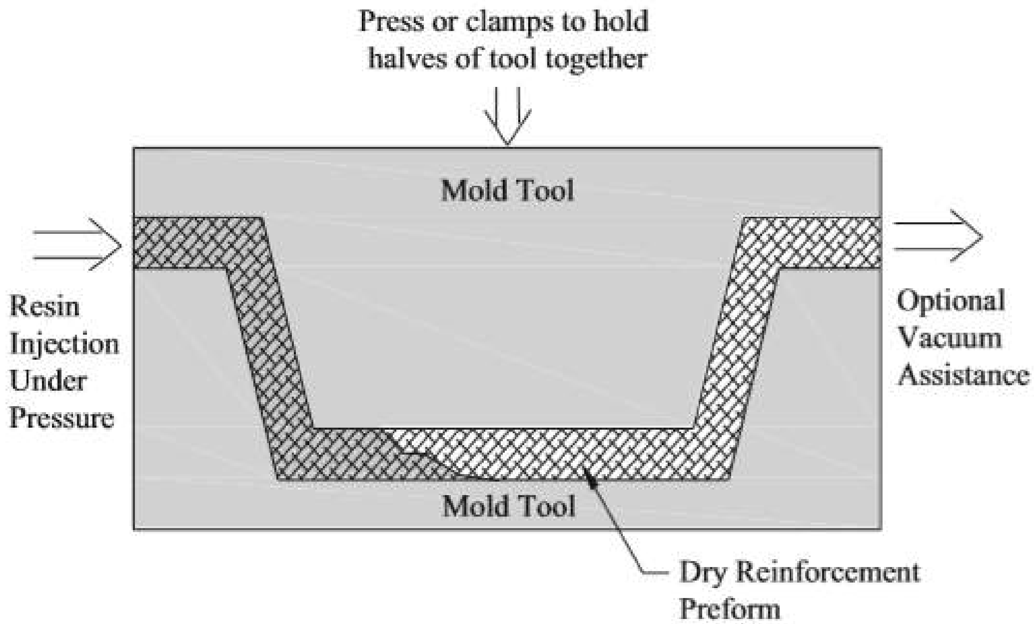

Fig. 1.8 Schematic of resin transfer molding

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.

Introduction to Composite Materials

LECTURE : 3: CHAPTER ONE

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1.3 Applications of Polymer Matrix Composites (PMCs)

Give typical applications of polymer matrix composites.

It is highly impossible to provide a complete list of PMC applications. However, some applications classified according to major market segments are indicated here.

Aerospace and Aircraft: PMCs has wide applications in aerospace industry such as construction of containers, gliders, control surfaces, and light aircraft, internal fittings, window masks, partitions and floors, galley units and trolleys, satellite components, aerials and associated enclosures, structural members, ground support equipment components and enclosures, etc.

In commercial airlines, the use of composites has been conservative because of safety concerns. Use of composites is limited to secondary structures such as rudders and elevators made of graphite/epoxy for the Boeing 767 and landing gear doors made of Kevlar–graphite/epoxy. Composites are also used in panels and floorings of airplanes. Some examples of using composites in the primary structure are the all-composite Lear Fan 2100 plane and the tail fin of the Airbus A310-300. In the latter case, the tail fin consists of graphite/epoxy and aramid honeycomb. It not only reduced the weight of the tail fin by 662 lb (300 kg) but also reduced the number of parts from 2000 to 100. Skins of aircraft engine cowls shown in Figure 1.19 are also made of polymer matrix composites for reducing weight.

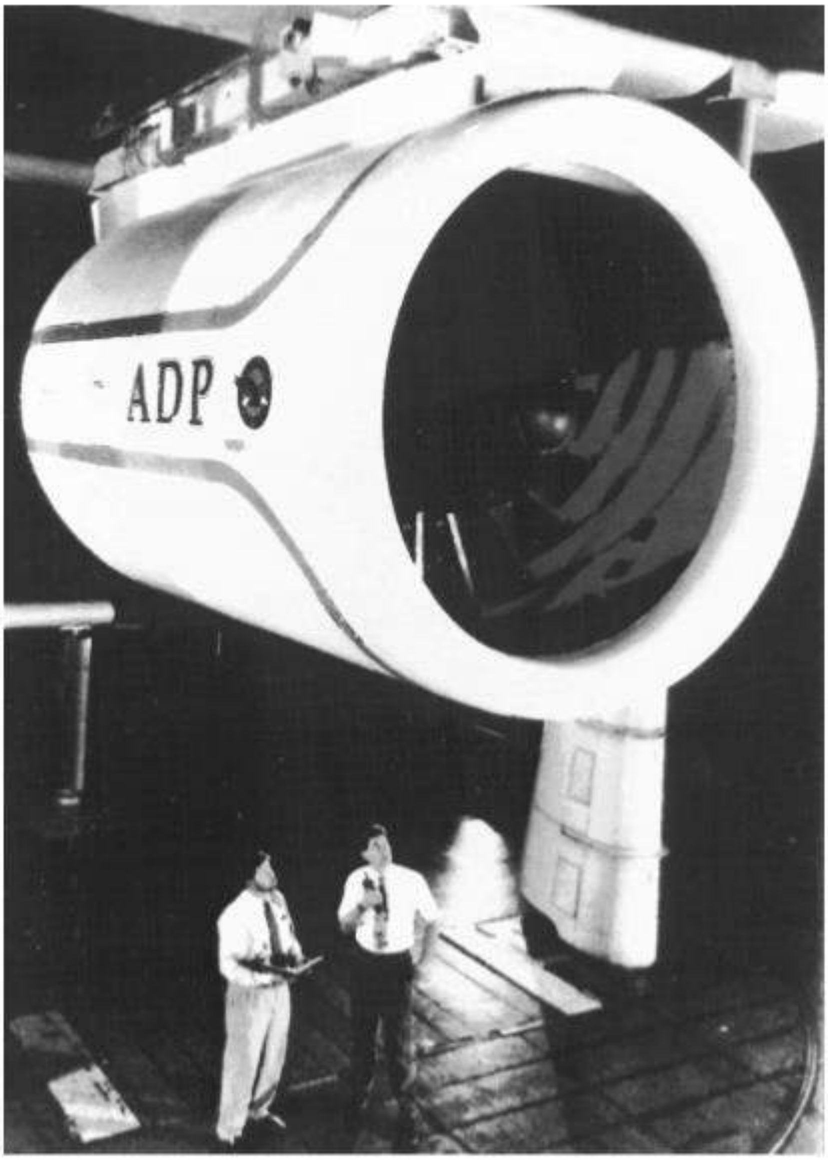

FIGURE 1.19
Aircraft engine cowling. (Photo provided courtesy of Alliant Techsystems, Inc.)

With increasing competition in model airplane flying, the weight of composite materials has been reduced. Figure 1.20 shows a World War II model airplane with fuselage made of glass/epoxy, wings made of balsa-wood facings/Styrofoam core sandwich construction, and wingspars made of graphite/epoxy.

FIGURE 1.20
Model BF109 WWII German fighter plane using glass/epoxy-molded fuselage and wing spars of graphite/epoxy. (Photo courtesy of Russell A. Lepré, Tampa, FL.)

Helicopters and tiltrotors (see Figure 1.21) use graphite/epoxy and glass/ epoxy rotor blades that not only increase the life of blades by more than 100% over metals but also increase the top speeds.

FIGURE 1.21
The BELL™ V-22 Osprey in combat configuration. (Courtesy of Bell Helicopter Textron Inc.)

Space: Two factors make composites the material of choice in space applications: high specific modulus and strength, and dimensional stability during large changes in temperature in space. Examples include the Graphite/ epoxy-honeycomb payload bay doors in the space shuttle (see Figure 1.22). Weight savings over conventional metal alloys translate to higher payloads that cost as much as $1000/lb ($2208/kg). Also, for the space shuttles, graphite/epoxy was chosen primarily for weight savings and for small mechanical and thermal deflections concerning the remote manipulator arm, which deploys and retrieves payloads.

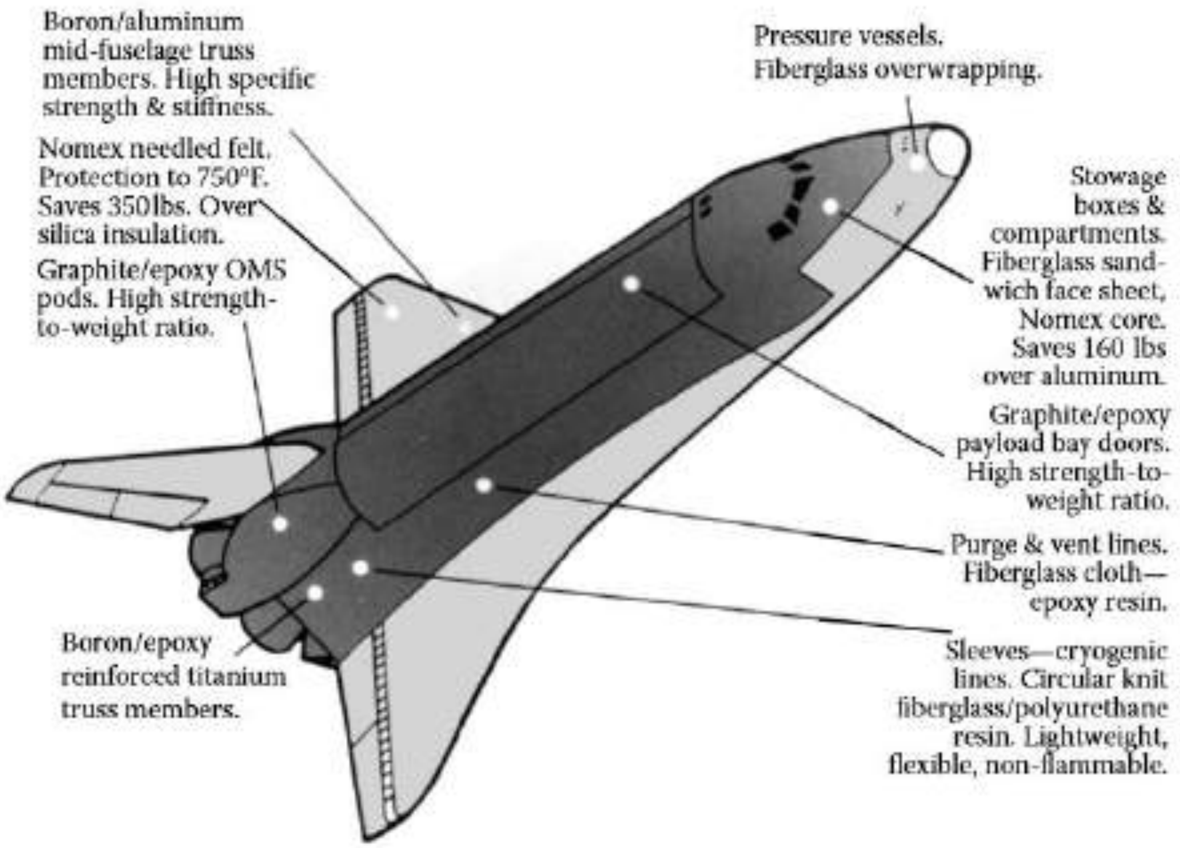

FIGURE 1.22
Use of composites in the space shuttle. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

Medical devices: Applications here include the use of glass–Kevlar/epoxy lightweight face masks for epileptic patients. Artificial portable lungs are made of graphite–glass/epoxy so that a patient can be mobile. X-ray tables made of graphite/epoxy facing sandwiches are used for their high stiffness, light weight, and transparency to radiation. The latter feature allows the patient to stay on one bed for an operation as well as x-rays and be subjected to a lower dosage of radiation.

Building and Construction: External and internal cladding, permanent and temporary formwork and shuttering, partitions, polymer concrete, prefabricated buildings, booth, cabins and housing, structural and decorative building elements, bridge elements and sections, quay facings, signposts and street furniture, staging, fencing and walkways, etc.

Consumer Product Components: For domestic and industrial furniture, sanitary ware, sporting goods, caravan components, archery and playground equipment, garden furniture, notice boards, theme park requirements, swimming pools, aqua tubes, diving boards, seating and benches, skis and snowboards, etc.

Sporting goods: Graphite/epoxy is replacing metals in golf club shafts (see Figure) mainly to decrease the weight and use the saved weight in the head. This increase in the head weight has improved driving distances by more than 25 yards (23 m).

Corrosion-Resistant Equipment: Chemical plant, linings, oil industry components, pipes and ducts, chimneys, grid flooring, staging and walkways, pressure vessels, processing tanks and vessels, fume hoods, scrubbers and cooling tower components, etc.

Electrical and Electronic: Internal and external aerial components and fittings, circuit boards, generation and transmission components, insulators, switch boxes and cabinets, booms, distribution posts and pylons, telegraph poles, fuse tubes, transformer elements, ladders and cableways, etc.

Marine Applications: PMC_s are used in the manufacture of canoes and boats or (yachts, see Figure), therefore most of these marine applications are made of fiber glass. Furthermore, hybrids of Kevlar–glass/epoxy are now replacing fiber glass for improved weight savings, vibration damping, and impact resistance. Kevlar–epoxy by itself would have poor compression properties.

Housings made of metals such as titanium to protect expensive oceanographic research instruments during explorations of sea wrecks are cost prohibitive. These housings are now made out of glass/epoxy and sustain pressures as high as 10 ksi (69 MPa) and extremely corrosive conditions.

Bridges made of polymer composite materials are gaining wide acceptance due to their low weight, corrosion resistance, longer life cycle, and limited earthquake damage. Although bridge components made of composites may cost $5/lb as opposed to components made of steel, reinforced concrete may only cost $0.30 to $1.00 per pound; the former weighs 80% less than the latter. Also, by lifetime costs, fewer composite bridges need to be built than traditional bridges.

Other marine applications: surf and sailboards, lifeboats and rescue vessels, buoys, boat accessories and subassemblies, window masks and internal moldings and fittings for ferries and cruise liners, work boats and trawlers, etc.

Transportation: Automotive (e.g., a body of car "Ford GT" made of carbon fibre completely, see Figure), bus, camper and vehicle components generally, both underbody, engine and body panels, truck, rail and other vehicle components and fittings, land and sea containers, railway track and signaling components, traffic signs, seating, window masks and partitions, etc.

1.2.2 Metal Matrix Composites

What are metal matrix composites?

Metal matrix composites (MMCs), as the name implies, have a metal matrix. Examples of matrices in such composites include aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, and large coefficients of thermal expansion and thermal and electric conductivities of metals can be reduced, by the addition of fibers such as silicon carbide.

What are the advantages of metal matrix composites?

Metal matrix composites (MMCs) are mainly used to provide advantages over monolithic metals such as steel and aluminum. These advantages include higher specific strength and modulus by reinforcing low-density metals, such as aluminum and titanium; lower coefficients of thermal expansion by reinforcing with fibers with low coefficients of thermal expansion, such as graphite; and maintaining properties such as strength at high temperatures. MMCs have several advantages over polymer matrix composites. These include higher elastic properties; higher service temperature; insensitivity to moisture; higher electric and thermal conductivities; and better wear, fatigue, and flaw resistances. The drawbacks of MMCs over PMCs include higher processing temperatures and higher densities.

Do any properties degrade when metals are reinforced with fibers?

Yes, reinforcing metals with fibers may reduce ductility and fracture toughness. Ductility of aluminum is 48% and it can decrease to below 10% with simple reinforcements of silicon carbide whiskers. The fracture toughness of aluminum alloys is 18.2 to 36.4 (20 to 40) and it reduces by 50% or more when reinforced with silicon fibers.

What are the typical mechanical properties of some metal matrix composites? Compare the properties with metals.

Typical mechanical properties of MMCs are given in Table 1.11.

TABLE 1.11

Typical Mechanical Properties of Metal Matrix Composites

Property	Units	SiC/ aluminum	Graphite/ aluminum	Steel	Aluminum
System of units: USCS					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	Msi	17	18	30	10
Ultimate tensile strength	ksi	175	65	94	34
Coefficient of thermal expansion	μin./in./°F	6.9	10	6.5	12.8
System of units: SI					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	GPa	117.2	124.1	206.8	68.95
Ultimate tensile strength	MPa	1206	448.2	648.1	234.40
Coefficient of thermal expansion	μm/m/°C	12.4	18	11.7	23

Show one process of how metal matrix composites (MMCs) are manufactured.

Fabrication methods for MMCs are varied. One method of manufacturing them is diffusion bonding (Figure 1.28), which is used in manufacturing boron/aluminum composite parts . A fiber mat of boron is placed between two thin aluminum foils about 0.002 in. (0.05 mm) thick. A polymer binder or an acrylic adhesive holds the fibers together in the mat. Layers of these metal foils are stacked at angles as required by the design. The laminate is first heated in a vacuum bag to remove the binder. The laminate is then hot pressed with a temperature of about 932°F (500°C) and pressure of about 5 ksi (35 MPa) in a die to form the required machine element.

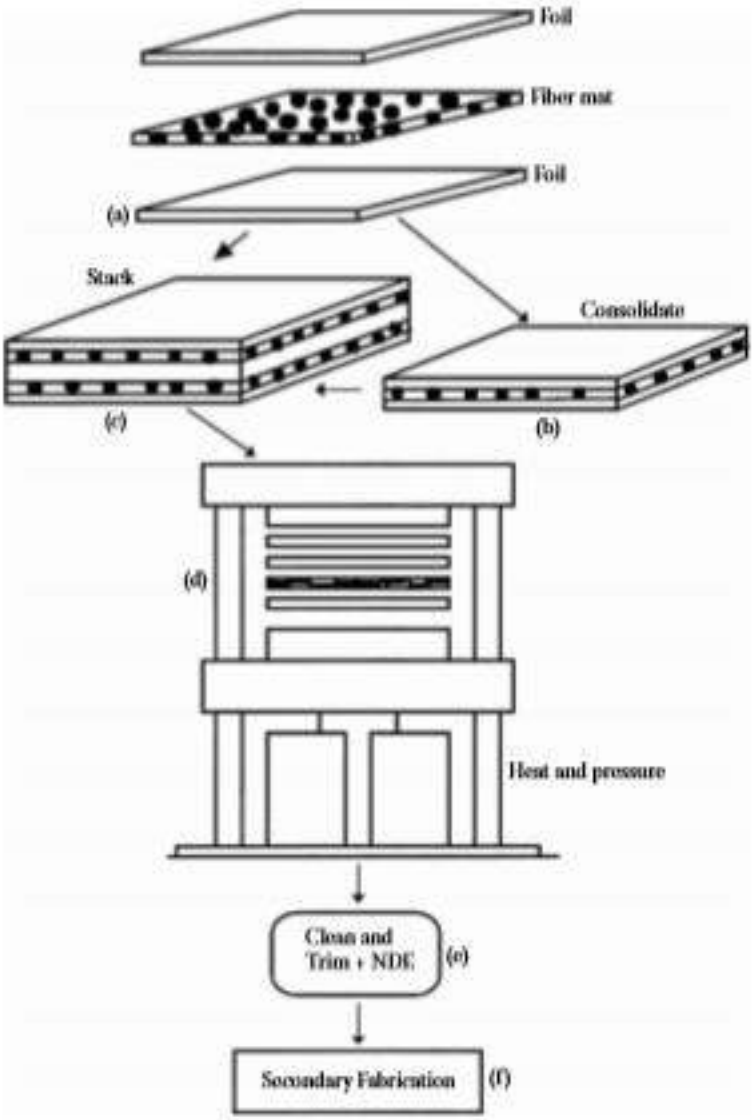

FIGURE 1.28
Schematic of diffusion bonding for metal matrix composites. (Reproduced with permission from Matthews, F.L. and Rawlings, R.D., *Composite Materials: Engineering and Science*, Chapman & Hall, London, 1994, Figure 3.1, p. 81. Copyright CRC Press, Boca Raton, FL.)

What are some of the applications of metal matrix composites? Or Metal matrix composites applications are:

• **Space:** The space shuttle uses boron/aluminum tubes to support its fuselage frame. In addition to decreasing the mass of the space shuttle by more than 320 lb (145 kg), boron/aluminum also reduced the thermal insulation requirements because of its low thermal conductivity. The mast of the Hubble Telescope uses carbon-reinforced aluminum.

