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.

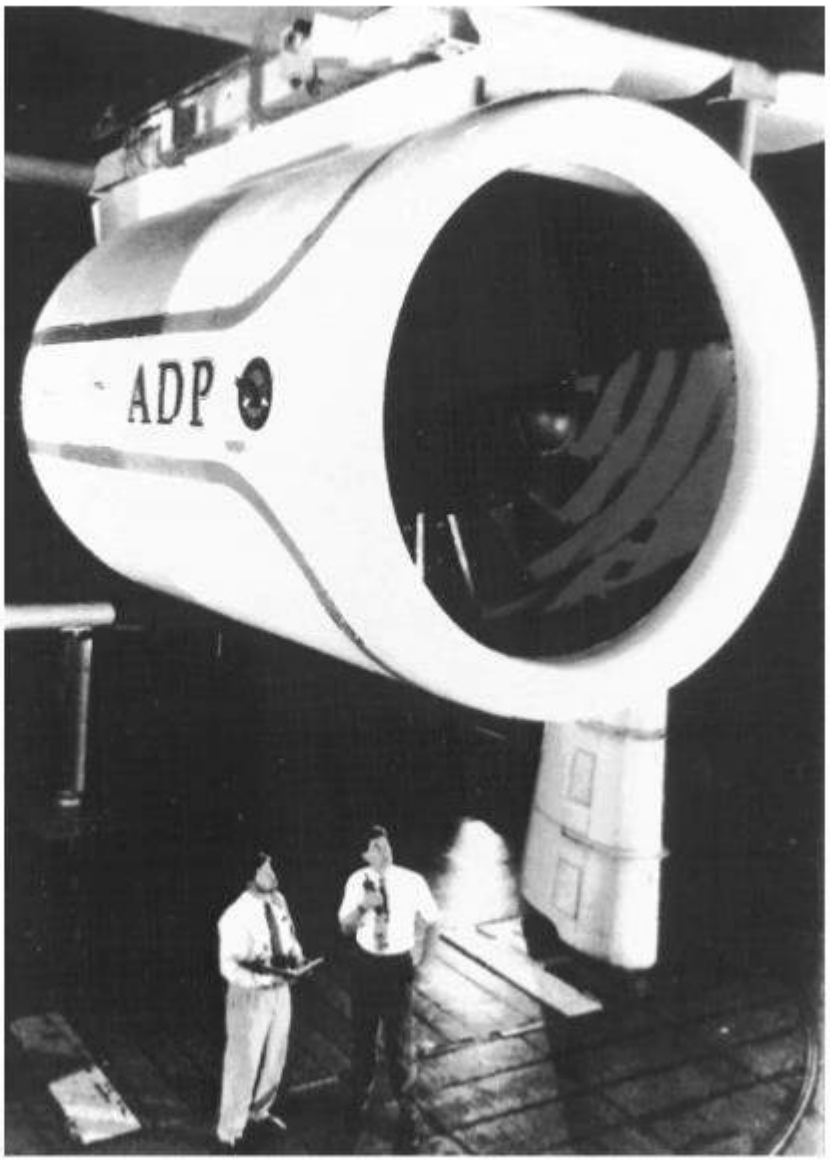


FIGURE 1.19
Aircraft engine cowling. (Photo provided courtesy of Alliant Techsystems, Inc.)

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.

