Chapter 1

Introduction to Composite and Advanced Materials

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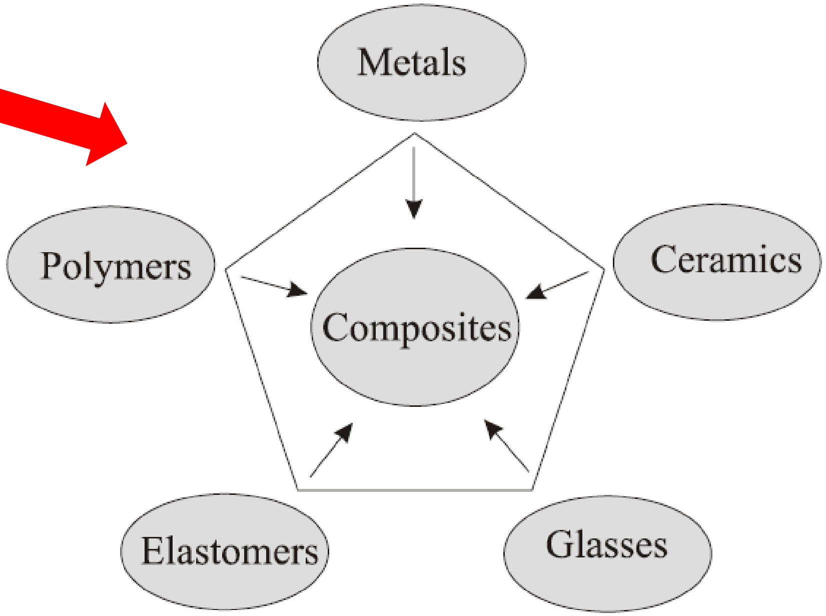
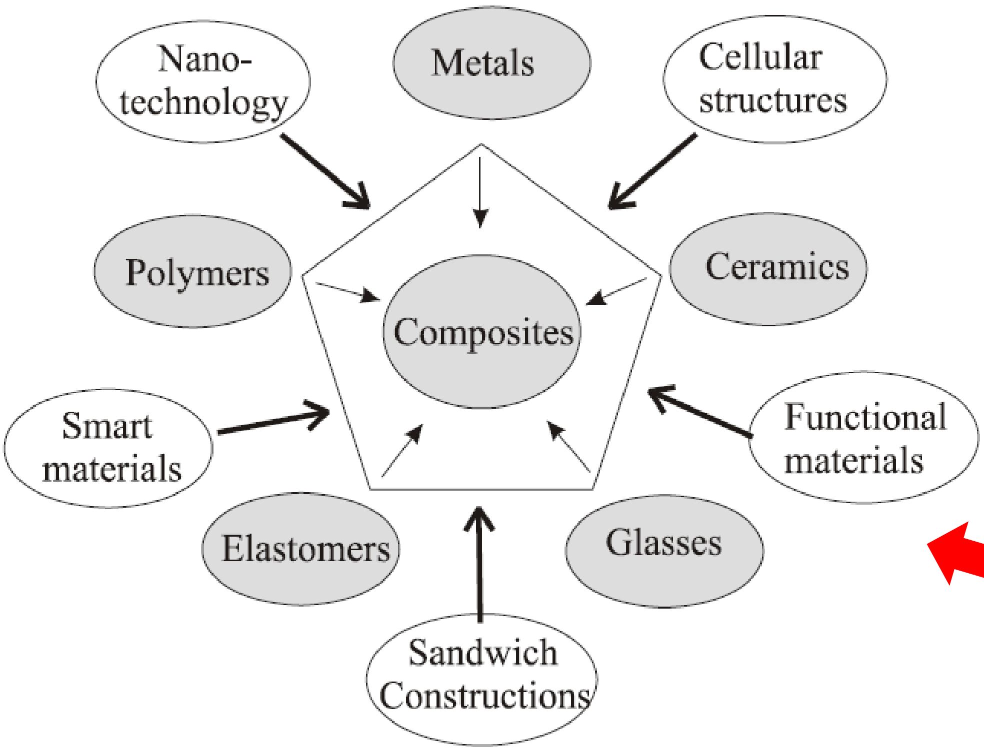
Contents

1.1. Introduction to Materials

- Materials are often classified into the six broad classes (metals, ceramics, glasses, elastomers, polymers and composites).





However, if we include material structures, the number is bigger, and the classification of the term "materials and structures".