• **Military:** Precision components of missile guidance systems demand dimensional stability — that is, the geometries of the components cannot change during use Metal matrix composites such as SiC/ aluminum composites satisfy this requirement because they have high micro yield strength.* In addition, the volume fraction of SiC can be varied to have a coefficient of thermal expansion compatible with other parts of the system assembly.

• **Transportation:** Metal matrix composites are finding use now in automotive engines that are lighter than their metal counterparts. Also, because of their high strength and low weight, metal matrix composites are the material of choice for gas turbine engines (Figure 1.30).

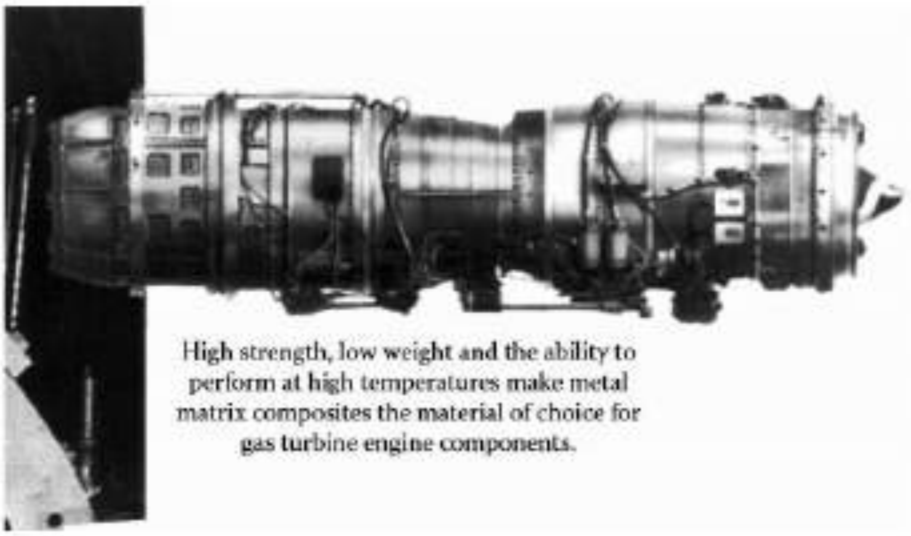

FIGURE 1.30
Gas turbine engine components made of metal matrix composites. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

1.2.3 Ceramic Matrix Composites

What are ceramic matrix composites?

Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina calcium alumino silicate reinforced by fibers such as carbon or silicon carbide.

What are the advantages of ceramic matrix composites?

Advantages of CMCs include high strength, hardness, high service temperature limits* for ceramics, chemical inertness, and low density. However, ceramics by themselves have low fracture toughness. Under tensile or impact loading, they fail catastrophically. Reinforcing ceramics with fibers, such as silicon carbide or carbon, increases their fracture toughness (Table 1.12) because it causes gradual failure of the composite. This combination of a fiber and ceramic matrix makes CMCs more attractive for applications in which high mechanical properties and extreme service temperatures are desired.

TABLE 1.12

Typical Fracture Toughness of Monolithic Materials and Ceramic Matrix Composites

Material	Fracture toughness (MPa $\sqrt{m}$)	Fracture toughness (ksi $\sqrt{in.}$)
Epoxy	3	2.73
Aluminum alloys	35	31.85
Silicon carbide	3	2.73
SiC/Al_2O_3	27	24.6
SiC/SiC	30	27.3

What are the applications of ceramic matrix composites?

Ceramic matrix composites are finding increased application in high-temperature areas in which metal and polymer matrix composites cannot be used. This is not to say that CMCs are not attractive otherwise, especially considering their high strength and modulus, and low density. Typical applications include cutting tool inserts in oxidizing and high-temperature environments. Textron Systems Corporation® has developed fiber-reinforced ceramics with SCS™ monofilaments for future aircraft engines (Figure 1.32).

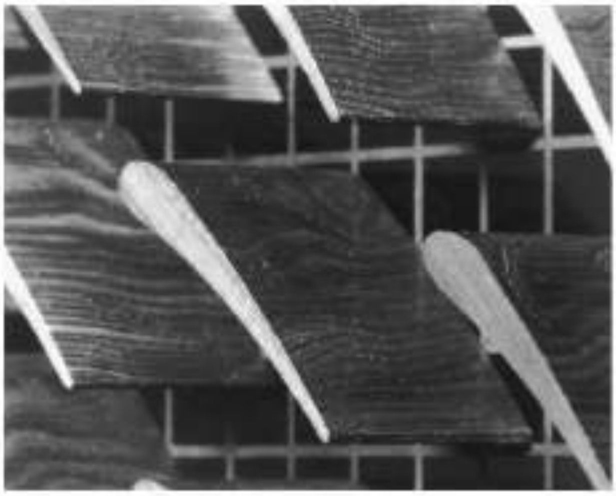

FIGURE 1.32
Ceramic matrix composites for high temperature and oxidation resistant application. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

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1.4 Recycling Fiber-Reinforced Composites

What types of processes are used for recycling of composites?

The two main processes are called chemical and mechanical processes.

Why is recycling of composites complex?

This is because of the many variables in material types — thermoset vs. thermoplastics, long vs. short fibers, glass vs. carbon, etc.

What are the various steps in mechanical recycling of short fiber-reinforced composites?

These are shredding, separation, washing, grinding, drying, and extrusion.

Why is chemical recycling not as popular as mechanical recycling?

Chemical processing is very costly. Processes such as pyrolysis (decomposing materials in an oxygen-free atmosphere) produce many gases, and hydrogenation gives high filler content. However, General Motors has adapted pyrolysis to recycle composite automobile parts. Gases and oils are recovered, and the residues are used as fillers in concrete and roof shingles. One other problem is the chlorine content. The scrap needs to be dehalogenated after separation, especially if carbon fibers were used as reinforcement. Glass fibers in recycled composites also pose the problem of low compressive strength of the new material.

What can one do if the different types of composites cannot be separated?

Incineration or use as fuel may be the only solution because metals, thermosets, and thermoplastics may be mixed, and they may be soiled with toxic materials. The fuel value* of polymer matrix composites is around 5000 BTU/lb (11,622 kJ/kg). This is about half the value for coal.

Which chemical process; incineration or use as fuel shows the most promise?

Incineration offers the most promise.

Its advantages include minimal cost, high-volume reduction, and no residual material. It is also feasible for low scrap volume.

1.4 Mechanics Terminology

How is a composite structure analyzed mechanically?

A composite material consists of two or more constituents; thus, the analysis and design of such materials is different from that for conventional materials such as metals. The approach to analyze the mechanical behavior of composite structures is as follows (**Figure 1.35**).

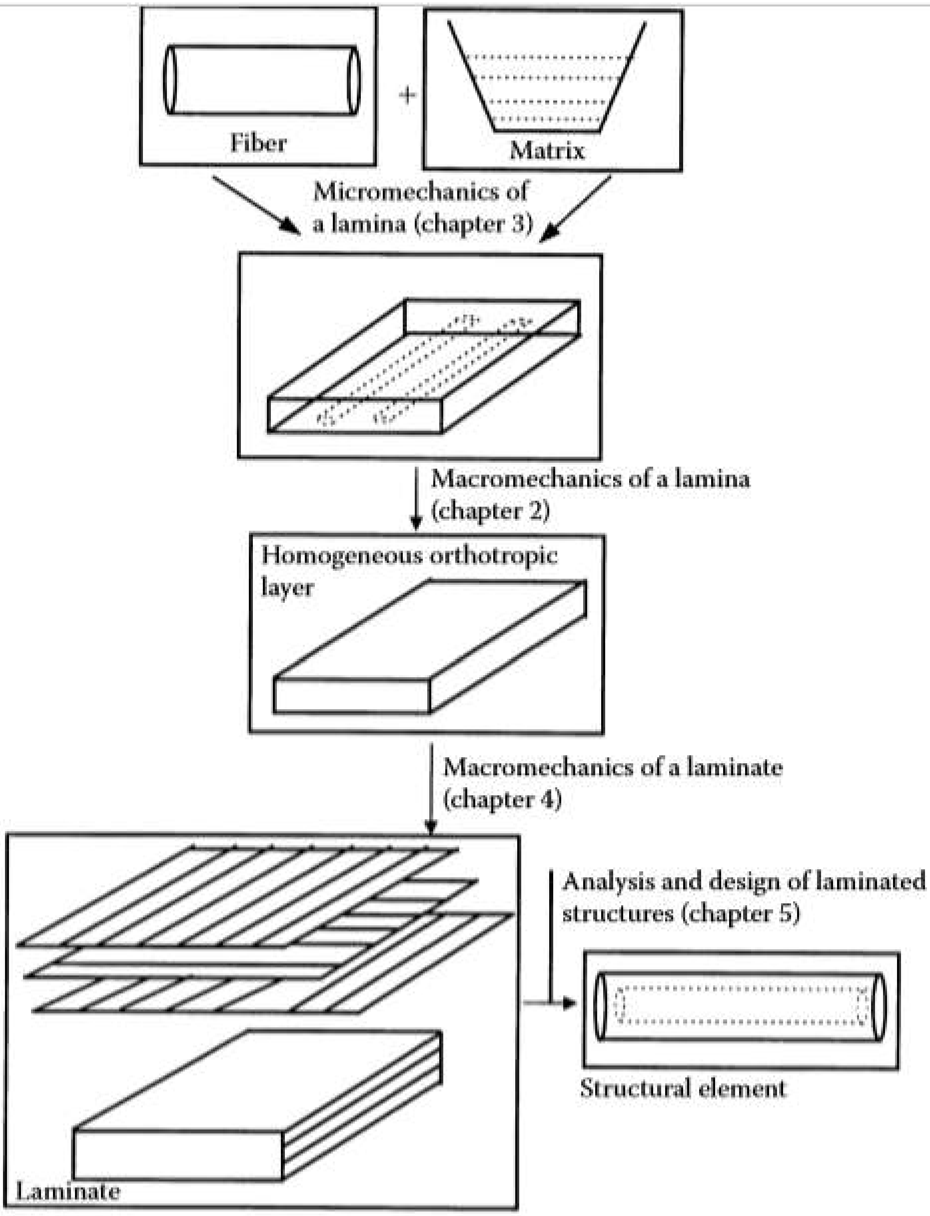

FIGURE 1.35
Schematic of analysis of laminated composites.

1. Find the average properties of a composite ply from the individual properties of the constituents. Properties include stiffness, strength, thermal, and moisture expansion coefficients. Note that average properties are derived by considering the ply to be homogeneous. At this level, one can optimize for the stiffness and strength requirements of a lamina. This is called the micromechanics of a lamina.
2. Develop the stress–strain relationships for a unidirectional/bidirectional lamina. Loads may be applied along the principal directions of symmetry of the lamina or off-axis. Also, one develops relationships for stiffness, thermal and moisture

expansion coefficients, and strengths of angle plies. Failure theories of a lamina are based on stresses in the lamina and strength properties of a lamina. This is called the macromechanics of a lamina.

A structure made of composite materials is generally a laminate structure made of various laminas stacked on each other. Knowing the macromechanics of a single lamina, one develops the macromechanics of a laminate. Stiffness, strengths, and thermal and moisture expansion coefficients can be found for the whole laminate. Laminate failure is based on stresses and application of failure theories to each ply. This knowledge of analysis of composites can then eventually form the basis for the mechanical design of structures made of composites. Several terms are defined to develop the fundamentals of the mechanical behavior of composites. These include the following.

What is an isotropic body? An isotropic material has properties that are the same in all directions. For example, the Young's modulus of steel is the same in all directions.

What is a homogeneous body? A homogeneous body has properties that are the same at all points in the body. A steel rod is an example of a homogeneous body. However, if one heats this rod at one end, the temperature at various points on the rod would be different. Because Young's modulus of steel varies with temperature, one no longer has a homogeneous body. The body is still isotropic because the properties at a particular point are still identical in all directions.

Are composite materials isotropic and/or homogeneous? Most composite materials are neither isotropic nor homogeneous. For example, consider epoxy reinforced with long glass fibers. If one chooses a location on the glass fiber, the properties are different from a location on the epoxy matrix. This makes the composite material nonhomogeneous (not homogeneous). Also, the stiffness in the direction parallel to the fibers is higher than in the direction perpendicular to the fibers and thus the properties are not independent of the direction. This makes the composite material anisotropic (not isotropic).

What is an anisotropic material?

At a point in an anisotropic material, material properties are different in all directions.

What is a nonhomogeneous body?

A nonhomogeneous or inhomogeneous body has material properties that are a function of the position on the body.

What is a lamina?

A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix.

What is a laminate?

A laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be made up of different material systems.

What is a hybrid laminate?

Hybrid composites contain more than one fiber or one matrix system in a laminate. The main four types of hybrid laminates follow.

• Interply hybrid laminates contain plies made of two or more different composite systems. Examples include car bumpers made of glass/ epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also lower the cost of the bumper.

• Intraply hybrid composites consist of two or more different fibers used in the same ply. Examples include golf clubs that use graphite and aramid fibers. Graphite fibers provide the torsional rigidity and the aramid fibers provide tensile strength and toughness.

• An interply–intraply hybrid consists of plies that have two or more different fibers in the same ply and distinct composite systems in more than one ply.

• Resin hybrid laminates combine two or more resins instead of combining two or more fibers in a laminate. Generally, one resin is flexible and the other one is rigid. Tests have proven that these resin hybrid laminates can increase shear and work of fracture properties by more than 50% over those of all-flexible or all-rigid resins.

Micromechanical Analysis of a Lamina

LECTURE 5: CHAPTER TWO

Print · April 2020.

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Chapter Two: Objectives

• Develop concepts of volume and weight fraction (mass fraction) of fiber and matrix, density, and void fraction in composites.

• Find the nine mechanical and four hygrothermal constants: four elastic moduli, five strength parameters, two coefficients of thermal expansion, and two coefficients of moisture expansion of a unidirectional lamina from the individual properties of the fiber and the matrix, fiber volume fraction, and fiber packing.

• Discuss the experimental characterization of the nine mechanical and four hygrothermal constants. The two main processes are called chemical and mechanical processes.

2.1 Introduction

The stress–strain relationships, engineering constants, and failure theories for an angle lamina were developed using **four elastic moduli**, **five strength parameters, two coefficients of thermal expansion (CTE)**, and **two coefficients of moisture expansion (CME) for a unidirectional lamina**. These **13** parameters can be found experimentally by conducting several tension, compression, shear, and hygrothermal tests on unidirectional lamina (laminates).

However, unlike in isotropic materials, experimental evaluation of these parameters is quite costly and time consuming because they are functions of several variables: the individual constituents of the composite material, fiber volume fraction, packing geometry, processing, etc. Thus, the need and motivation for developing analytical models to find these parameters are very important.

In this chapter, we will develop simple relationships for the these parameters in terms of the stiffnesses, strengths, coefficients of thermal and moisture expansion of the individual constituents of a composite, fiber volume fraction, packing geometry, etc. An understanding of this relationship, called micromechanics of lamina, helps the designer to select the constituents of a composite material for use in a laminated structure. Because this text is for a first course in composite materials, details will be explained only for the simple models based on the mechanics of materials approach and the semi-empirical approach. Results from other methods based on advanced topics such as elasticity are also explained for completeness. As mentioned in a previous chapter, a unidirectional lamina is not homogeneous. However, one can assume the lamina to be homogeneous by focusing on the average response of the lamina to mechanical and hygrothermal loads (Figure 3.1).

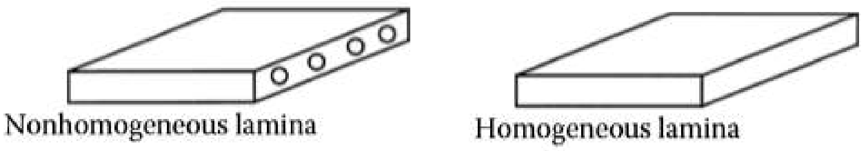

FIGURE 3.1
A nonhomogeneous lamina with fibers and matrix approximated as a homogeneous lamina.

The lamina is simply looked at as a material whose properties are different in various directions, but not different from one location to another. Also, the chapter focuses on a unidirectional continuous fiber-reinforced lamina. This is because it forms the basic building block of a composite structure, which is generally made of several unidirectional laminae placed at various angles. The modeling in the evaluation of the parameters is discussed first. This is followed by examples and experimental methods for finding these parameters.

2.2 Volume and Mass Fractions, Density, and Void Content

Before modeling the 13 parameters of a unidirectional composite, we introduce the concept of relative fraction of fibers by volume. This concept is critical because theoretical formulas for finding the stiffness, strength, and hygrothermal properties of a unidirectional lamina are a function of fiber volume fraction. Measurements of the constituents are generally based on their mass, so fiber mass fractions must also be defined. Moreover, defining the density of a composite also becomes necessary because its value is used in the experimental determination of fiber volume and void fractions of a composite. Also, the value of density is used in the definition of specific modulus and specific strength in Chapter 1.

2.2.1 Volume Fractions

Consider a composite consisting of fiber and matrix. Take the following symbol notations:

$v_{c,f,m}$ = volume of composite, fiber, and matrix, respectively

$\rho_{c,f,m}$ = density of composite, fiber, and matrix, respectively.

Now define the fiber volume fraction V_f and the matrix volume fraction V_m as

$$V_f = \frac{v_f}{v_c},$$

and

$$V_m = \frac{v_m}{v_c}. \qquad (3.1a, b)$$

Note that the sum of volume fractions is

$$V_f + V_m = 1,$$

from Equation (3.1) as

$$v_f + v_m = v_c.$$

2.2.2 Mass Fractions

Consider a composite consisting of fiber and matrix and take the following symbol notation: $w_{c,f,m}$ = mass of composite, fiber, and matrix, respectively. The mass fraction (weight fraction) of the fibers (W_f) and the matrix (W_m) are defined as

$$W_f = \frac{w_f}{w_c}, \text{ and}$$

$$W_m = \frac{w_m}{w_c}. \qquad (3.2a, b)$$

Note that the sum of mass fractions is

$$W_f + W_m = 1 ,$$

from Equation (3.2) as

$$w_f + w_m = w_c .$$

From the definition of the density of a single material,

$$w_c = r_c v_c ,$$

$$w_f = r_f v_f , \text{ and} \qquad (3.3a–c)$$

$$w_m = r_m v_m .$$

Substituting Equation (3.3) in Equation (3.2), the mass fractions and volume fractions are related as

$$W_f = \frac{\rho_f}{\rho_c} V_f , \text{ and}$$

$$W_m = \frac{\rho_m}{\rho_c} V_m , \qquad (3.4a, b)$$

in terms of the fiber and matrix volume fractions. In terms of individual constituent properties, the mass fractions and volume fractions are related by

$$W_f = \frac{\dfrac{\rho_f}{\rho_m}}{\dfrac{\rho_f}{\rho_m} V_f + V_m} V_f \,,$$

$$W_m = \frac{1}{\dfrac{\rho_f}{\rho_m}(1 - V_m) + V_m} V_m \,. \qquad (3.5a,\ b)$$

One should always state the basis of calculating the fiber content of a composite. It is given in terms of mass or volume. Based on Equation (3.4), it is evident that volume and mass fractions are not equal and that the mismatch between the mass and volume fractions increases as the ratio between the density of fiber and matrix differs from one.