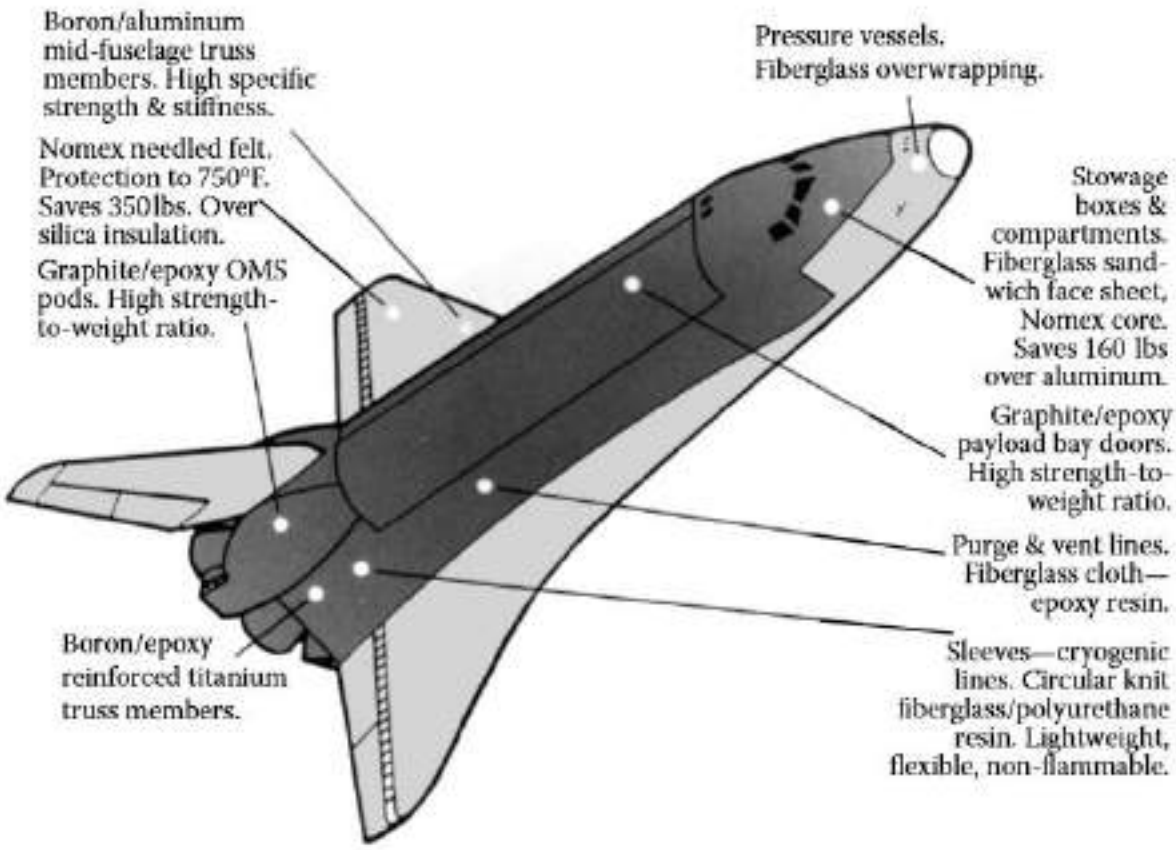


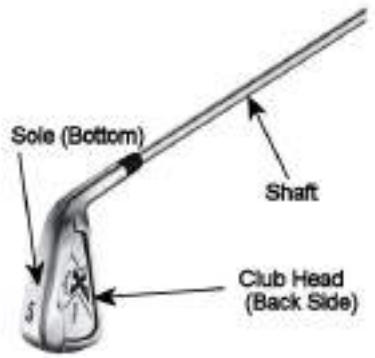
FIGURE 1.22
Use of composites in the space shuttle. (Graphic courtesy of M.C. Gill Corporation, http://www.mcgillcorp.com.)

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.