1.1. Introduction to Materials

1) Metals and Alloys

- Composed of one or more metallic elements (*e.g. iron, aluminium and gold*) and often also nonmetallic elements (*carbon, nitrogen and oxygen*) in relatively small amounts.
- Metals are elements that generally have good electrical and thermal conductivity. Many metals have high strength, high stiffness, and have good ductility.

2) Ceramics and Glasses

- Inorganic nonmetallic materials.
- Compounds between metallic and non-metallic elements
- Most frequently oxides, nitrides and carbides (*e.g. aluminum oxide, silicon carbide and glass*)

3) Polymers, Plastics and Elastomers

- Organic materials characterized by long chain-like molecules.
- Polymers and plastics (nylon, epoxy, polyester, polyethylene).
- Elastomers: silicone, rubber materials.

4) Composites

- Composed of two (or more) individual materials.
- Natural composites, Man-made composites, Polymer matrix composites, Metal matrix composites, Ceramic composites, etc.

1.2. Advanced Materials

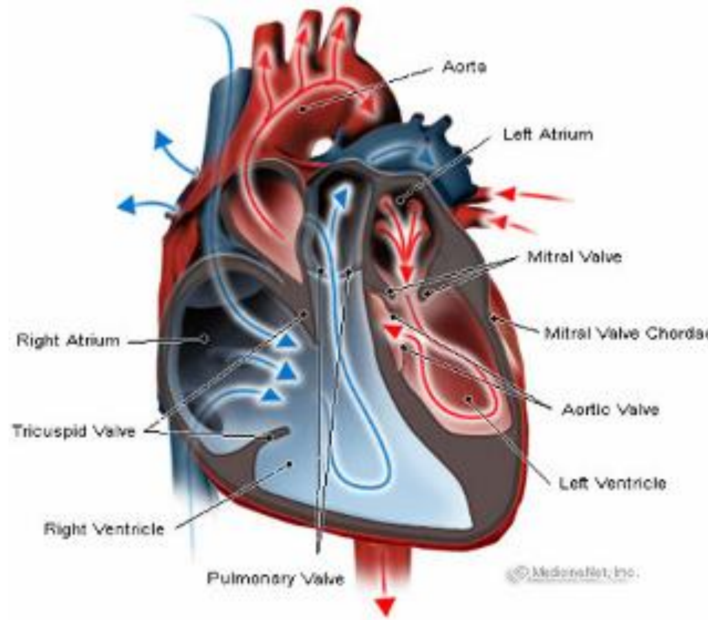
Materials that are utilized in high-technology or advanced applications

1. ***Biomaterials***
   - *Materials that are used and adapted for medical applications.*
2. ***Smart (Intelligent) Materials (responsive or functional materials)***
   - *A group of materials being developed that will have a significant influence on many of our technologies.*
   - *'smart' implies that the material is able to sense changes in their environment and then respond to these changes in a predetermined manner.*
3. ***Nanomaterials and Nanotechnology***
   - *The study of the controlling of matter on an atomic and molecular scale.*
   - *Developing new materials with dimensions on the nanoscale.*
   - *One nanometer (nm) is one billionth, or 10^{-9}, of a meter .*
4. ***Other Advanced Materials***
   - *Solar cell materials: A solar cell or photovoltaic cell is a device that converts light energy into electrical energy. Materials for solar cells: light-absorbing material (absorb photons and generate electrons), Silicon, Thin films.*
   - *Functional Gradient Materials, Cellular Solids, Structures & Foams.*

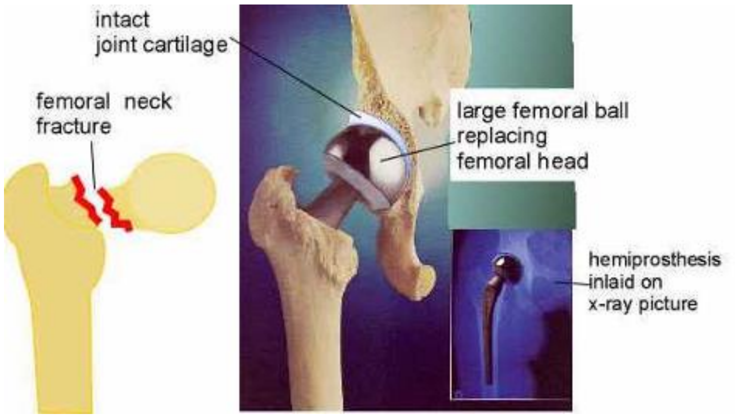
1.2. Advanced Materials

Biomaterials

- *“A biomaterial is any material, natural or man-made, that comprises whole or part of a living structure or biomedical device which performs, augments, or replaces a natural function".*
- Can also be defined as “*a nonviable material used in a medical device, intended to interact with biological systems*”
- Encompasses aspects of medicine, biology, chemistry and materials science (engineering).
- Rarely used as isolated materials but are commonly integrated into devices or implants.
- Biocompatibility — The ability of a material to perform with an appropriate host response in a specific application.
- Host Response — The response of the host organism (local and systemic) to the implanted material or device.