2.2.3 Density

The derivation of the density of the composite in terms of volume fractions is found as follows. The mass of composite w_c is the sum of the mass of the fibers w_f and the mass of the matrix w_m as

$$w_c = w_f + w_m. \tag{3.6}$$

Substituting Equation (3.3) in Equation (3.6) yields

$$\rho_c v_c = \rho_f v_f + \rho_m v_m,$$

and

$$\rho_c = \rho_f \frac{v_f}{v_c} + \rho_m \frac{v_m}{v_c}. \tag{3.7}$$

Using the definitions of fiber and matrix volume fractions from Equation (3.1),

$$\rho_c = \rho_f V_f + \rho_m V_m. \tag{3.8}$$

Now, consider that the volume of a composite v_c is the sum of the volumes of the fiber v_f and matrix (v_m):

$$v_c = v_f + v_m. \tag{3.9}$$

The density of the composite in terms of mass fractions can be found as

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}. \tag{3.10}$$

Example 2.1: A glass/epoxy lamina consists of a 70% fiber volume fraction. Use properties of glass and epoxy from Table 3.1* and Table 3.2, respectively, to determine:

1. Density of lamina

2. Mass fractions of the glass and epoxy

3. Volume of composite lamina if the mass of the lamina is 4 kg

4. Volume and mass of glass and epoxy in part (3)

TABLE 3.1

Typical Properties of Fibers (SI System of Units)

Property	Units	Graphite	Glass	Aramid
Axial modulus	GPa	230	85	124
Transverse modulus	GPa	22	85	8
Axial Poisson's ratio	—	0.30	0.20	0.36
Transverse Poisson's ratio	—	0.35	0.20	0.37
Axial shear modulus	GPa	22	35.42	3
Axial coefficient of thermal expansion	μm/m/°C	–1.3	5	–5.0
Transverse coefficient of thermal expansion	μm/m/°C	7.0	5	4.1
Axial tensile strength	MPa	2067	1550	1379
Axial compressive strength	MPa	1999	1550	276
Transverse tensile strength	MPa	77	1550	7
Transverse compressive strength	MPa	42	1550	7
Shear strength	MPa	36	35	21
Specific gravity	—	1.8	2.5	1.4

TABLE 3.2

Typical Properties of Matrices (SI System of Units)

Property	Units	Epoxy	Aluminum	Polyamide
Axial modulus	GPa	3.4	71	3.5
Transverse modulus	GPa	3.4	71	3.5
Axial Poisson's ratio	—	0.30	0.30	0.35
Transverse Poisson's ratio	—	0.30	0.30	0.35
Axial shear modulus	GPa	1.308	27	1.3
Coefficient of thermal expansion	μm/m/°C	63	23	90
Coefficient of moisture expansion	m/m/kg/kg	0.33	0.00	0.33
Axial tensile strength	MPa	72	276	54
Axial compressive strength	MPa	102	276	108
Transverse tensile strength	MPa	72	276	54
Transverse compressive strength	MPa	102	276	108
Shear strength	MPa	34	138	54
Specific gravity	—	1.2	2.7	1.2

Solution:

1. From Table 3.1, the density of the fiber is

$$\rho_f = 2500\ kg\ /\ m^3.$$

From Table 3.2, the density of the matrix is

$$\rho_m = 1200\ kg\ /\ m^3.$$

Using Equation (3.8), the density of the composite is

$$\rho_c = (2500)(0.7) + (1200)(0.3)$$
$$= 2110\ kg\ /\ m^3.$$

2. Using Equation (3.4), the fiber and matrix mass fractions are

$$W_f = \frac{2500}{2110} \times 0.3$$

$$= 0.8294$$

$$W_m = \frac{1200}{2110} \times 0.3 \, .$$

$$= 0.1706$$

Note that the sum of the mass fractions,

$$W_f + W_m = 0.8294 + 0.1706$$

$$= 1.000.$$

3. The volume of composite is

$$v_c = \frac{w_c}{\rho_c}$$

$$= \frac{4}{2110}$$

$$= 1.896 \times 10^{-3} m^3 \, .$$

4. The volume of the fiber is

$$v_f = V_f v_c$$

$$= (0.7)(1.896 \times 10^{-3})$$

$$= 1.327 \times 10^{-3} m^3 \, .$$

The volume of the matrix is

$$v_m = V_m v_c$$

$$=(0.3)(0.1896 \times 10^{-3})$$

$$= 0.5688 \times 10^{-3} \ m^3 \ .$$

The mass of the fiber is

$$w_f = \rho_f v_f$$

$$= (2500)(1.327 \times 10^{-3})$$

$$= 3.318 \ kg \ .$$

The mass of the matrix is

$$w_m = \rho_m v_m$$

$$= (1200)(0.5688 \times 10^{-3})$$

$$= 0.6826 \ kg \ .$$

An E-glass fiber reinforced vinyl ester composite has a fiber volume fraction of 40%. Experimentally measured density of E-glass fiber and vinyl ester is 2.54 g/cm^3 and 1.3 g/cm^3, respectively. What is the weight fraction of fibers?

Solution:

$V_f = 40\%$; $V_m = (1 - V_f) = 60\%$ $\rho_f = 2.54$ g/cm^3; $\rho_m = 1.3$ g/cm^3

According to Equation (7.1)

$$W_f = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m} = \frac{0.4 \times 2.54}{0.4 \times 2.54 \times 0.6 \times 1.3} = \frac{1.016}{1.016 + 0.78} = 57\%$$

The glass vinyl ester composite has a fiber weight fraction of 57%.

A carbon fiber reinforced polyphenylene sulfide (PPS) composite has a resin weight fraction of 48%. What is the volume fraction of carbon fiber in this composite? The density of carbon fiber is 1.8 g/cm^3 and the density of PPS is 1.48 g/cm^3.

Solution:

$W_m = 48\%$; $W_f = (1 - W_m) = 52\%$; $\rho_f = 1.8$ g/cm^3; $\rho_m = 1.48$ g/cm^3

According to Equation (7.4)

$$V_f = \frac{W_f / \rho_f}{W_f / \rho_f + W_m / \rho_m + W_a / \rho_a} = \frac{0.52 / 18}{0.52 / 18 + 0.48 / 1.48} = \frac{0.289}{0.289 + 0.324} = 47\%$$

The fiber volume fraction of the composite is 47%.

MECHANICS OF COMPOSITE MATERIALS

(ME 4306E)

College of Engineering

Mechanical Department

(Stage 4)

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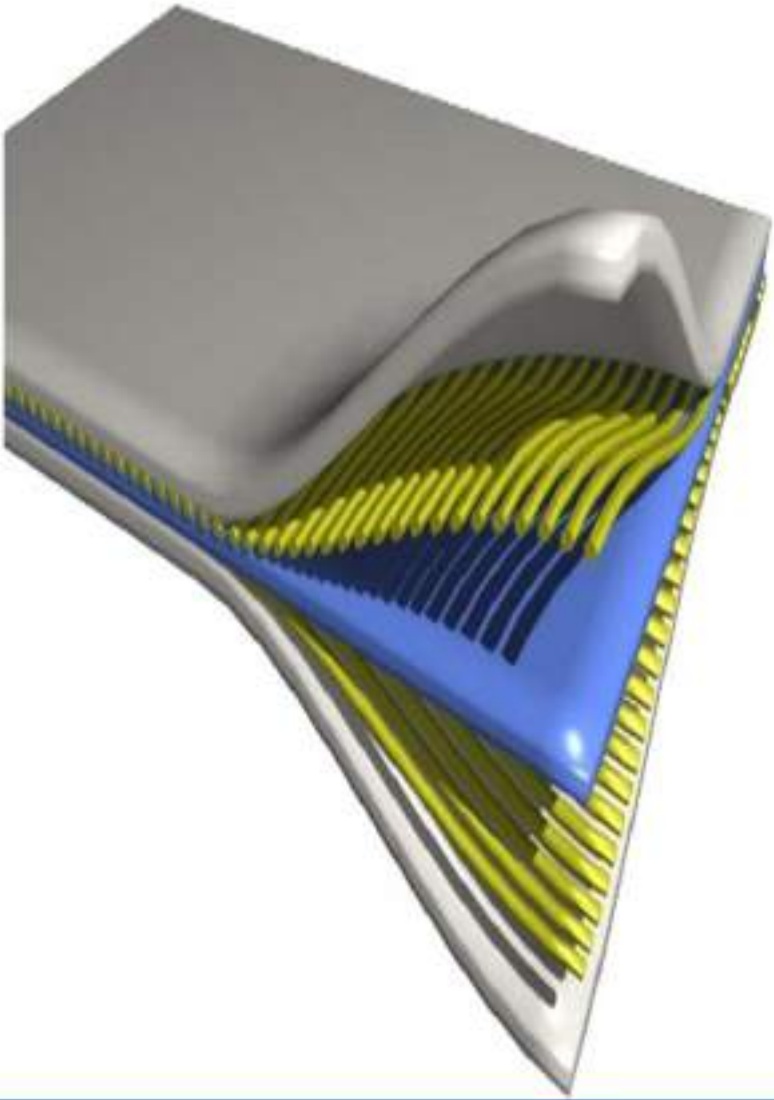
Introduction to Composite Materials



Introduction to Composite Materials

LECTURE : 1: CHAPTER ONE

Print · Feb 2020.

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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°F (–160°C) and 200°F (93.3°C). Limitations on coefficient of thermal expansion‡ thus are low and may be of the order of $\pm 1 \times 10^{-7}$ in./in./°F ($\pm 1.8 \times 10^{-7}$ m/m/°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

$$u = \frac{PL}{AE}, \tag{1.1}$$

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

$$M = \rho AL, \tag{1.2}$$

where ρ = density of the material of the rod, we have

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

This implies that the lightest beam for specified deflection under a specified load is one with the highest ***(E/ρ)*** value. Thus, to measure the mechanical advantage, the ***(E/ρ)*** ratio is calculated and is called the **specific modulus** **(**ratio between the Young's modulus ***(E)*** and the density ***(ρ)*** of the material**)**. The other parameter is called the specific strength and is defined as the ratio between the strength ***(σ_{ult})*** and the density of the material ***(ρ)***, 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. **<u>What does this mean to a designer?</u>** 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.3 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^2 or 9.81 m/s^2).

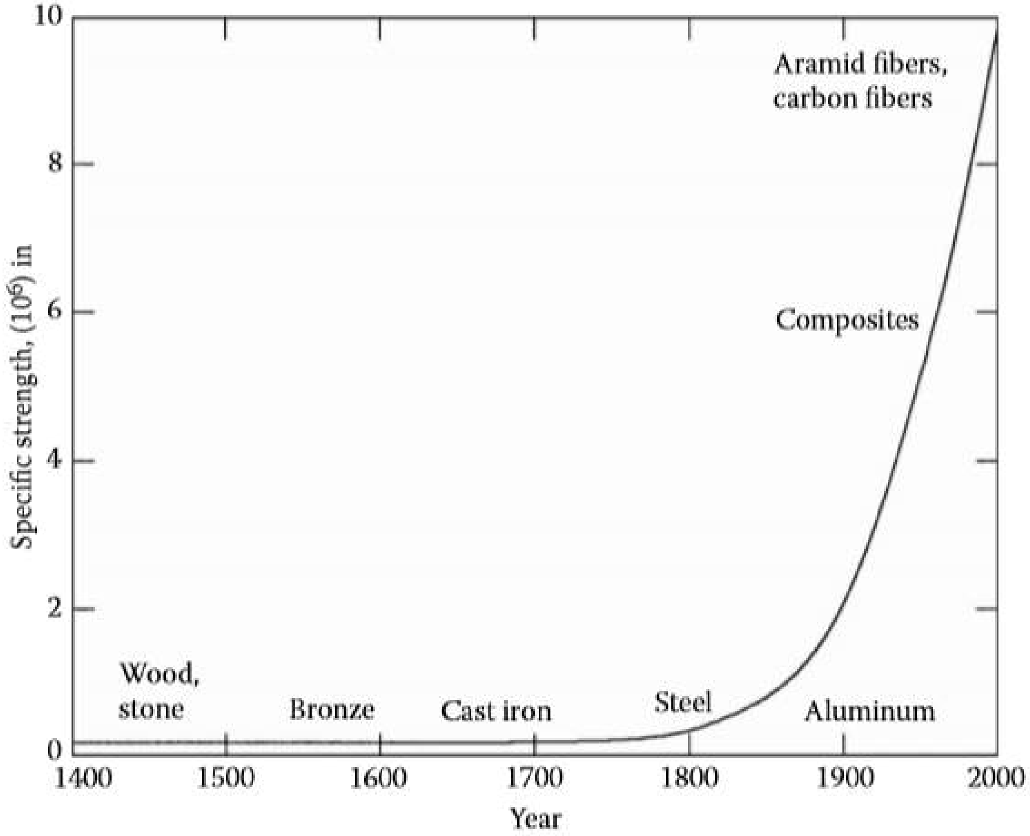

FIGURE 1.1
Specific strength as a function of time of use of materials. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

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[a]	Young's modulus (Msi)	Ultimate strength (ksi)	Specific modulus (Msi-in.^{3}/lb)	Specific strength (ksi-in.^{3}/lb)
System of Units: USCS					
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^3/kg)	Specific strength (MPa-m^3/kg)
System of Units: SI					
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

[a] 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.

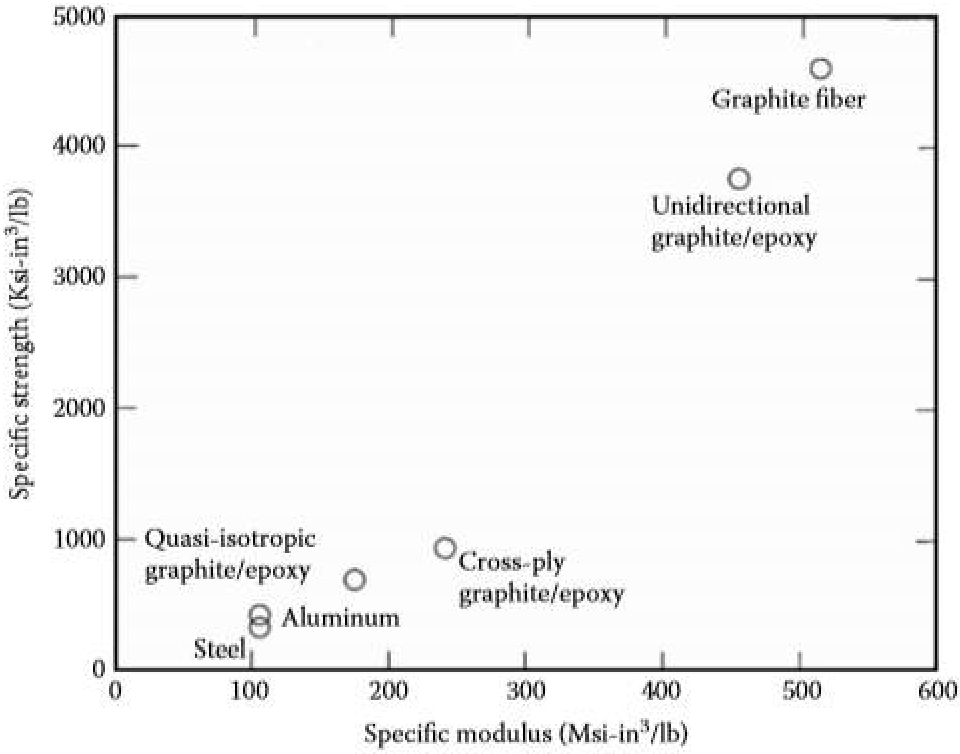

FIGURE 1.2
Specific strength as a function of specific modulus for metals, fibers, and composites.

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:

$$P_{cr} = \frac{\pi^2 EI}{L^2}, \tag{1.4}$$

where

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

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

$$I = \pi \frac{d^4}{64} \tag{1.5}$$

and the mass of the rod is

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

where

M = mass of the beam (lb or kg)
ρ = density of beam (lb/in.^{3} or kg/m^3)
d = diameter of beam (in. or m)

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

$$M = \frac{2L^2\sqrt{P_{cr}}}{\sqrt{\pi}}\frac{1}{E^{1/2}/\rho}. \tag{1.7}$$

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

Material Units	Specific gravity	Young's modulus (Msi)	E/ρ (Msi-in.^{3}/lb)	$E^{1/2}/\rho$ (psi$^{1/2}$-in.^{3}/lb)	$E^{1/3}/\rho$ (psi$^{1/3}$-in.^{3}/lb)
System of Units: USCS					
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/ρ (GPa-m^3/kg)**	**$E^{1/2}/\rho$ (Pa-m^3/kg)**	**$E^{1/3}/\rho$ (Pa$^{1/3}$-m^3/kg)**
System of Units: SI					
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:

* 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 σ (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.

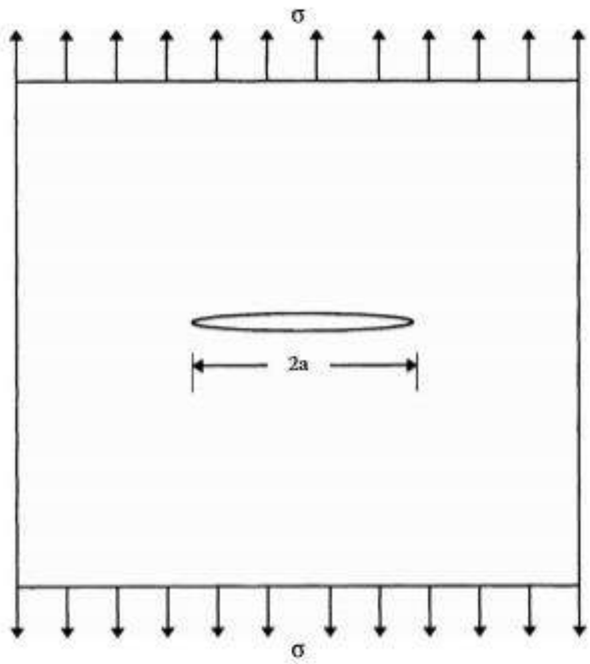

FIGURE 1.3
A uniformly loaded plate with a crack.

• 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.)

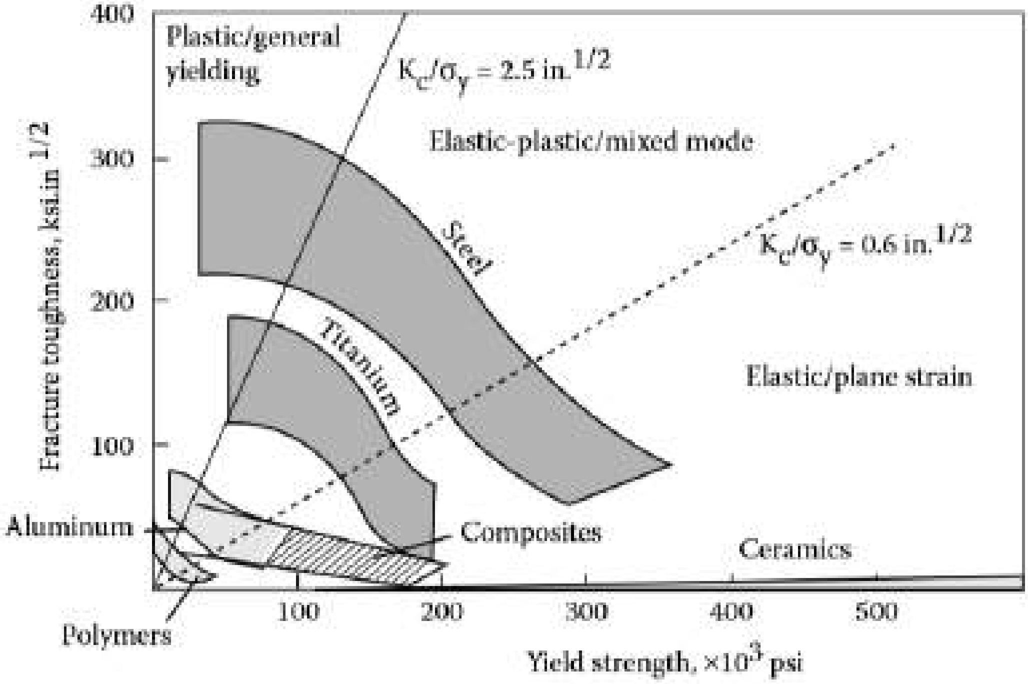

FIGURE 1.4
Fracture toughness as a function of yield strength for monolithic metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

• 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.

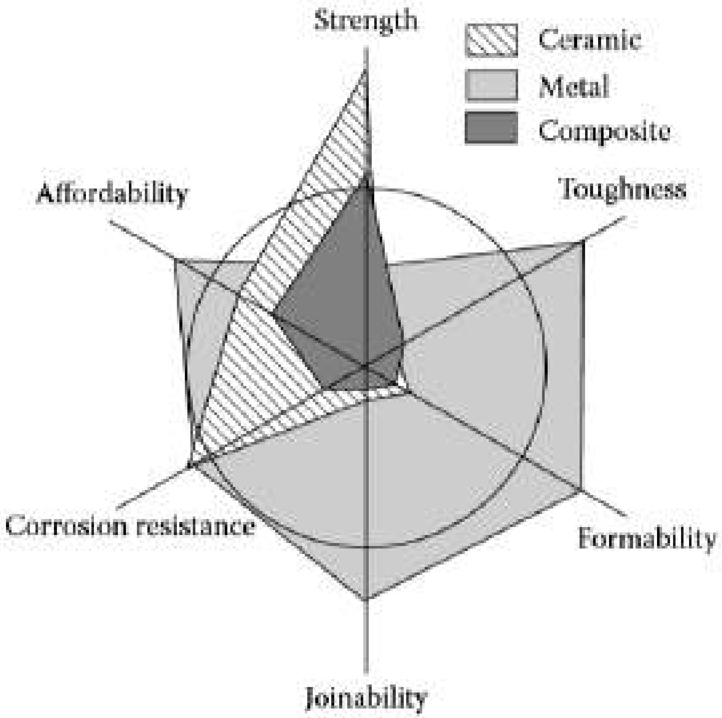

FIGURE 1.5
Primary material selection parameters for a hypothetical situation for metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

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.