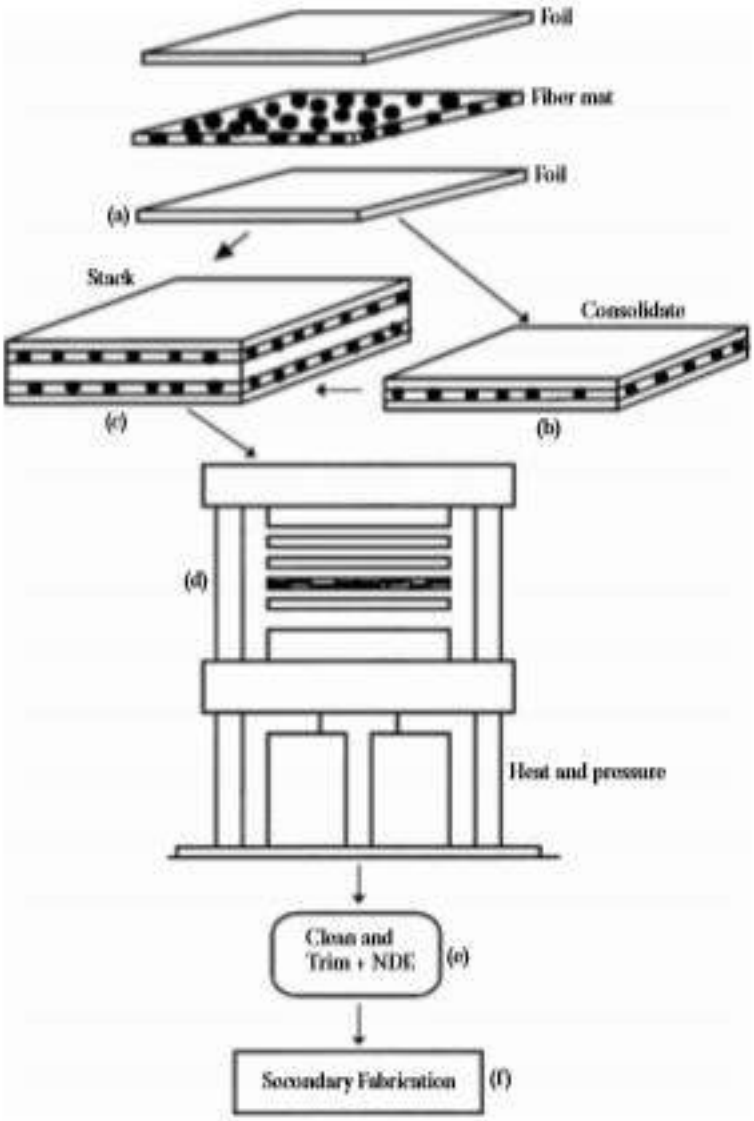


FIGURE 1.28
Schematic of diffusion bonding for metal matrix composites. (Reproduced with permission from Matthews, F.L. and Rawlings, R.D., *Composite Materials: Engineering and Science*, Chapman & Hall, London, 1994, Figure 3.1, p. 81. Copyright CRC Press, Boca Raton, FL.)

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).

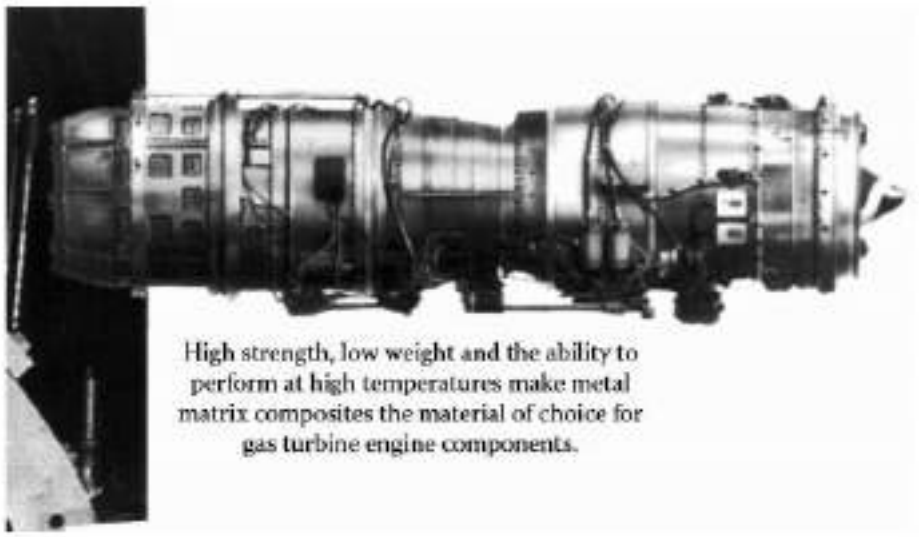


FIGURE 1.30
Gas turbine engine components made of metal matrix composites. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

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).

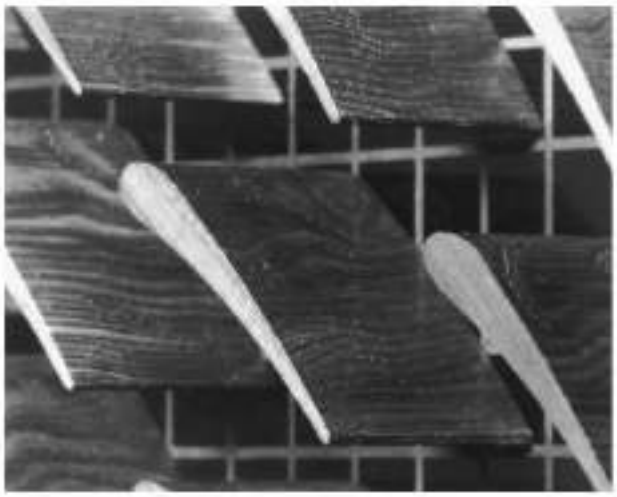


FIGURE 1.32
Ceramic matrix composites for high temperature and oxidation resistant application. (Photo courtesy of Specialty Materials, Inc., http://www.specmaterials.com.)