Heart and Valves



Artificial Hip Joints

Smart (Intelligent) Materials

- Materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.
- They have capability to sense and react to environment or external stimuli.

1. *Piezoelectric materials*

- *Piezoelecticity is the electric charge that accumulates in certain solid materials—such as crystals, ceramics, and biological matter such as bone, DNA, and various proteins—in response to applied mechanical stress. When a piezoelectric material is deformed, it gives off a small but measurable electrical discharge. Alternately, when an electrical current is passed through a piezoelectric material it experiences a significant increase in size (up to a 4% change in volume).*

2. *Shape memory alloys*

- *SMA (smart metal, memory alloy, muscle wire, smart alloy) is an alloy that demonstrate the ability to return to its original, cold, forged shape, after being deformed by applying heat. The most effective and widely used alloys include NiTi (Nickel - Titanium), CuZnAl, and CuAlNi.*

3. *Other smart materials*

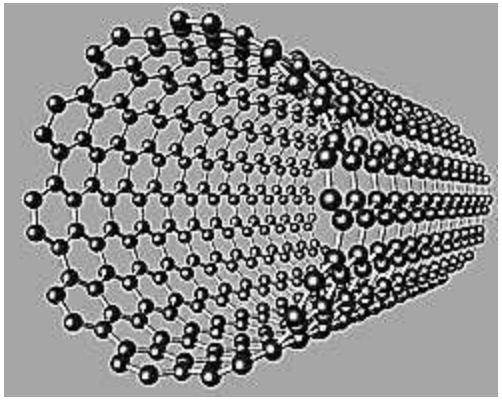
- *Magnetostrictive materials, Magnetorheological materials (exhibit change in shape under the application of magnetic field and also exhibit change in their magnetization under the influence of mechanical stress), Electrorheological materials, etc.*

4. *Smart coatings*

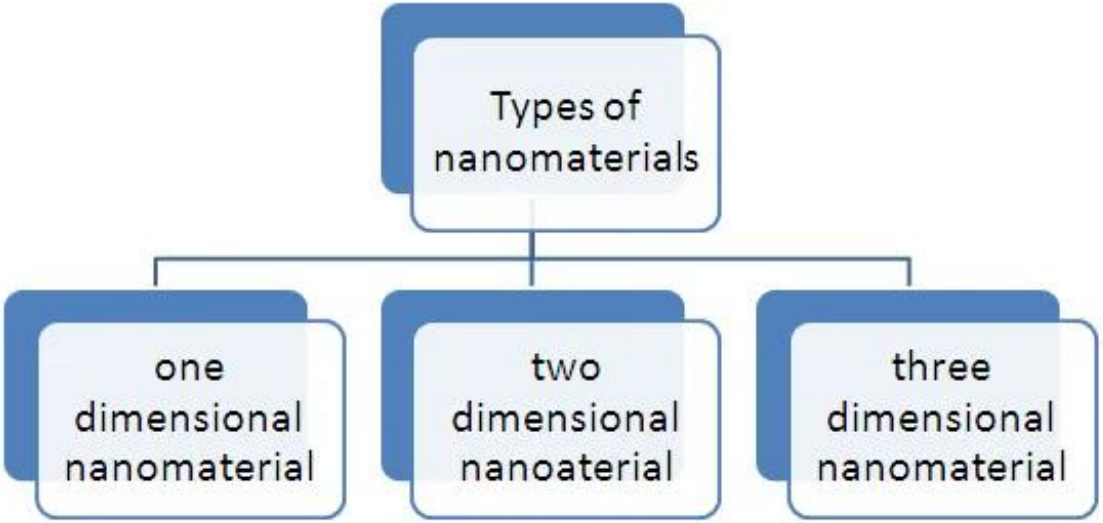
- *Smart corrosion protective coatings (e.g. self-healing paint, self-cooling paint, anti-microbial paint, etc.): not only provide corrosive protection but also have the ability to sense changes in the environment and its condition; then generate an appropriate response.*