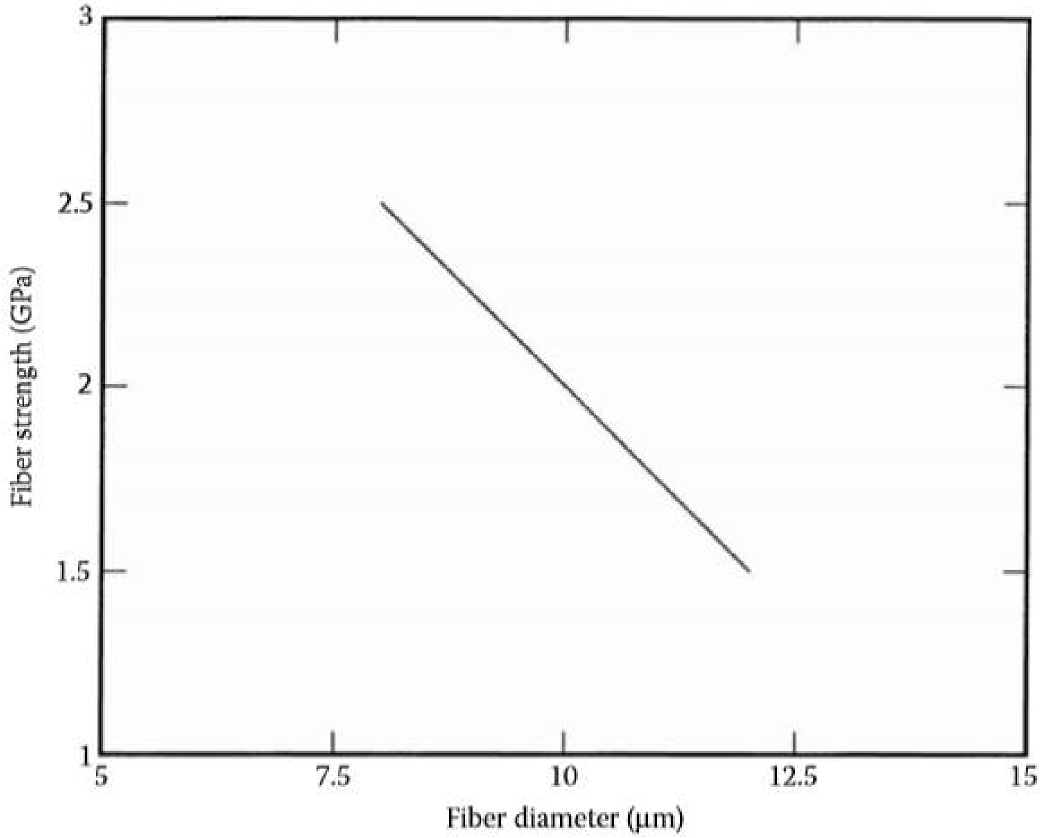

FIGURE 1.6
Fiber strength as a function of fiber diameter for carbon fibers. (Reprinted from Lamotte, E. De, and Perry, A.J., *Fibre Sci. Technol.*, 3, 159, 1970. With permission from Elsevier.)

• 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

$$A_I = N\,\pi\,D\,L. \tag{1.8}$$

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

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

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

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

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:

* ***<u>Ductility</u>*** 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,

$R = 1 - (A_f/A_i)$.

• 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.

<u>Bending stiffness</u> is the resistance to bending moments. According to the Strength of Materials course, if a beam is subjected to a pure bending moment, M,

$$\frac{d^2v}{dx^2} = \frac{M}{EI}, \tag{1.11}$$

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.^{4} or m^4)
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

$$I = \frac{\pi d^4}{64}, \tag{1.12}$$

then

$$\text{Flexibility} \propto \frac{1}{Ed^4}. \tag{1.13}$$

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?

<u>Other factors</u> 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.

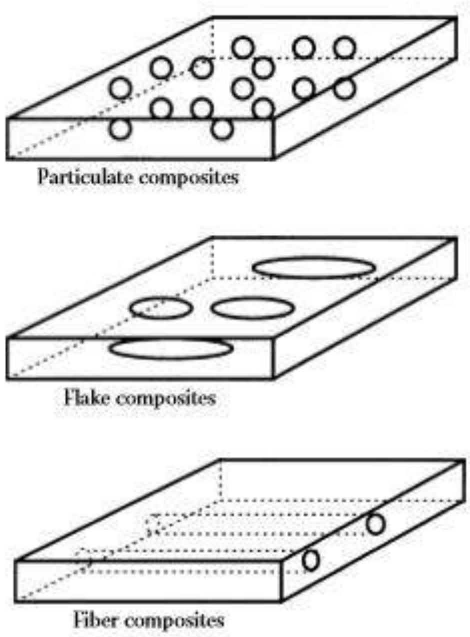

FIGURE 1.8
Types of composites based on reinforcement shape.

- **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–alumino 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, theproperties 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 olefinbased nanocomposites.9 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
System of units: USCS					
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
System of units: SI					
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
System of units: USCS						
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	μin./in./°F	−0.722	−2.778	2.778	6.5	12.8
System of units: SI						
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	μm/m/°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	% Weight 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).

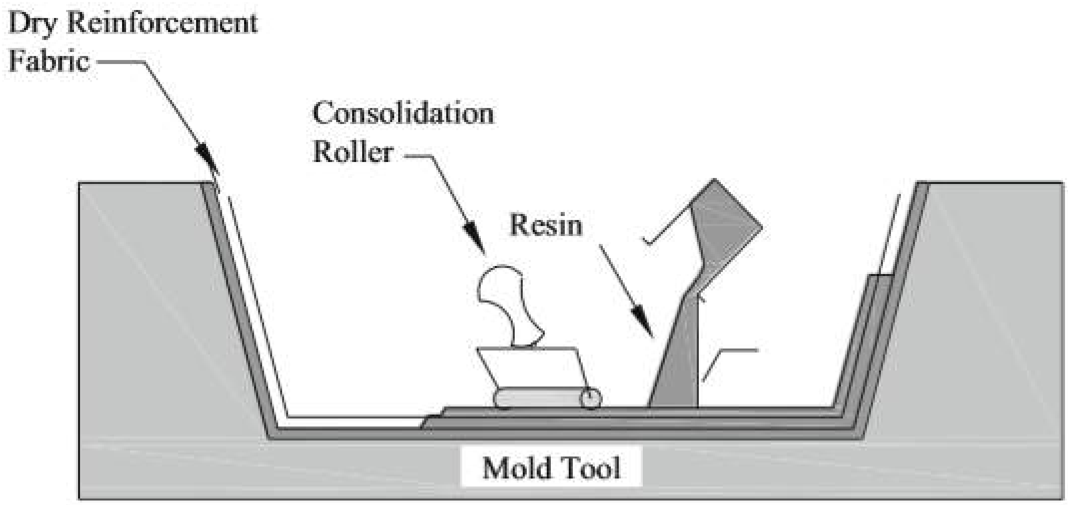

Fig. 1.3 Schematic of hand layup

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.

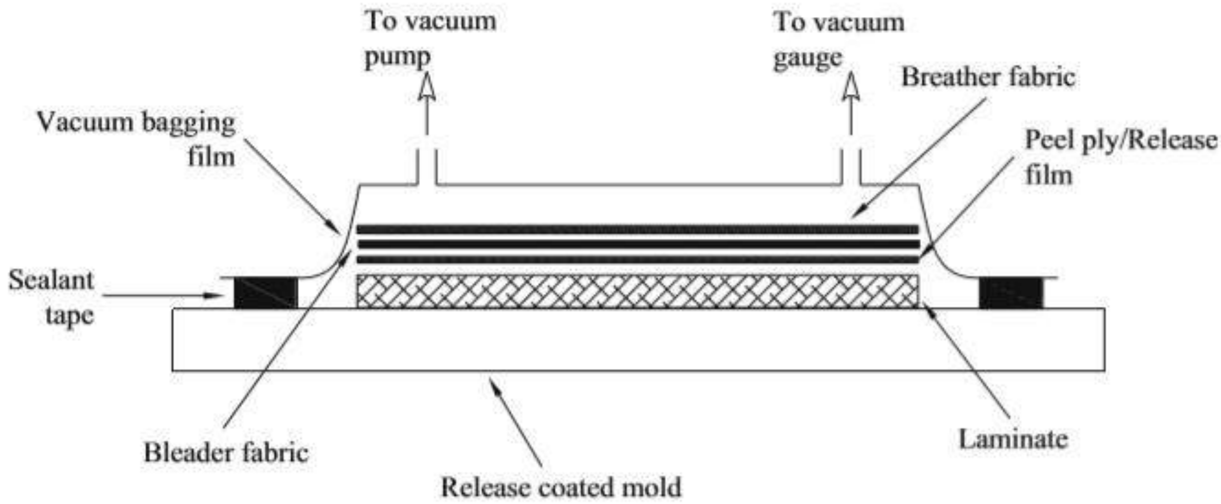

Fig. 1.4 Schematic of vacuum bag molding

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.

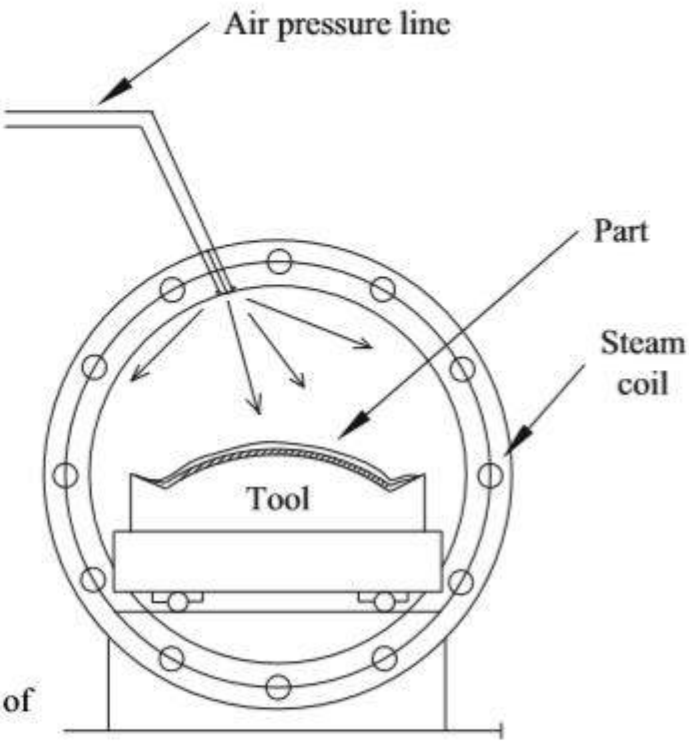

Fig. 1.5 Schematic of autoclave

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 <u>one to six bars</u> 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.

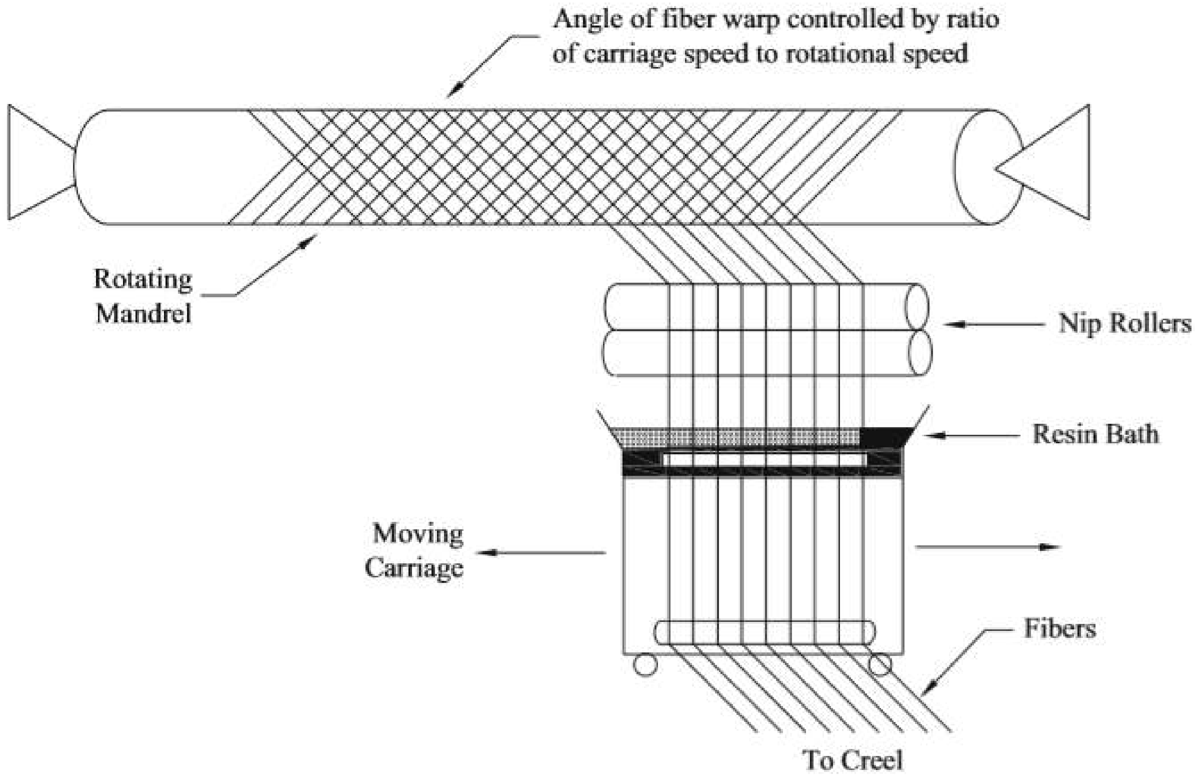

Fig. 1.6 Schematic of filament winding

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.

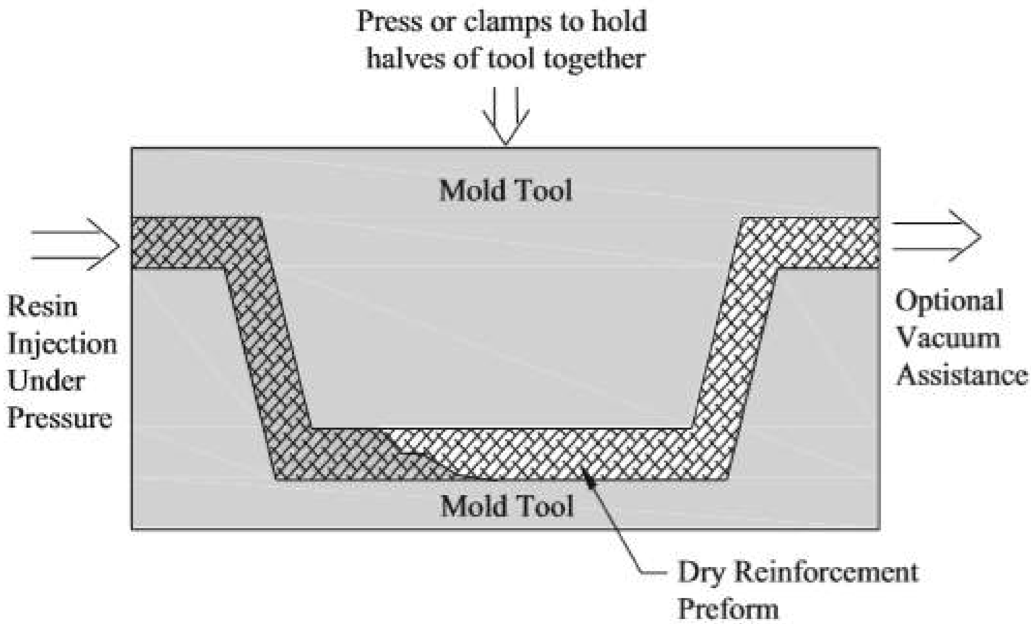

Fig. 1.8 Schematic of resin transfer molding

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.

Introduction to Composite Materials

LECTURE : 2: CHAPTER ONE

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1.1 Introduction to Composite Materials

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.

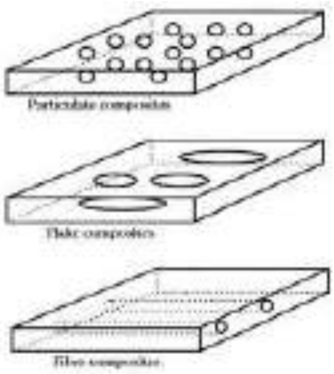

FIGURE 1.8
Types of composites based on reinforcement shape.

- **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–alumino silicate. Continuous fiber composites are emphasized in this lecture 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 olefinbased nanocomposites.9 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
System of units: USCS					
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
System of units: SI					
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
System of units: USCS						
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	μin./in./°F	−0.722	−2.778	2.778	6.5	12.8
System of units: SI						
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	μm/m/°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

	% Weight	
Material	**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

<u>Typical examples of thermoplastics</u> 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

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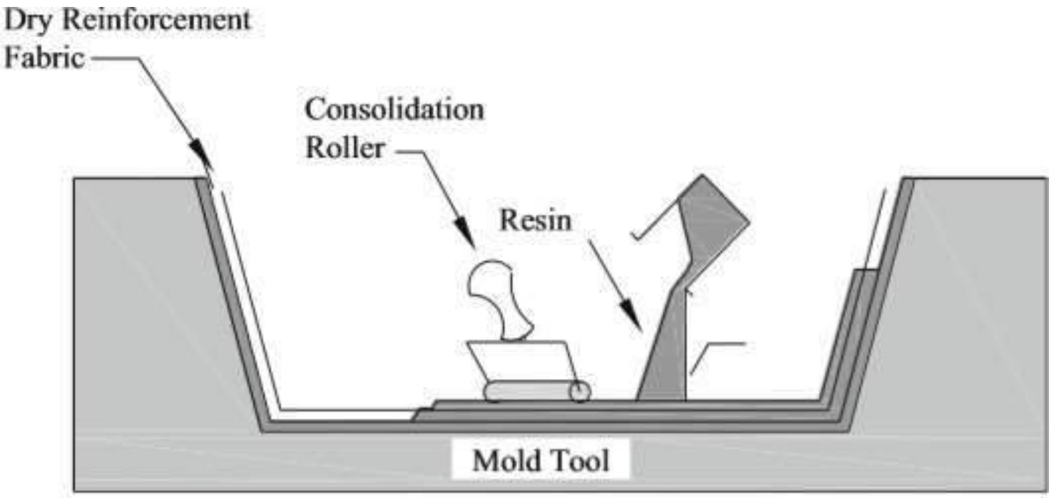
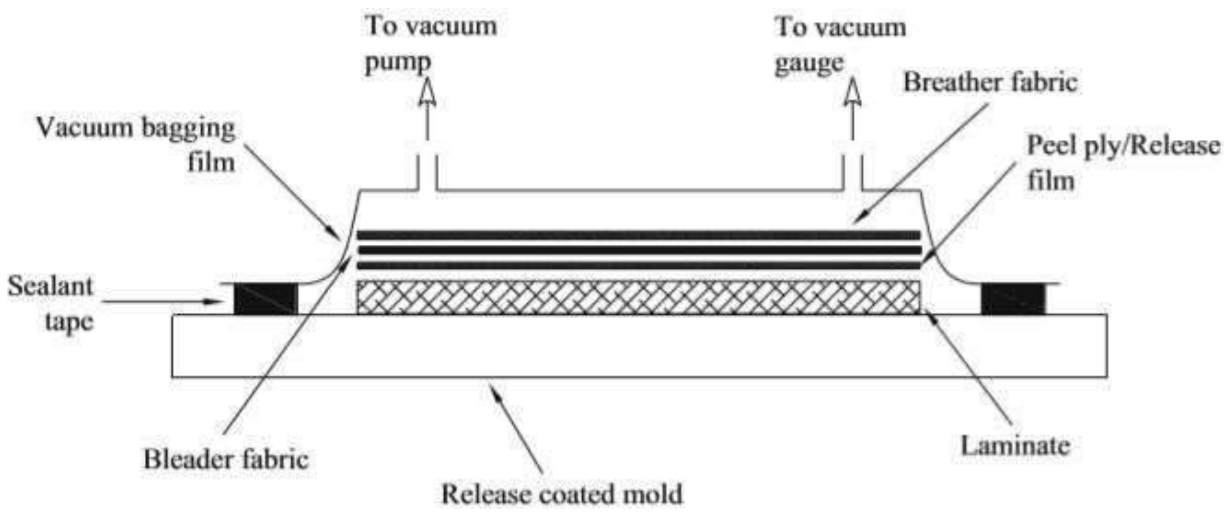


Fig. 1.3 Schematic of hand layup

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.