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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**).

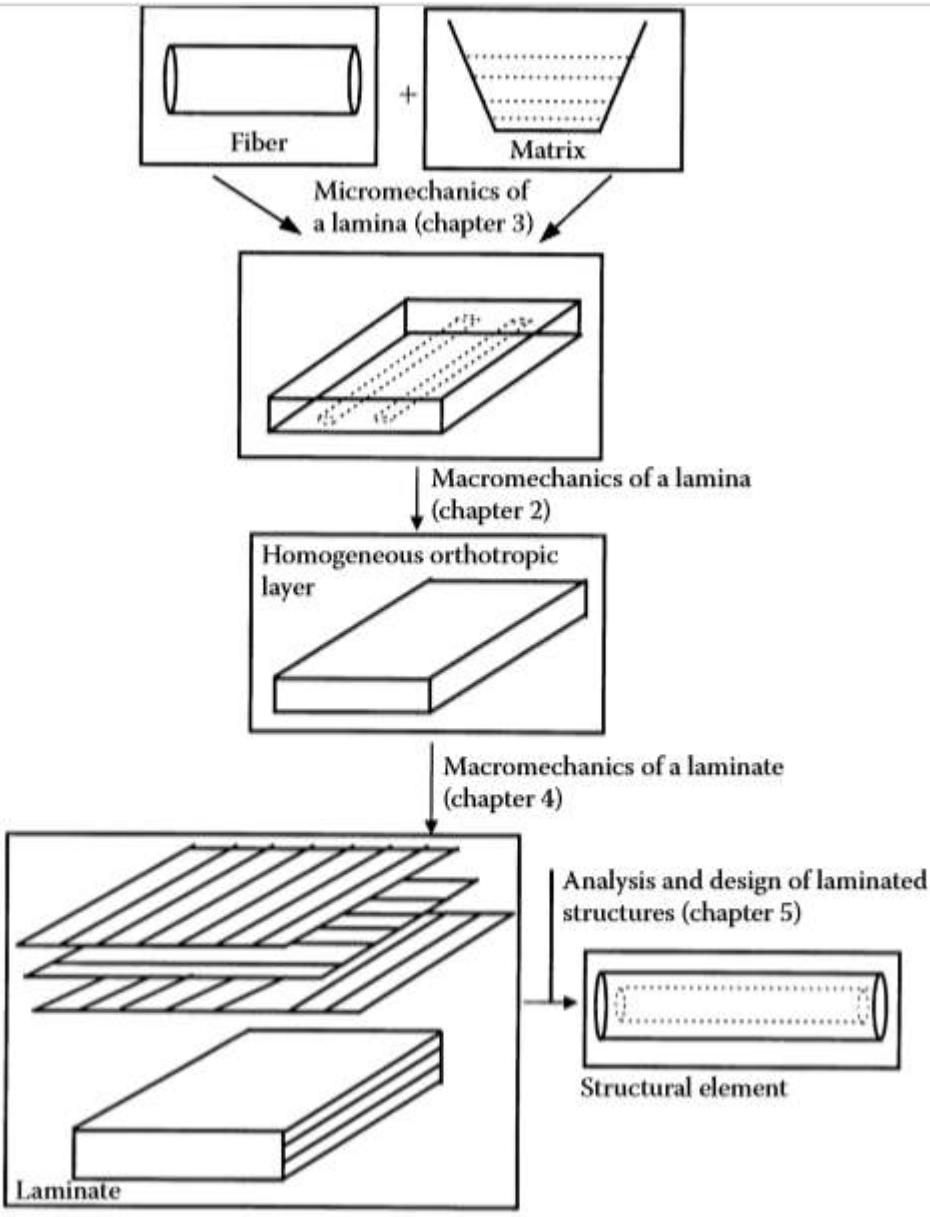

FIGURE 1.35
Schematic of analysis of laminated composites.

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.