Nanomaterials and Nanotechnology

- Nanoelectronics, Nanotechnology, Nanoconductor, Nanocomputer, Nanobots, from are all technology based on nanoparticles which is a new functional material with length from 1 to 100 nm, where 1 nanometer is $1 \cdot 10^{-9}$ meter. In recent years, it has attracted worldwide attention in R&D of nanomaterials.
- Nanotechnology is the engineering of functional systems at the molecular scale.
- Nanotechnology refers to the projected ability to construct items from the bottom up, to make complete, high performance products.



A "nano-tube", 1nm in diameter

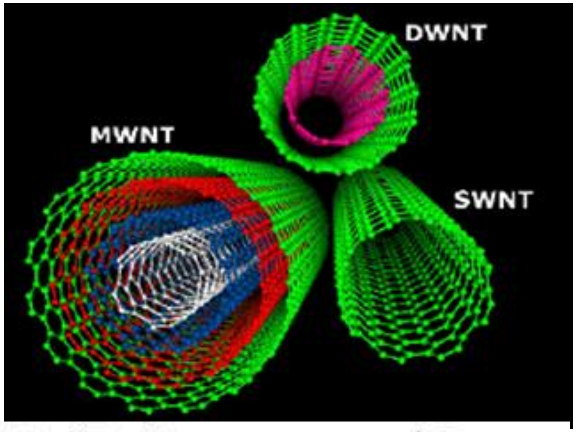


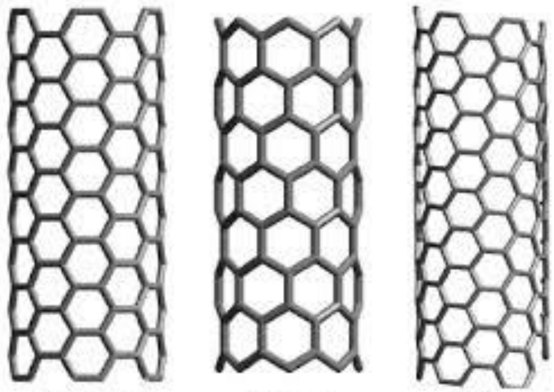
- 1-D nanomaterials: surface coatings and thin films.
- 2-D nanomaterials: biopolymers, nanotubes, and nanowires.
- 3-D nanomaterials are fullerenes.

Nanomaterials - Carbon nanotubes (CNTs)