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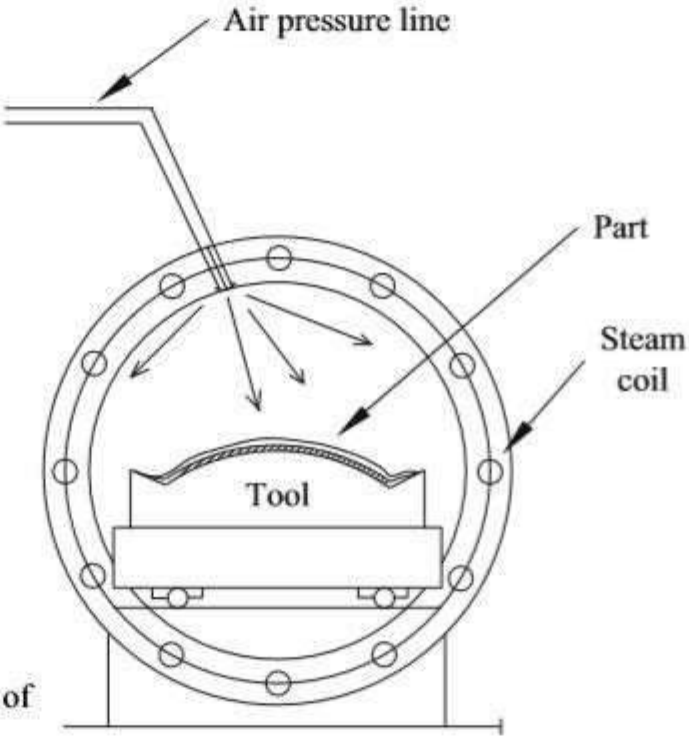

Fig. 1.5 Schematic of autoclave

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 <u>one to six bars</u> 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.

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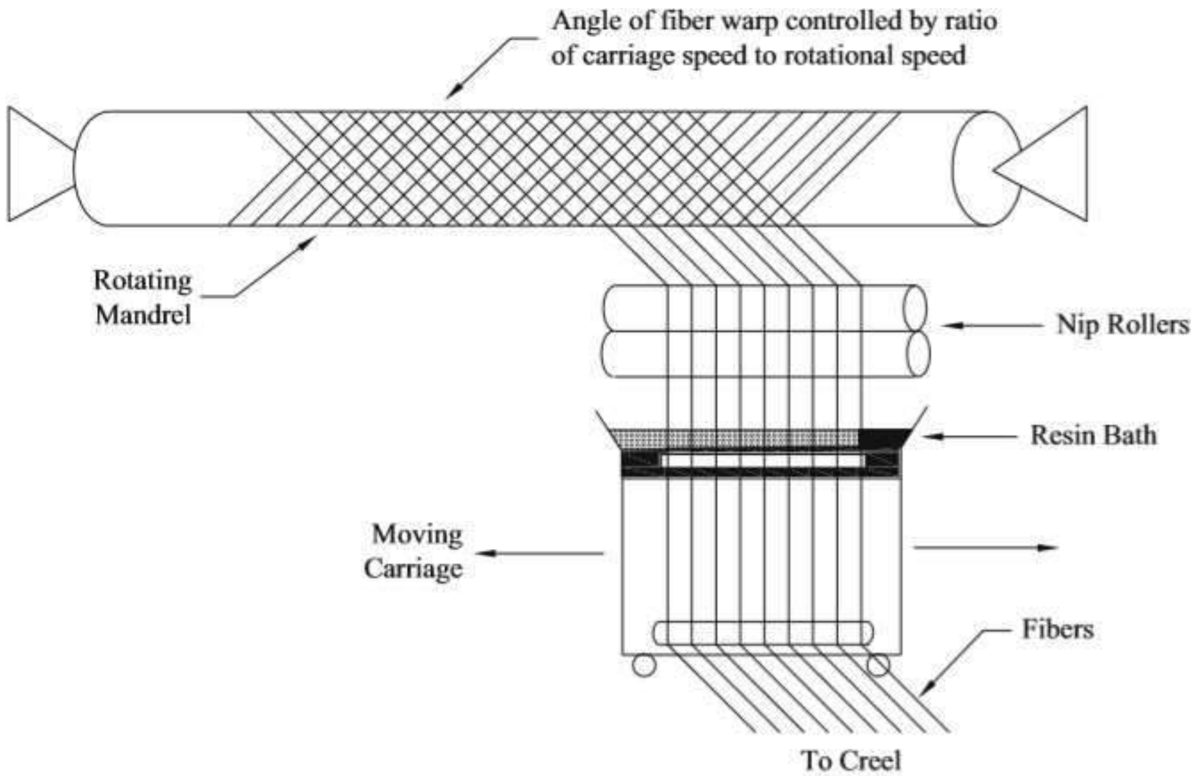

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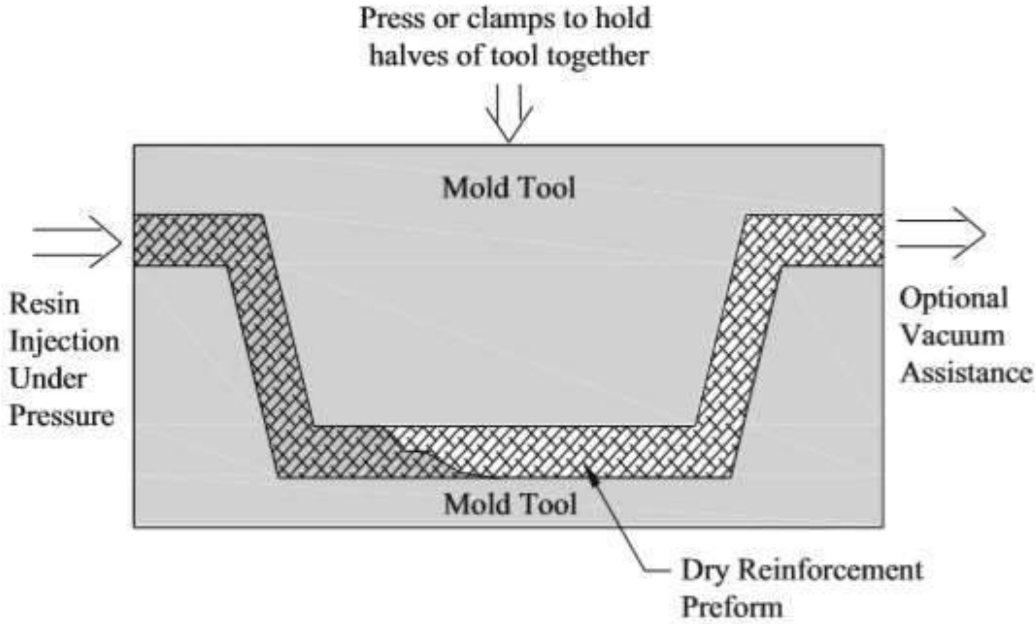

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Introduction to Composite Materials

LECTURE : 4: CHAPTER ONE
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1.4 Recycling Fiber-Reinforced Composites

What types of processes are used for recycling of composites?

The two main processes are called chemical and mechanical processes.

Why is recycling of composites complex?

This is because of the many variables in material types — thermoset vs. thermoplastics, long vs. short fibers, glass vs. carbon, etc.

What are the various steps in mechanical recycling of short fiber-reinforced composites?

These are shredding, separation, washing, grinding, drying, and extrusion.

Why is chemical recycling not as popular as mechanical recycling?

Chemical processing is very costly. Processes such as pyrolysis (decomposing materials in an oxygen-free atmosphere) produce many gases, and hydrogenation gives high filler content. However, General Motors has adapted pyrolysis to recycle composite automobile parts. Gases and oils are recovered, and the residues are used as fillers in concrete and roof shingles. One other problem is the chlorine content. The scrap needs to be dehalogenated after separation, especially if carbon fibers were used as reinforcement. Glass fibers in recycled composites also pose the problem of low compressive strength of the new material.

What can one do if the different types of composites cannot be separated?

Incineration or use as fuel may be the only solution because metals, thermosets, and thermoplastics may be mixed, and they may be soiled with toxic materials. The fuel value* of polymer matrix composites is around 5000 BTU/lb (11,622 kJ/kg). This is about half the value for coal.

Which chemical process; incineration or use as fuel shows the most promise?

Incineration offers the most promise.

Its advantages include minimal cost, high-volume reduction, and no residual material. It is also feasible for low scrap volume.

1.4 Mechanics Terminology

How is a composite structure analyzed mechanically?

A composite material consists of two or more constituents; thus, the analysis and design of such materials is different from that for conventional materials such as metals. The approach to analyze the mechanical behavior of composite structures is as follows (**Figure 1.35**).

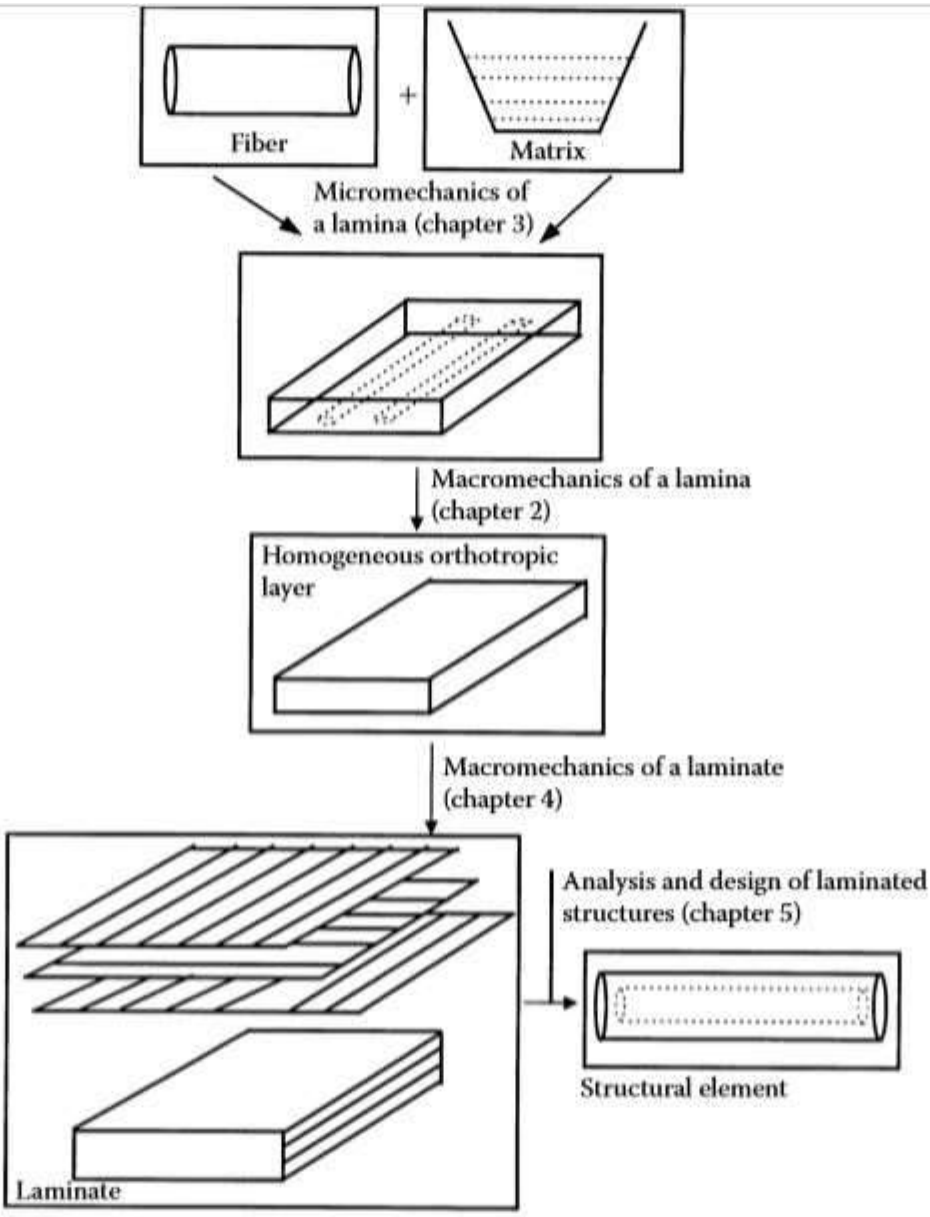

FIGURE 1.35
Schematic of analysis of laminated composites.

1. Find the average properties of a composite ply from the individual properties of the constituents. Properties include stiffness, strength, thermal, and moisture expansion coefficients. Note that average properties are derived by considering the ply to be homogeneous. At this level, one can optimize for the stiffness and strength requirements of a lamina. This is called the micromechanics of a lamina.
2. Develop the stress–strain relationships for a unidirectional/bidirectional lamina. Loads may be applied along the principal directions of symmetry of the lamina or off-axis. Also, one develops relationships for stiffness, thermal and moisture

expansion coefficients, and strengths of angle plies. Failure theories of a lamina are based on stresses in the lamina and strength properties of a lamina. This is called the macromechanics of a lamina.

A structure made of composite materials is generally a laminate structure made of various laminas stacked on each other. Knowing the macromechanics of a single lamina, one develops the macromechanics of a laminate. Stiffness, strengths, and thermal and moisture expansion coefficients can be found for the whole laminate. Laminate failure is based on stresses and application of failure theories to each ply. This knowledge of analysis of composites can then eventually form the basis for the mechanical design of structures made of composites. Several terms are defined to develop the fundamentals of the mechanical behavior of composites. These include the following.

What is an isotropic body? An isotropic material has properties that are the same in all directions. For example, the Young's modulus of steel is the same in all directions.

What is a homogeneous body? A homogeneous body has properties that are the same at all points in the body. A steel rod is an example of a homogeneous body. However, if one heats this rod at one end, the temperature at various points on the rod would be different. Because Young's modulus of steel varies with temperature, one no longer has a homogeneous body. The body is still isotropic because the properties at a particular point are still identical in all directions.

Are composite materials isotropic and/or homogeneous? Most composite materials are neither isotropic nor homogeneous. For example, consider epoxy reinforced with long glass fibers. If one chooses a location on the glass fiber, the properties are different from a location on the epoxy matrix. This makes the composite material nonhomogeneous (not homogeneous). Also, the stiffness in the direction parallel to the fibers is higher than in the direction perpendicular to the fibers and thus the properties are not independent of the direction. This makes the composite material anisotropic (not isotropic).

What is an anisotropic material?

At a point in an anisotropic material, material properties are different in all directions.

What is a nonhomogeneous body?

A nonhomogeneous or inhomogeneous body has material properties that are a function of the position on the body.

What is a lamina?

A lamina (also called a ply or layer) is a single flat layer of unidirectional fibers or woven fibers arranged in a matrix.

What is a laminate?

A laminate is a stack of plies of composites. Each layer can be laid at various orientations and can be made up of different material systems.

What is a hybrid laminate?

Hybrid composites contain more than one fiber or one matrix system in a laminate. The main four types of hybrid laminates follow.

• Interply hybrid laminates contain plies made of two or more different composite systems. Examples include car bumpers made of glass/ epoxy layers to provide torsional rigidity and graphite/epoxy to give stiffness. The combinations also lower the cost of the bumper.

• Intraply hybrid composites consist of two or more different fibers used in the same ply. Examples include golf clubs that use graphite and aramid fibers. Graphite fibers provide the torsional rigidity and the aramid fibers provide tensile strength and toughness.

• An interply–intraply hybrid consists of plies that have two or more different fibers in the same ply and distinct composite systems in more than one ply.

• Resin hybrid laminates combine two or more resins instead of combining two or more fibers in a laminate. Generally, one resin is flexible and the other one is rigid. Tests have proven that these resin hybrid laminates can increase shear and work of fracture properties by more than 50% over those of all-flexible or all-rigid resins.

Introduction to Composite Materials

LECTURE : 3: CHAPTER ONE
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1.3 Applications of Polymer Matrix Composites (PMCs)

Give typical applications of polymer matrix composites.

It is highly impossible to provide a complete list of PMC applications. However, some applications classified according to major market segments are indicated here.

Aerospace and Aircraft: PMCs has wide applications in aerospace industry such as construction of containers, gliders, control surfaces, and light aircraft, internal fittings, window masks, partitions and floors, galley units and trolleys, satellite components, aerials and associated enclosures, structural members, ground support equipment components and enclosures, etc.

In commercial airlines, the use of composites has been conservative because of safety concerns. Use of composites is limited to secondary structures such as rudders and elevators made of graphite/epoxy for the Boeing 767 and landing gear doors made of Kevlar–graphite/epoxy. Composites are also used in panels and floorings of airplanes. Some examples of using composites in the primary structure are the all-composite Lear Fan 2100 plane and the tail fin of the Airbus A310-300. In the latter case, the tail fin consists of graphite/epoxy and aramid honeycomb. It not only reduced the weight of the tail fin by 662 lb (300 kg) but also reduced the number of parts from 2000 to 100. Skins of aircraft engine cowls shown in Figure 1.19 are also made of polymer matrix composites for reducing weight.

FIGURE 1.19
Aircraft engine cowling. (Photo provided courtesy of Alliant Techsystems, Inc.)

With increasing competition in model airplane flying, the weight of composite materials has been reduced. Figure 1.20 shows a World War II model airplane with fuselage made of glass/epoxy, wings made of balsa-wood facings/Styrofoam core sandwich construction, and wingspars made of graphite/epoxy.

FIGURE 1.20
Model BF109 WWII German fighter plane using glass/epoxy-molded fuselage and wing spars of graphite/epoxy. (Photo courtesy of Russell A. Lepré, Tampa, FL.)

Helicopters and tiltrotors (see Figure 1.21) use graphite/epoxy and glass/ epoxy rotor blades that not only increase the life of blades by more than 100% over metals but also increase the top speeds.

FIGURE 1.21
The BELL™ V-22 Osprey in combat configuration. (Courtesy of Bell Helicopter Textron Inc.)

Space: Two factors make composites the material of choice in space applications: high specific modulus and strength, and dimensional stability during large changes in temperature in space. Examples include the Graphite/ epoxy-honeycomb payload bay doors in the space shuttle (see Figure 1.22). Weight savings over conventional metal alloys translate to higher payloads that cost as much as $1000/lb ($2208/kg). Also, for the space shuttles, graphite/epoxy was chosen primarily for weight savings and for small mechanical and thermal deflections concerning the remote manipulator arm, which deploys and retrieves payloads.

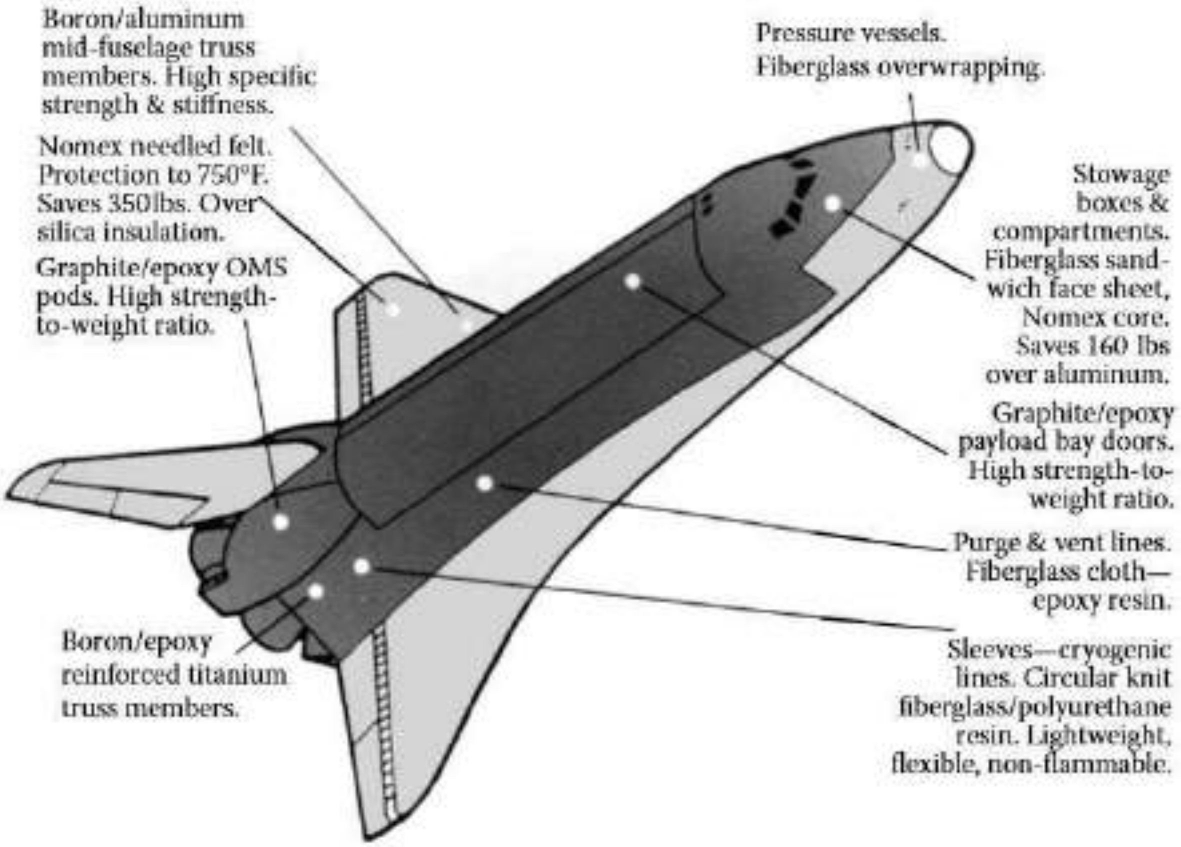


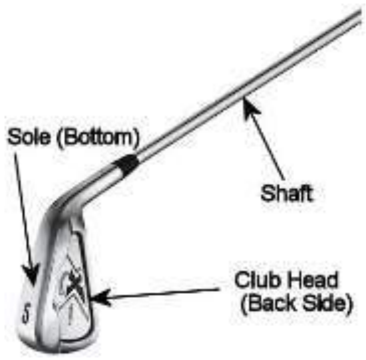
FIGURE 1.22
Use of composites in the space shuttle. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

Medical devices: Applications here include the use of glass–Kevlar/epoxy lightweight face masks for epileptic patients. Artificial portable lungs are made of graphite–glass/epoxy so that a patient can be mobile. X-ray tables made of graphite/epoxy facing sandwiches are used for their high stiffness, light weight, and transparency to radiation. The latter feature allows the patient to stay on one bed for an operation as well as x-rays and be subjected to a lower dosage of radiation.

Building and Construction: External and internal cladding, permanent and temporary formwork and shuttering, partitions, polymer concrete, prefabricated buildings, booth, cabins and housing, structural and decorative building elements, bridge elements and sections, quay facings, signposts and street furniture, staging, fencing and walkways, etc.

Consumer Product Components: For domestic and industrial furniture, sanitary ware, sporting goods, caravan components, archery and playground equipment, garden furniture, notice boards, theme park requirements, swimming pools, aqua tubes, diving boards, seating and benches, skis and snowboards, etc.

Sporting goods: Graphite/epoxy is replacing metals in golf club shafts (see Figure) mainly to decrease the weight and use the saved weight in the head. This increase in the head weight has improved driving distances by more than 25 yards (23 m).



Corrosion-Resistant Equipment: Chemical plant, linings, oil industry components, pipes and ducts, chimneys, grid flooring, staging and walkways, pressure vessels, processing tanks and vessels, fume hoods, scrubbers and cooling tower components, etc.

Electrical and Electronic: Internal and external aerial components and fittings, circuit boards, generation and transmission components, insulators, switch boxes and cabinets, booms, distribution posts and pylons, telegraph poles, fuse tubes, transformer elements, ladders and cableways, etc.

Marine Applications: PMC$_s$ are used in the manufacture of canoes and boats or (yachts, see Figure), therefore most of these marine applications are made of fiber glass. Furthermore, hybrids of Kevlar–glass/epoxy are now replacing fiber glass for improved weight savings, vibration damping, and impact resistance. Kevlar–epoxy by itself would have poor compression properties.

Housings made of metals such as titanium to protect expensive oceanographic research instruments during explorations of sea wrecks are cost prohibitive. These housings are now made out of glass/epoxy and sustain pressures as high as 10 ksi (69 MPa) and extremely corrosive conditions.

Bridges made of polymer composite materials are gaining wide acceptance due to their low weight, corrosion resistance, longer life cycle, and limited earthquake damage. Although bridge components made of composites may cost \$5/lb as opposed to components made of steel, reinforced concrete may only cost \$0.30 to \$1.00 per pound; the former weighs 80% less than the latter. Also, by lifetime costs, fewer composite bridges need to be built than traditional bridges.

Other marine applications: surf and sailboards, lifeboats and rescue vessels, buoys, boat accessories and subassemblies, window masks and internal moldings and fittings for ferries and cruise liners, work boats and trawlers, etc.

Transportation: Automotive (e.g., a body of car "Ford GT" made of carbon fibre completely, see Figure), bus, camper and vehicle components generally, both underbody, engine and body panels, truck, rail and other vehicle components and fittings, land and sea containers, railway track and signaling components, traffic signs, seating, window masks and partitions, etc.

1.2.2 Metal Matrix Composites

What are metal matrix composites?

Metal matrix composites (MMCs), as the name implies, have a metal matrix. Examples of matrices in such composites include aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide. Metals are mainly reinforced to increase or decrease their properties to suit the needs of design. For example, the elastic stiffness and strength of metals can be increased, and large coefficients of thermal expansion and thermal and electric conductivities of metals can be reduced, by the addition of fibers such as silicon carbide.

What are the advantages of metal matrix composites?

Metal matrix composites (MMCs) are mainly used to provide advantages over monolithic metals such as steel and aluminum. These advantages include higher specific strength and modulus by reinforcing low-density metals, such as aluminum and titanium; lower coefficients of thermal expansion by reinforcing with fibers with low coefficients of thermal expansion, such as graphite; and maintaining properties such as strength at high temperatures. MMCs have several advantages over polymer matrix composites. These include higher elastic properties; higher service temperature; insensitivity to moisture; higher electric and thermal conductivities; and better wear, fatigue, and flaw resistances. The drawbacks of MMCs over PMCs include higher processing temperatures and higher densities.

Do any properties degrade when metals are reinforced with fibers?

Yes, reinforcing metals with fibers may reduce ductility and fracture toughness. Ductility of aluminum is 48% and it can decrease to below 10% with simple reinforcements of silicon carbide whiskers. The fracture toughness of aluminum alloys is 18.2 to 36.4 (20 to 40) and it reduces by 50% or more when reinforced with silicon fibers.

What are the typical mechanical properties of some metal matrix composites? Compare the properties with metals.

Typical mechanical properties of MMCs are given in Table 1.11.

TABLE 1.11

Typical Mechanical Properties of Metal Matrix Composites

Property	Units	SiC/ aluminum	Graphite/ aluminum	Steel	Aluminum
System of units: USCS					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	Msi	17	18	30	10
Ultimate tensile strength	ksi	175	65	94	34
Coefficient of thermal expansion	µin./in./°F	6.9	10	6.5	12.8
System of units: SI					
Specific gravity	—	2.6	2.2	7.8	2.6
Young's modulus	GPa	117.2	124.1	206.8	68.95
Ultimate tensile strength	MPa	1206	448.2	648.1	234.40
Coefficient of thermal expansion	µm/m/°C	12.4	18	11.7	23

Show one process of how metal matrix composites (MMCs) are manufactured.

Fabrication methods for MMCs are varied. One method of manufacturing them is diffusion bonding (Figure 1.28), which is used in manufacturing boron/aluminum composite parts . A fiber mat of boron is placed between two thin aluminum foils about 0.002 in. (0.05 mm) thick. A polymer binder or an acrylic adhesive holds the fibers together in the mat. Layers of these metal foils are stacked at angles as required by the design. The laminate is first heated in a vacuum bag to remove the binder. The laminate is then hot pressed with a temperature of about 932°F (500°C) and pressure of about 5 ksi (35 MPa) in a die to form the required machine element.

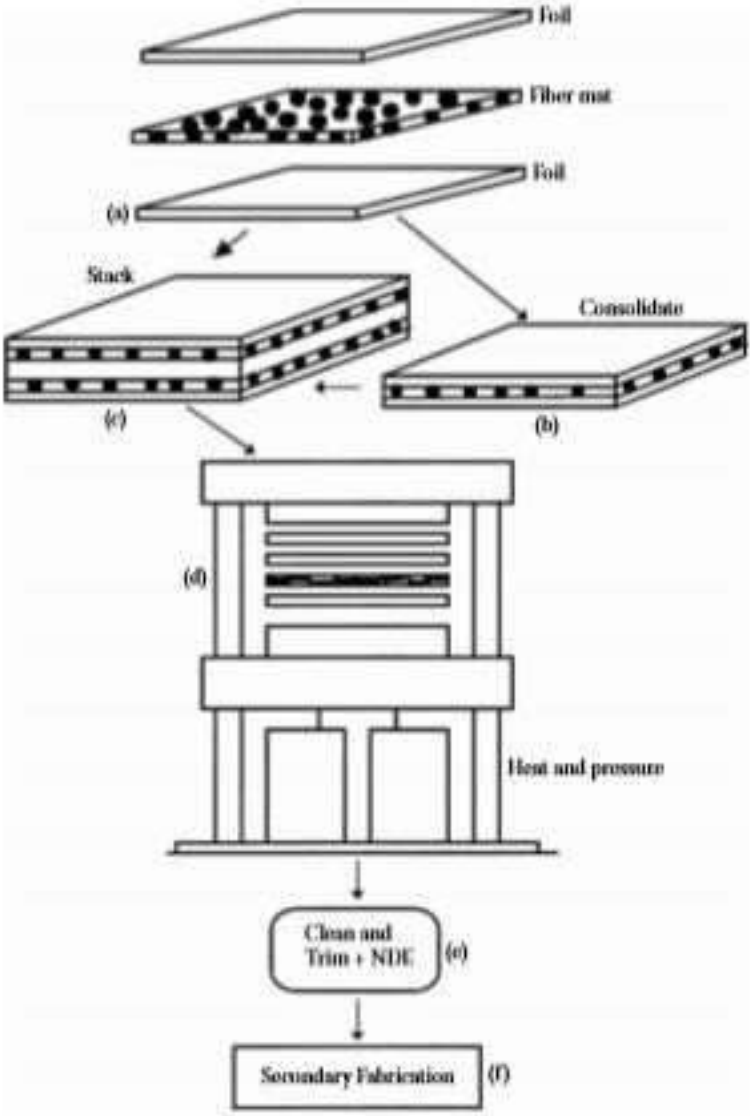


FIGURE 1.28
Schematic of diffusion bonding for metal matrix composites. (Reproduced with permission from Matthews, F.L. and Rawlings, R.D., *Composite Materials: Engineering and Science*, Chapman & Hall, London, 1994, Figure 3.1, p. 81. Copyright CRC Press, Boca Raton, FL.)

What are some of the applications of metal matrix composites? Or Metal matrix composites applications are:

• **Space:** The space shuttle uses boron/aluminum tubes to support its fuselage frame. In addition to decreasing the mass of the space shuttle by more than 320 lb (145 kg), boron/aluminum also reduced the thermal insulation requirements because of its low thermal conductivity. The mast of the Hubble Telescope uses carbon-reinforced aluminum.

• **Military:** Precision components of missile guidance systems demand dimensional stability — that is, the geometries of the components cannot change during use Metal matrix composites such as SiC/ aluminum composites satisfy this requirement because they have high micro yield strength.* In addition, the volume fraction of SiC can be varied to have a coefficient of thermal expansion compatible with other parts of the system assembly.

• **Transportation:** Metal matrix composites are finding use now in automotive engines that are lighter than their metal counterparts. Also, because of their high strength and low weight, metal matrix composites are the material of choice for gas turbine engines (Figure 1.30).

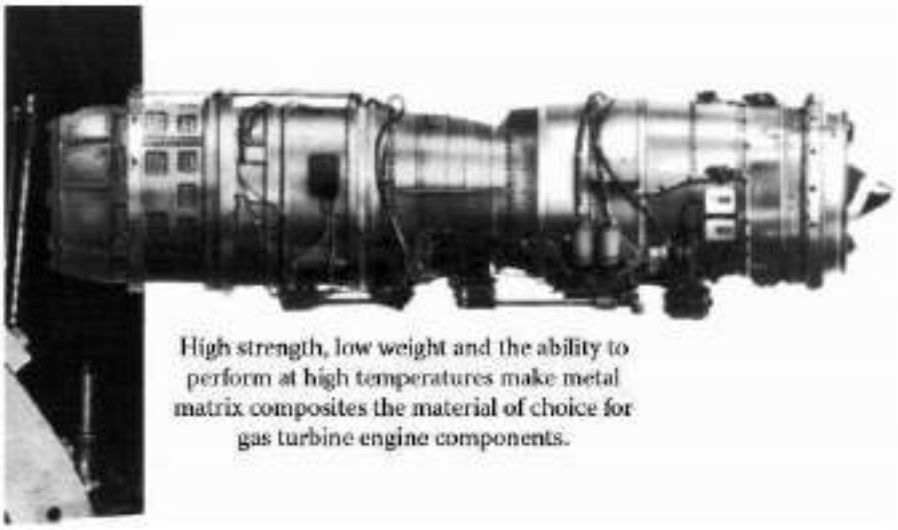


FIGURE 1.30
Gas turbine engine components made of metal matrix composites. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

1.2.3 Ceramic Matrix Composites

What are ceramic matrix composites?

Ceramic matrix composites (CMCs) have a ceramic matrix such as alumina calcium alumino silicate reinforced by fibers such as carbon or silicon carbide.

What are the advantages of ceramic matrix composites?

Advantages of CMCs include high strength, hardness, high service temperature limits* for ceramics, chemical inertness, and low density. However, ceramics by themselves have low fracture toughness. Under tensile or impact loading, they fail catastrophically. Reinforcing ceramics with fibers, such as silicon carbide or carbon, increases their fracture toughness (Table 1.12) because it causes gradual failure of the composite. This combination of a fiber and ceramic matrix makes CMCs more attractive for applications in which high mechanical properties and extreme service temperatures are desired.

TABLE 1.12

Typical Fracture Toughness of Monolithic Materials and Ceramic Matrix Composites

Material	Fracture toughness (MPa $\sqrt{m}$)	Fracture toughness (ksi $\sqrt{in.}$)
Epoxy	3	2.73
Aluminum alloys	35	31.85
Silicon carbide	3	2.73
SiC/Al_2O_3	27	24.6
SiC/SiC	30	27.3

What are the applications of ceramic matrix composites?

Ceramic matrix composites are finding increased application in high-temperature areas in which metal and polymer matrix composites cannot be used. This is not to say that CMCs are not attractive otherwise, especially considering their high strength and modulus, and low density. Typical applications include cutting tool inserts in oxidizing and high-temperature environments. Textron Systems Corporation® has developed fiber-reinforced ceramics with SCS™ monofilaments for future aircraft engines (Figure 1.32).

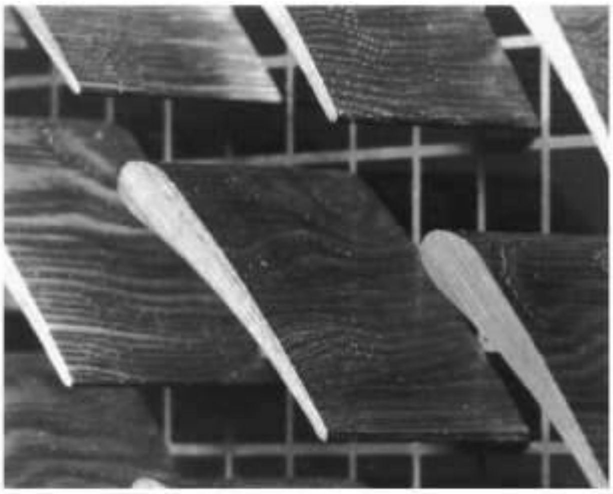


FIGURE 1.32
Ceramic matrix composites for high temperature and oxidation resistant application. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

Micromechanical Analysis of a Lamina

LECTURE 5: CHAPTER TWO
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Chapter Two: Objectives

• Develop concepts of volume and weight fraction (mass fraction) of fiber and matrix, density, and void fraction in composites.

• Find the nine mechanical and four hygrothermal constants: four elastic moduli, five strength parameters, two coefficients of thermal expansion, and two coefficients of moisture expansion of a unidirectional lamina from the individual properties of the fiber and the matrix, fiber volume fraction, and fiber packing.

• Discuss the experimental characterization of the nine mechanical and four hygrothermal constants. The two main processes are called chemical and mechanical processes.

2.1 Introduction

The stress–strain relationships, engineering constants, and failure theories for an angle lamina were developed using **four elastic moduli**, **five strength parameters, two coefficients of thermal expansion (CTE)**, and **two coefficients of moisture expansion (CME) for a unidirectional lamina**. These **13** parameters can be found experimentally by conducting several tension, compression, shear, and hygrothermal tests on unidirectional lamina (laminates).

However, unlike in isotropic materials, experimental evaluation of these parameters is quite costly and time consuming because they are functions of several variables: the individual constituents of the composite material, fiber volume fraction, packing geometry, processing, etc. Thus, the need and motivation for developing analytical models to find these parameters are very important.

In this chapter, we will develop simple relationships for the these parameters in terms of the stiffnesses, strengths, coefficients of thermal and moisture expansion of the individual constituents of a composite, fiber volume fraction, packing geometry, etc. An understanding of this relationship, called micromechanics of lamina, helps the designer to select the constituents of a composite material for use in a laminated structure. Because this text is for a first course in composite materials, details will be explained only for the simple models based on the mechanics of materials approach and the semi-empirical approach. Results from other methods based on advanced topics such as elasticity are also explained for completeness. As mentioned in a previous chapter, a unidirectional lamina is not homogeneous. However, one can assume the lamina to be homogeneous by focusing on the average response of the lamina to mechanical and hygrothermal loads (Figure 3.1).

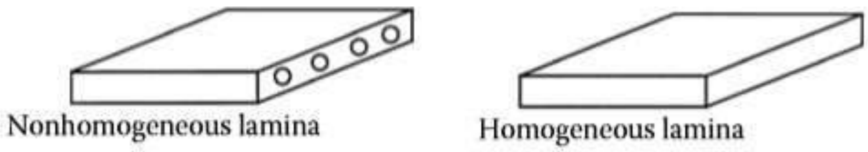

FIGURE 3.1
A nonhomogeneous lamina with fibers and matrix approximated as a homogeneous lamina.

The lamina is simply looked at as a material whose properties are different in various directions, but not different from one location to another. Also, the chapter focuses on a unidirectional continuous fiber-reinforced lamina. This is because it forms the basic building block of a composite structure, which is generally made of several unidirectional laminae placed at various angles. The modeling in the evaluation of the parameters is discussed first. This is followed by examples and experimental methods for finding these parameters.

2.2 Volume and Mass Fractions, Density, and Void Content

Before modeling the 13 parameters of a unidirectional composite, we introduce the concept of relative fraction of fibers by volume. This concept is critical because theoretical formulas for finding the stiffness, strength, and hygrothermal properties of a unidirectional lamina are a function of fiber volume fraction. Measurements of the constituents are generally based on their mass, so fiber mass fractions must also be defined. Moreover, defining the density of a composite also becomes necessary because its value is used in the experimental determination of fiber volume and void fractions of a composite. Also, the value of density is used in the definition of specific modulus and specific strength in Chapter 1.

2.2.1 Volume Fractions

Consider a composite consisting of fiber and matrix. Take the following symbol notations:

$v_{c,f,m}$ = volume of composite, fiber, and matrix, respectively

$\rho_{c,f,m}$ = density of composite, fiber, and matrix, respectively.

Now define the fiber volume fraction V_f and the matrix volume fraction V_m as

$$V_f = \frac{v_f}{v_c},$$

and

$$V_m = \frac{v_m}{v_c}. \qquad (3.1a, b)$$

Note that the sum of volume fractions is

$$V_f + V_m = 1,$$

from Equation (3.1) as

$$v_f + v_m = v_c.$$

2.2.2 Mass Fractions

Consider a composite consisting of fiber and matrix and take the following symbol notation: $w_{c,f,m}$ = mass of composite, fiber, and matrix, respectively. The mass fraction (weight fraction) of the fibers (W_f) and the matrix (W_m) are defined as

$$W_f = \frac{w_f}{w_c}, \text{ and}$$

$$W_m = \frac{w_m}{w_c}. \tag{3.2a, b}$$

Note that the sum of mass fractions is

$$W_f + W_m = 1,$$

from Equation (3.2) as

$$w_f + w_m = w_c.$$

From the definition of the density of a single material,

$$w_c = r_c v_c,$$
$$w_f = r_f v_f, \text{ and} \tag{3.3a–c}$$
$$w_m = r_m v_m.$$

Substituting Equation (3.3) in Equation (3.2), the mass fractions and volume fractions are related as

$$W_f = \frac{\rho_f}{\rho_c} V_f, \text{ and}$$

$$W_m = \frac{\rho_m}{\rho_c} V_m, \tag{3.4a, b}$$

in terms of the fiber and matrix volume fractions. In terms of individual constituent properties, the mass fractions and volume fractions are related by

$$W_f = \frac{\frac{\rho_f}{\rho_m}}{\frac{\rho_f}{\rho_m} V_f + V_m} V_f ,$$

$$W_m = \frac{1}{\frac{\rho_f}{\rho_m}(1 - V_m) + V_m} V_m . \qquad (3.5a, b)$$

One should always state the basis of calculating the fiber content of a composite. It is given in terms of mass or volume. Based on Equation (3.4), it is evident that volume and mass fractions are not equal and that the mismatch between the mass and volume fractions increases as the ratio between the density of fiber and matrix differs from one.

2.2.3 Density

The derivation of the density of the composite in terms of volume fractions is found as follows. The mass of composite w_c is the sum of the mass of the fibers w_f and the mass of the matrix w_m as

$$w_c = w_f + w_m. \tag{3.6}$$

Substituting Equation (3.3) in Equation (3.6) yields

$$\rho_c v_c = \rho_f v_f + \rho_m v_m,$$

and

$$\rho_c = \rho_f \frac{v_f}{v_c} + \rho_m \frac{v_m}{v_c}. \tag{3.7}$$

Using the definitions of fiber and matrix volume fractions from Equation (3.1),

$$\rho_c = \rho_f V_f + \rho_m V_m. \tag{3.8}$$

Now, consider that the volume of a composite v_c is the sum of the volumes of the fiber v_f and matrix (v_m):

$$v_c = v_f + v_m. \tag{3.9}$$

The density of the composite in terms of mass fractions can be found as

$$\frac{1}{\rho_c} = \frac{W_f}{\rho_f} + \frac{W_m}{\rho_m}. \tag{3.10}$$

Example 2.1: A glass/epoxy lamina consists of a 70% fiber volume fraction. Use properties of glass and epoxy from Table 3.1* and Table 3.2, respectively, to determine:

1. Density of lamina

2. Mass fractions of the glass and epoxy

3. Volume of composite lamina if the mass of the lamina is 4 kg

4. Volume and mass of glass and epoxy in part (3)

TABLE 3.1

Typical Properties of Fibers (SI System of Units)

Property	Units	Graphite	Glass	Aramid
Axial modulus	GPa	230	85	124
Transverse modulus	GPa	22	85	8
Axial Poisson's ratio	—	0.30	0.20	0.36
Transverse Poisson's ratio	—	0.35	0.20	0.37
Axial shear modulus	GPa	22	35.42	3
Axial coefficient of thermal expansion	μm/m/°C	-1.3	5	-5.0
Transverse coefficient of thermal expansion	μm/m/°C	7.0	5	4.1
Axial tensile strength	MPa	2067	1550	1379
Axial compressive strength	MPa	1999	1550	276
Transverse tensile strength	MPa	77	1550	7
Transverse compressive strength	MPa	42	1550	7
Shear strength	MPa	36	35	21
Specific gravity	—	1.8	2.5	1.4

TABLE 3.2

Typical Properties of Matrices (SI System of Units)

Property	Units	Epoxy	Aluminum	Polyamide
Axial modulus	GPa	3.4	71	3.5
Transverse modulus	GPa	3.4	71	3.5
Axial Poisson's ratio	—	0.30	0.30	0.35
Transverse Poisson's ratio	—	0.30	0.30	0.35
Axial shear modulus	GPa	1.308	27	1.3
Coefficient of thermal expansion	μm/m/°C	63	23	90
Coefficient of moisture expansion	m/m/kg/kg	0.33	0.00	0.33
Axial tensile strength	MPa	72	276	54
Axial compressive strength	MPa	102	276	108
Transverse tensile strength	MPa	72	276	54
Transverse compressive strength	MPa	102	276	108
Shear strength	MPa	34	138	54
Specific gravity	—	1.2	2.7	1.2

Solution:

1. From Table 3.1, the density of the fiber is

$$\rho_f = 2500\ kg/m^3.$$

From Table 3.2, the density of the matrix is

$$\rho_m = 1200\ kg/m^3.$$

Using Equation (3.8), the density of the composite is

$$\begin{aligned}\rho_c &= (2500)(0.7) + (1200)(0.3)\\ &= 2110\ kg/m^3.\end{aligned}$$

2. Using Equation (3.4), the fiber and matrix mass fractions are

$$W_f = \frac{2500}{2110} \times 0.3$$
$$= 0.8294$$

$$W_m = \frac{1200}{2110} \times 0.3 \, .$$
$$= 0.1706$$

Note that the sum of the mass fractions,

$$W_f + W_m = 0.8294 + 0.1706$$
$$= 1.000.$$

3. The volume of composite is

$$v_c = \frac{w_c}{\rho_c}$$

$$= \frac{4}{2110}$$

$$= 1.896 \times 10^{-3} m^3 \, .$$

4. The volume of the fiber is

$$v_f = V_f v_c$$

$$= (0.7)(1.896 \times 10^{-3})$$

$$= 1.327 \times 10^{-3} m^3 \, .$$

The volume of the matrix is

$$v_m = V_m v_c$$

$$=(0.3)(0.1896 \times 10^{-3})$$

$$= 0.5688 \times 10^{-3}\ m^3 .$$

The mass of the fiber is

$$w_f = \rho_f v_f$$

$$= (2500)(1.327 \times 10^{-3})$$

$$= 3.318\ kg\ .$$

The mass of the matrix is

$$w_m = \rho_m v_m$$

$$= (1200)(0.5688 \times 10^{-3})$$

$$= 0.6826\ kg\ .$$

An E-glass fiber reinforced vinyl ester composite has a fiber volume fraction of 40%. Experimentally measured density of E-glass fiber and vinyl ester is 2.54 g/cm^3 and 1.3 g/cm^3, respectively. What is the weight fraction of fibers?

Solution:

$V_f = 40\%$; $V_m = (1 - V_f) = 60\%$ $\rho_f = 2.54$ g/cm^3; $\rho_m = 1.3$ g/cm^3

According to Equation (7.1)

$$W_f = \frac{V_f \rho_f}{V_f \rho_f + V_m \rho_m} = \frac{0.4 \times 2.54}{0.4 \times 2.54 \times 0.6 \times 1.3} = \frac{1.016}{1.016 + 0.78} = 57\%$$

The glass vinyl ester composite has a fiber weight fraction of 57%.

A carbon fiber reinforced polyphenylene sulfide (PPS) composite has a resin weight fraction of 48%. What is the volume fraction of carbon fiber in this composite? The density of carbon fiber is 1.8 g/cm^3 and the density of PPS is 1.48 g/cm^3.

Solution:

$W_m = 48\%$; $W_f = (1 - W_m) = 52\%$; $\rho_f = 1.8$ g/cm^3; $\rho_m = 1.48$ g/cm^3

According to Equation (7.4)

$$V_f = \frac{W_f / \rho_f}{W_f / \rho_f + W_m / \rho_m + W_v / \rho_v} = \frac{052/18}{052/18 + 0.48/1.48} = \frac{0.289}{0.289 + 0.324} = 47\%$$

The fiber volume fraction of the composite is 47%.

MECHANICS OF COMPOSITE MATERIALS

(ME 4306E)

College of Engineering

Mechanical Department

(Stage 4)

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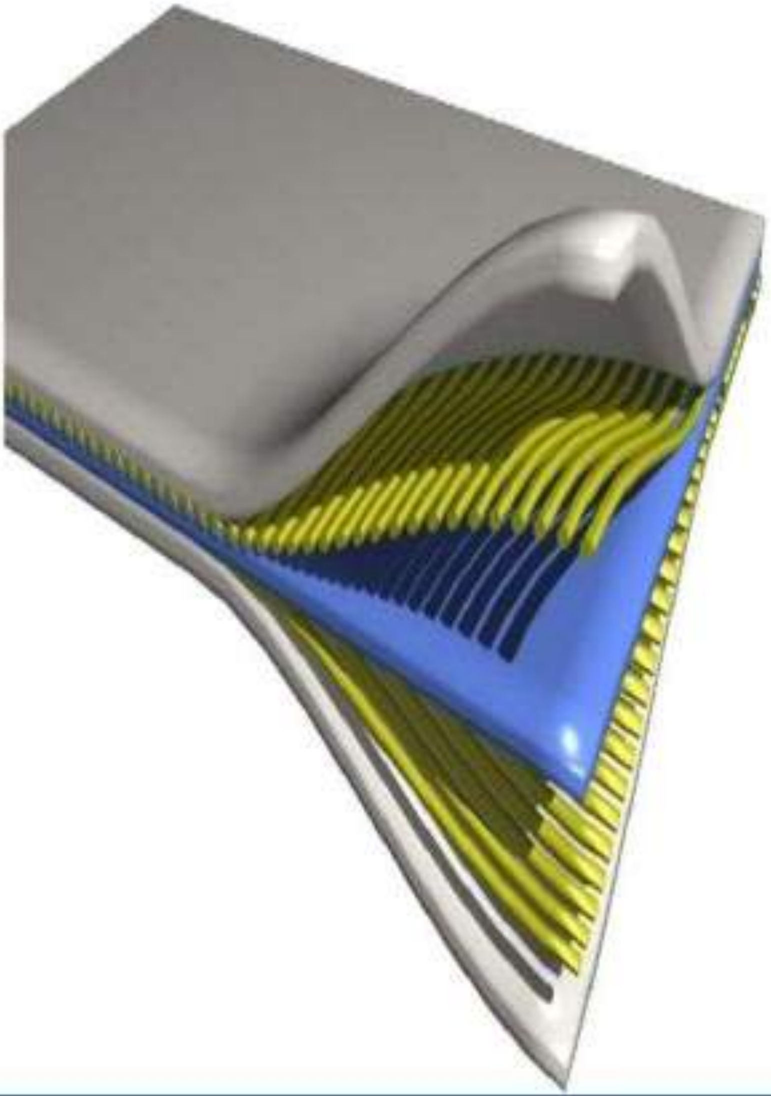
Introduction to Composite Materials



Introduction to Composite Materials

LECTURE : 1: CHAPTER ONE

Print · Feb 2020.

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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°F (–160°C) and 200°F (93.3°C). Limitations on coefficient of thermal expansion‡ thus are low and may be of the order of $\pm 1 \times 10^{-7}$ in./in./°F ($\pm 1.8 \times 10^{-7}$ m/m/°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

$$u = \frac{PL}{AE}, \tag{1.1}$$

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

$$M = \rho AL, \tag{1.2}$$

where ρ = density of the material of the rod, we have

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

This implies that the lightest beam for specified deflection under a specified load is one with the highest ***(E/ρ)*** value. Thus, to measure the mechanical advantage, the ***(E/ρ)*** ratio is calculated and is called the **specific modulus** **(**ratio between the Young's modulus ***(E)*** and the density ***(ρ)*** of the material**)**. The other parameter is called the specific strength and is defined as the ratio between the strength ***(σ_{ult})*** and the density of the material ***(ρ)***, 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.3 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^2 or 9.81 m/s^2).

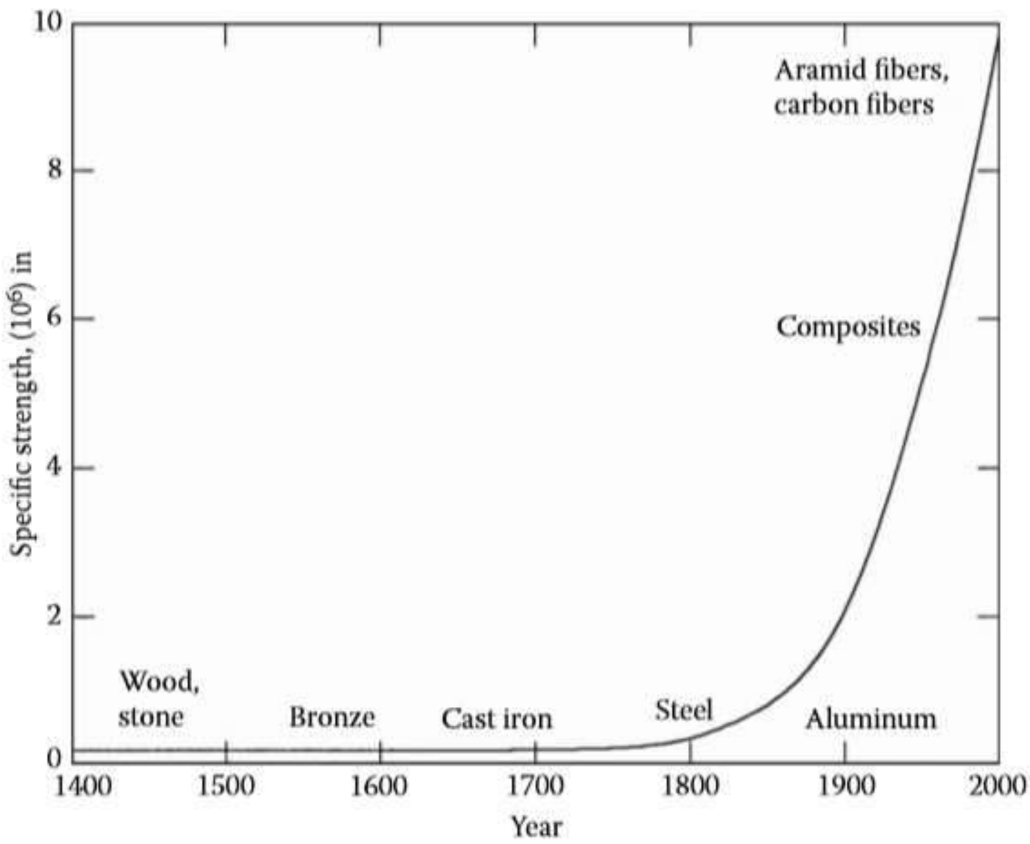

FIGURE 1.1
Specific strength as a function of time of use of materials. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

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.

<u>* A unidirectional laminate</u> is a laminate in which all fibers are oriented in the same direction.

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

<u>‡ Quasi-isotropic laminate</u> , 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[a]	Young's modulus (Msi)	Ultimate strength (ksi)	Specific modulus (Msi-in.^{3}/lb)	Specific strength (ksi-in.^{3}/lb)
System of Units: USCS					
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^3/kg)	Specific strength (MPa-m^3/kg)
System of Units: SI					
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

[a] 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.

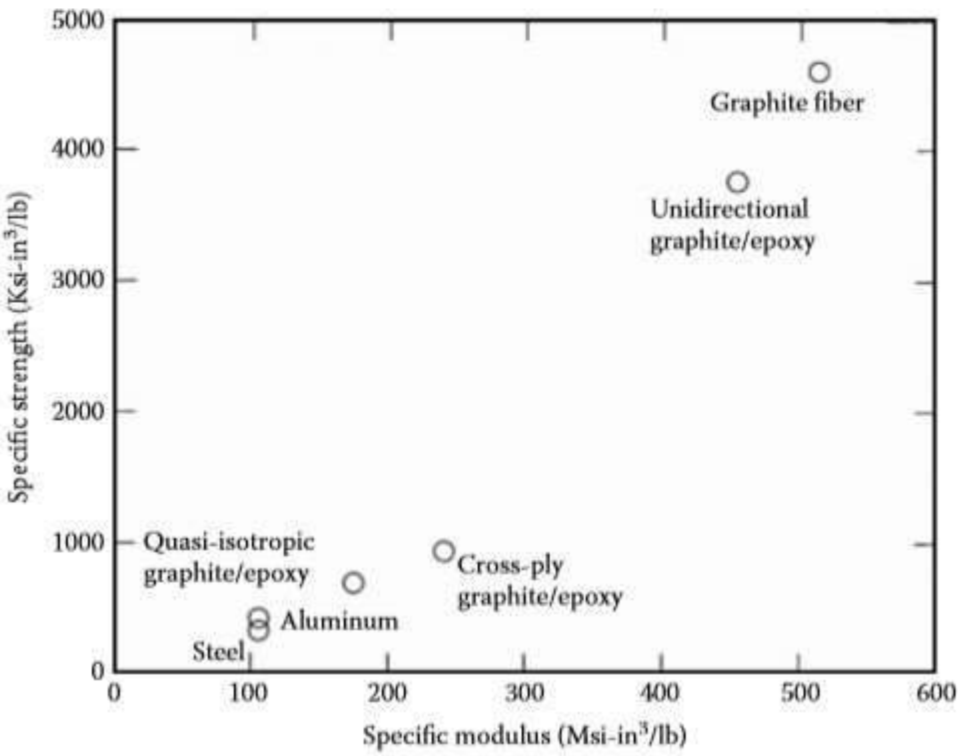

FIGURE 1.2
Specific strength as a function of specific modulus for metals, fibers, and composites.

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:

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

when

Pg = critical buckling load (lb or N)
I = Young's modulus of column (lb/in.^{2} or N/m')
i = second moment of area (in.'or m')
1 = len$tt› of beam (In. or m)

If the column has a cixular cmss mdon, the bond moment of area 1s

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

and the mass of the rod 1s

$$M = p \frac{2}{\quad} , \qquad (1.6)$$

where

M = mass of the beam (lb or kg)
ρ = density of beam (lb/in.^{3} or kg/m^3)
d = diameter of beam (in. or m)

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

$$M = \frac{2L^2\sqrt{P_{cr}}}{\sqrt{\pi}} \frac{1}{E^{1/2}/\rho}. \tag{1.7}$$

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

Material Units	Specific gravity	Young's modulus (Msi)	E/ρ (Msi-in.^{3}/lb)	$E^{1/2}/\rho$ (psi$^{1/2}$-in.^{3}/lb)	$E^{1/3}/\rho$ (psi$^{1/3}$-in.^{3}/lb)
System of Units: USCS					
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/ρ (GPa-m^3/kg)**	**$E^{1/2}/\rho$ (Pa-m^3/kg)**	**$E^{1/3}/\rho$ (Pa$^{1/3}$-m^3/kg)**
System of Units: SI					
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:

* 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 σ (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.

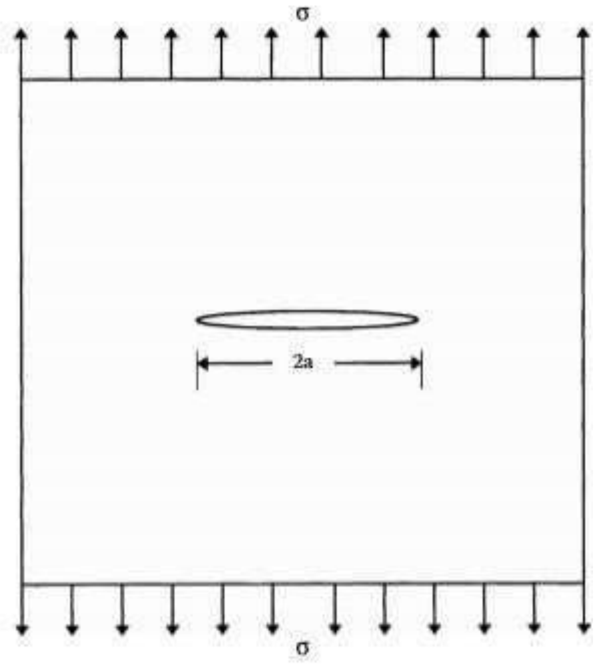

FIGURE 1.3
A uniformly loaded plate with a crack.

• 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.)

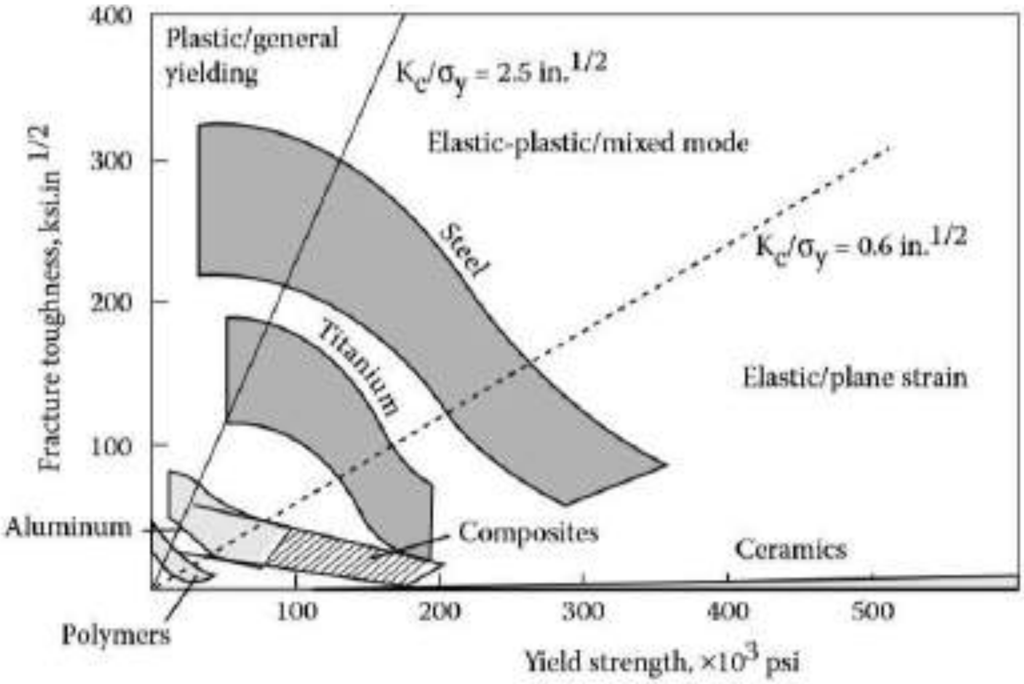

FIGURE 1.4
Fracture toughness as a function of yield strength for monolithic metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

• 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.

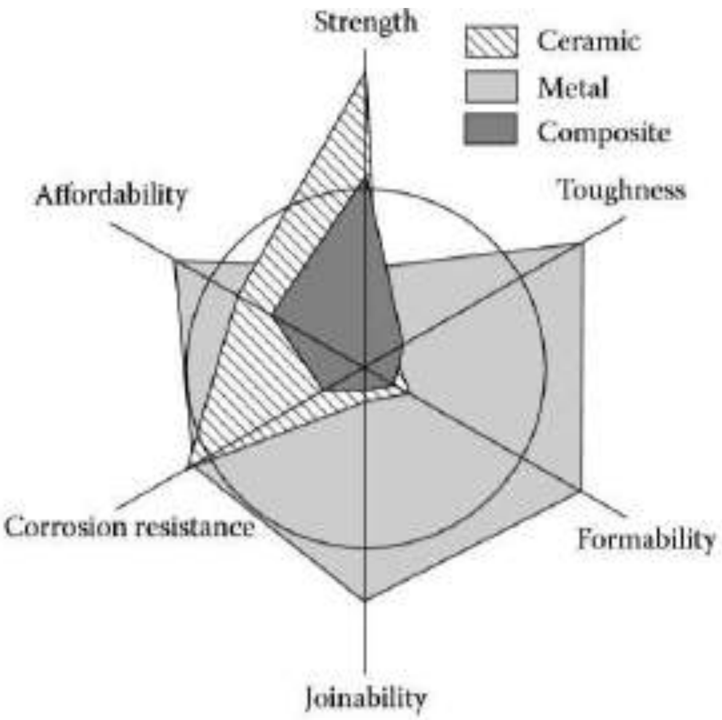

FIGURE 1.5
Primary material selection parameters for a hypothetical situation for metals, ceramics, and metal–ceramic composites. (Source: Eager, T.W., Whither advanced materials? *Adv. Mater. Processes*, ASM International, June 1991, 25–29.)

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.

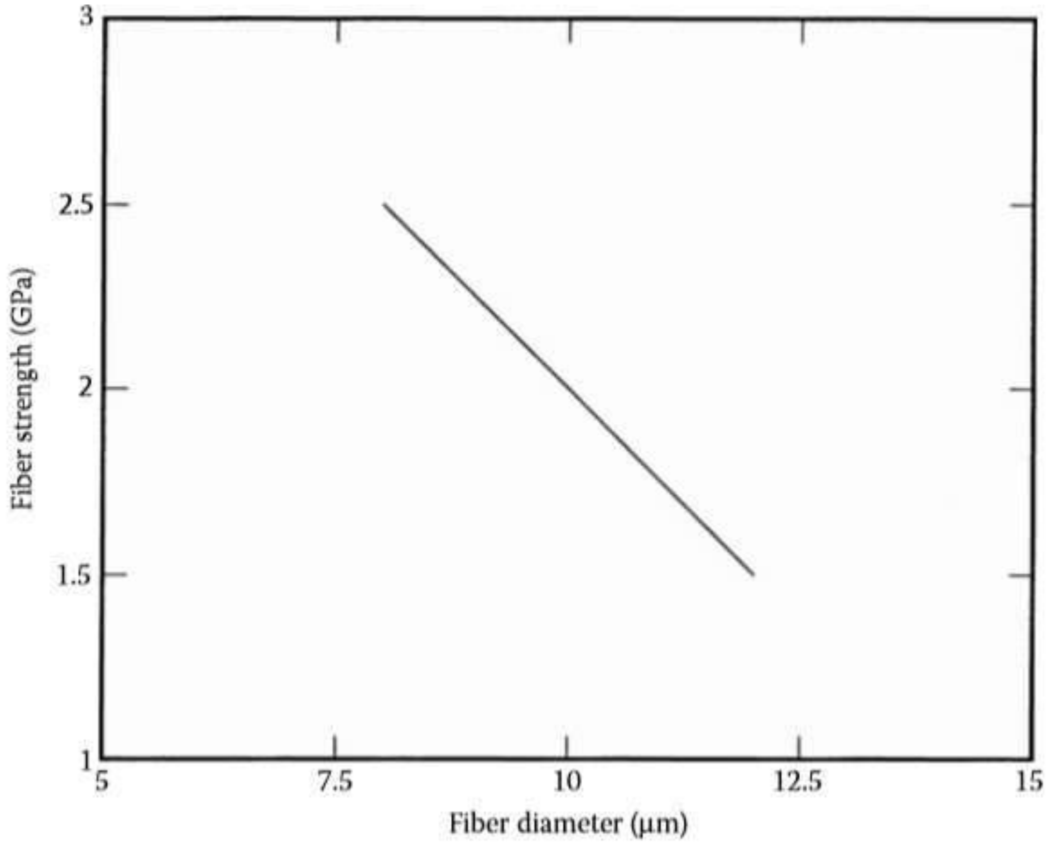

FIGURE 1.6
Fiber strength as a function of fiber diameter for carbon fibers. (Reprinted from Lamotte, E. De, and Perry, A.J., *Fibre Sci. Technol.*, 3, 159, 1970. With permission from Elsevier.)

• 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

$$A_t = N \pi D L. \tag{1.8}$$

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

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

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

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

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,

$R = 1 - (A_f/A_i)$.

• 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,

$$\frac{d^2v}{dx^2} = \frac{M}{EI}, \tag{1.11}$$

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.^{4} or m^4)
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

$$I = \frac{\pi d^4}{64}, \tag{1.12}$$

then

$$\text{Flexibility} \propto \frac{1}{Ed^4}. \tag{1.13}$$

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.

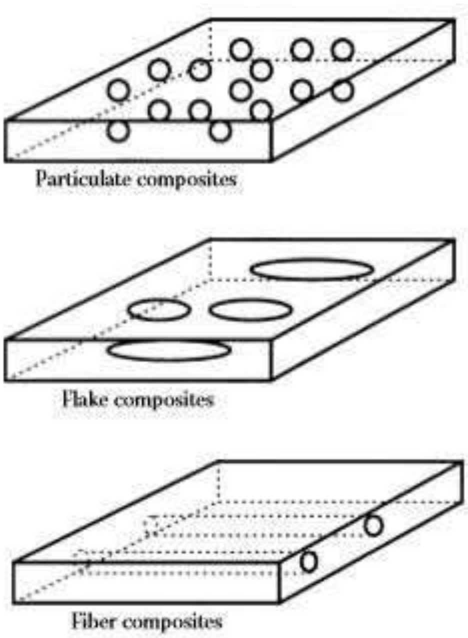

FIGURE 1.8
Types of composites based on reinforcement shape.

- **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–alumino 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, theproperties 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 olefinbased nanocomposites.9 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
System of units: USCS					
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
System of units: SI					
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
System of units: USCS						
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	μin./in./°F	−0.722	−2.778	2.778	6.5	12.8
System of units: SI						
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	μm/m/°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

<u>Typical examples of thermoplastics</u> 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).

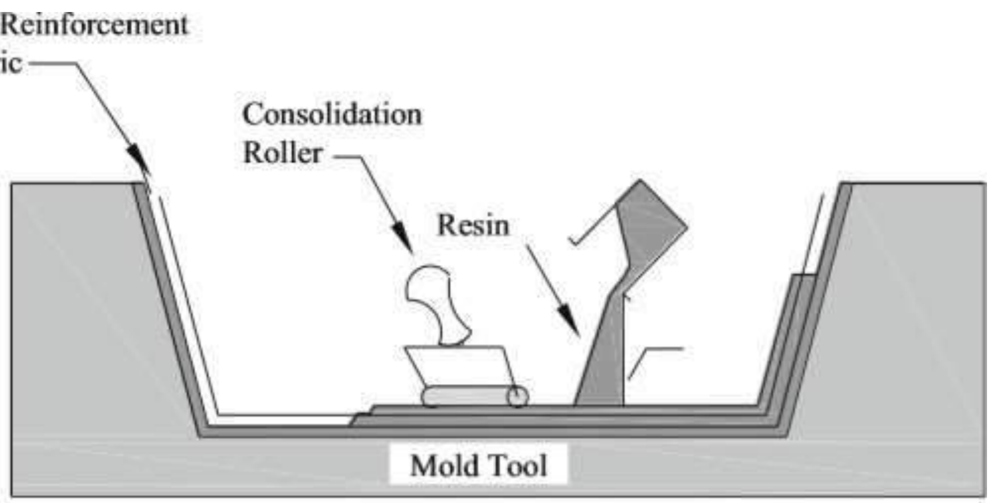

Fig. 1.3 Schematic of hand layup

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.

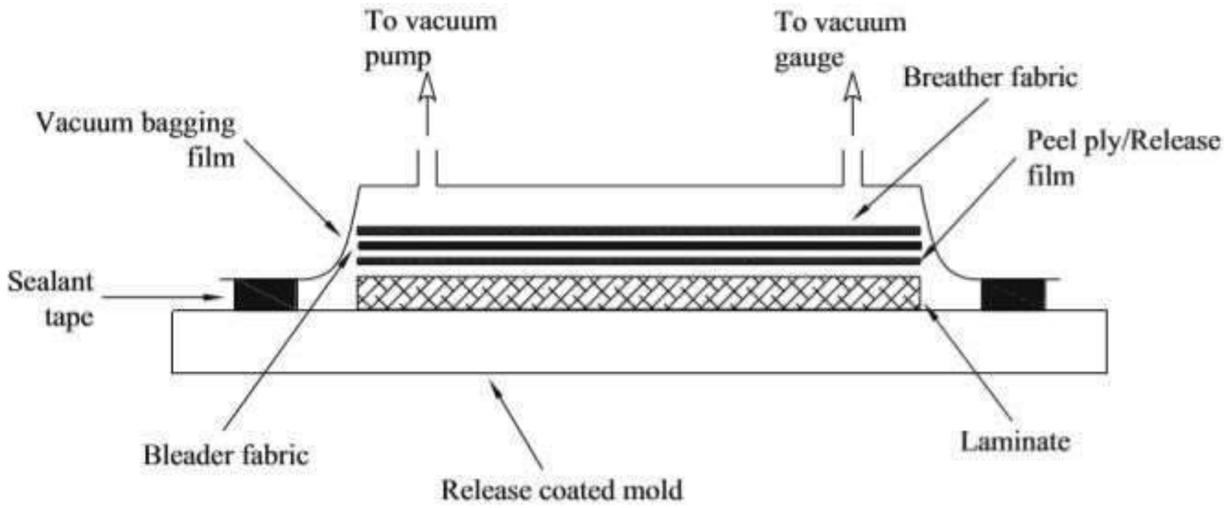

Fig. 1.4 Schematic of vacuum bag molding

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.

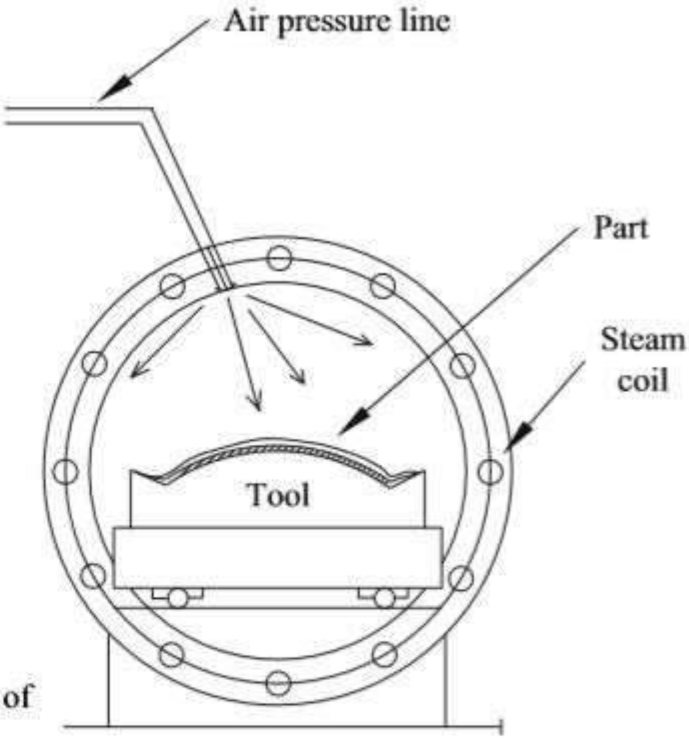

Fig. 1.5 Schematic of autoclave

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.

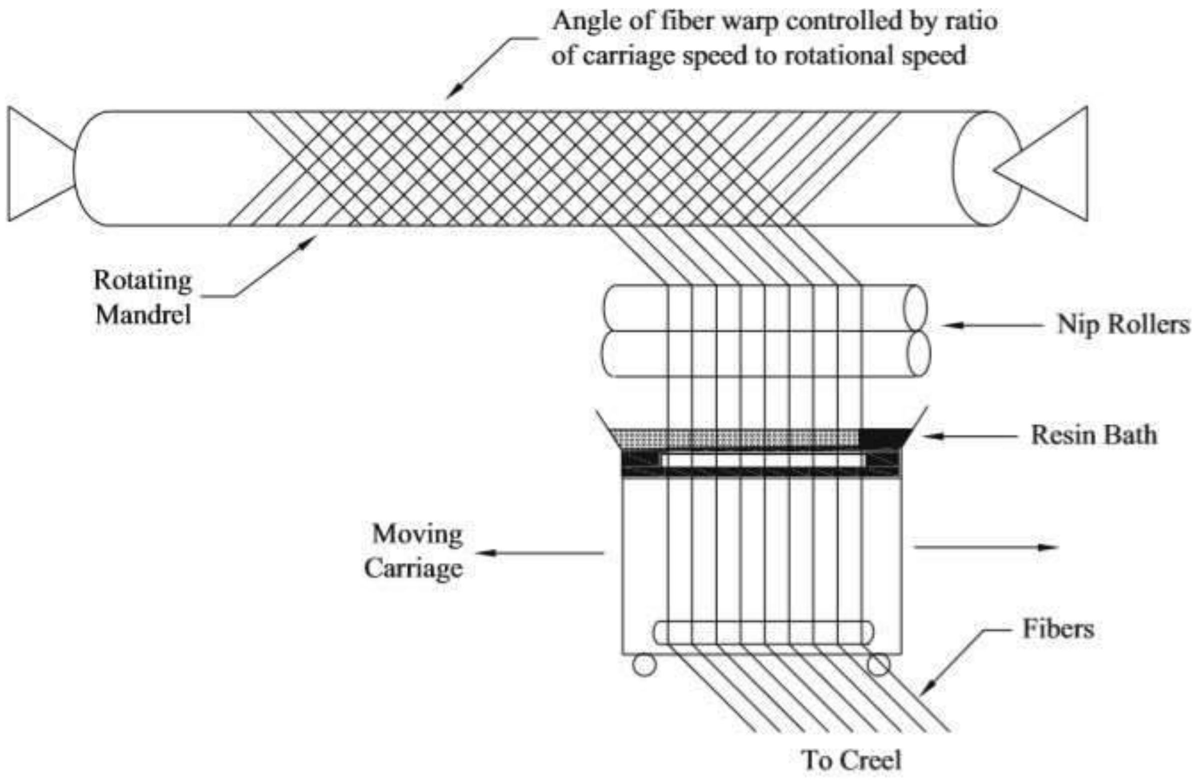

Fig. 1.6 Schematic of filament winding

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.

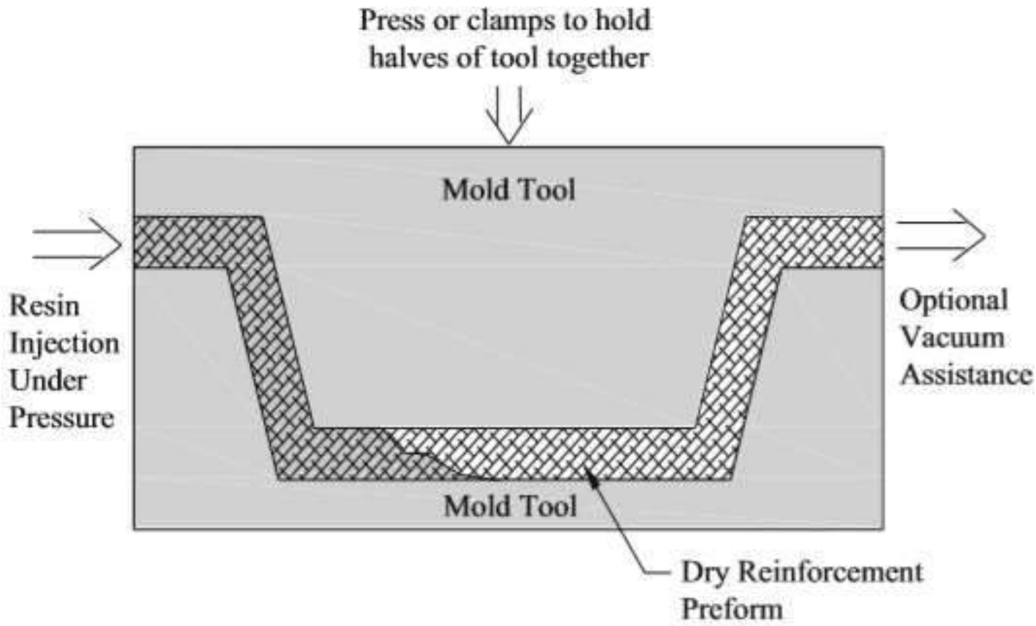

Fig. 1.8 Schematic of resin transfer molding

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.