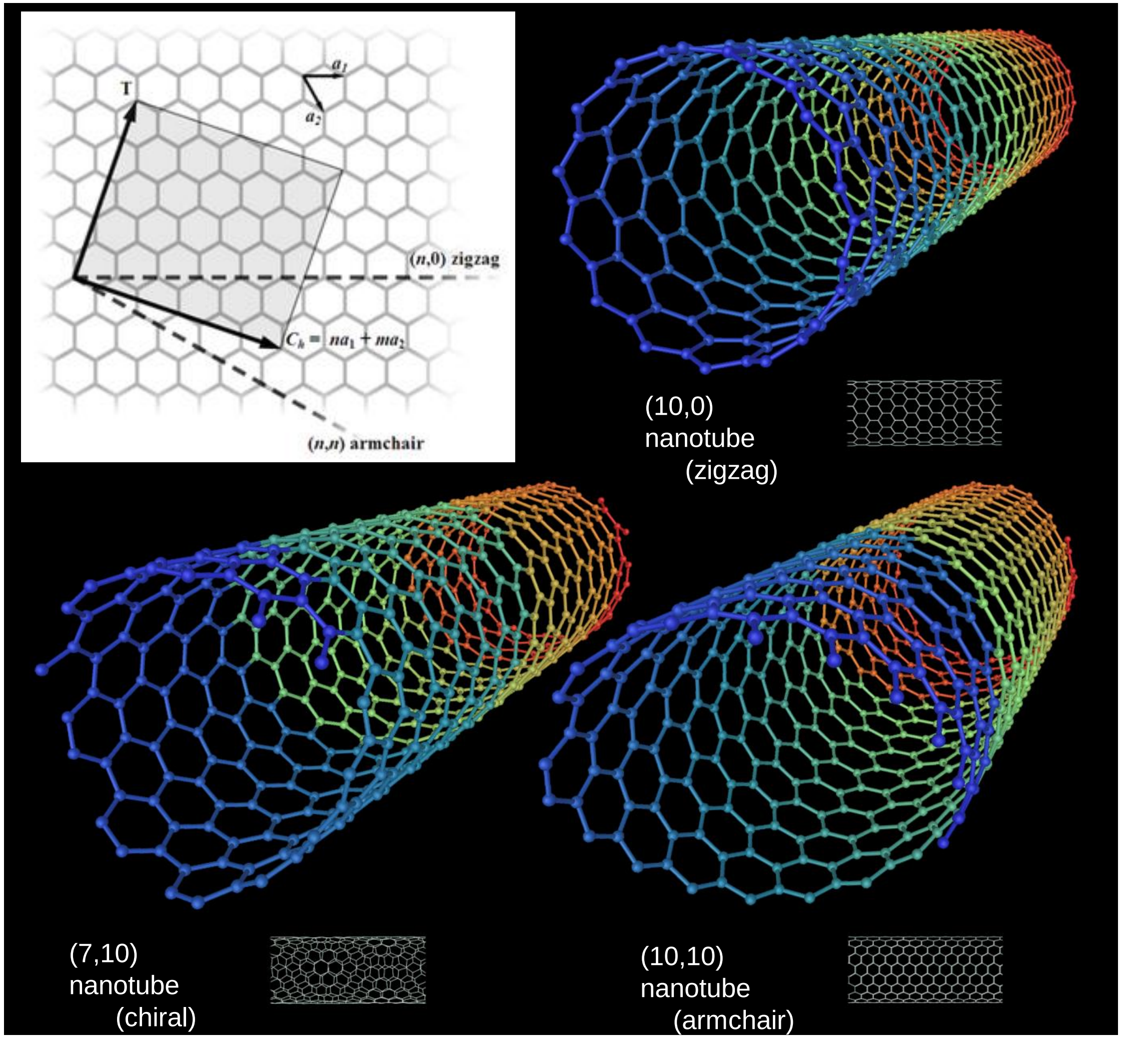
The graphene sheet can be rolled in different ways to get three types of nanotubes:

1. Zigzag
2. Armchair
3. Chiral



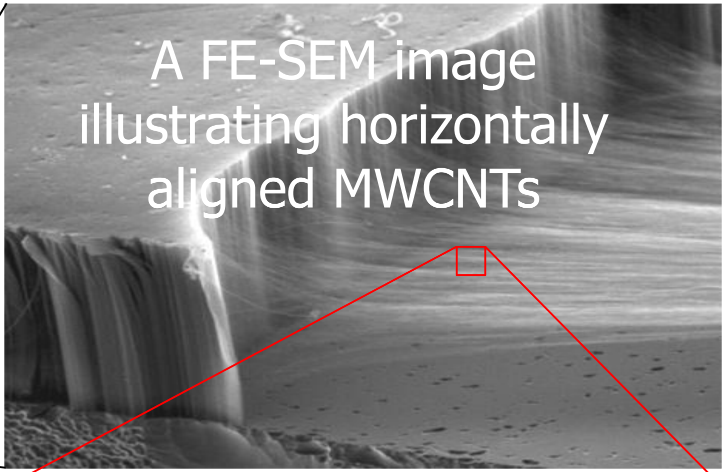


Structure of carbon nanotubes

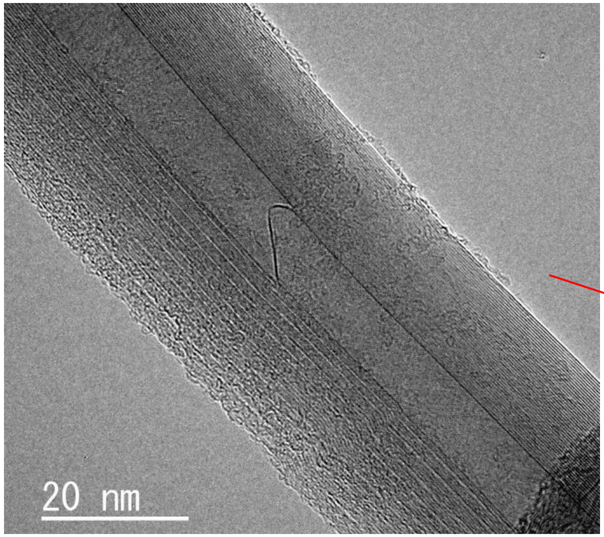


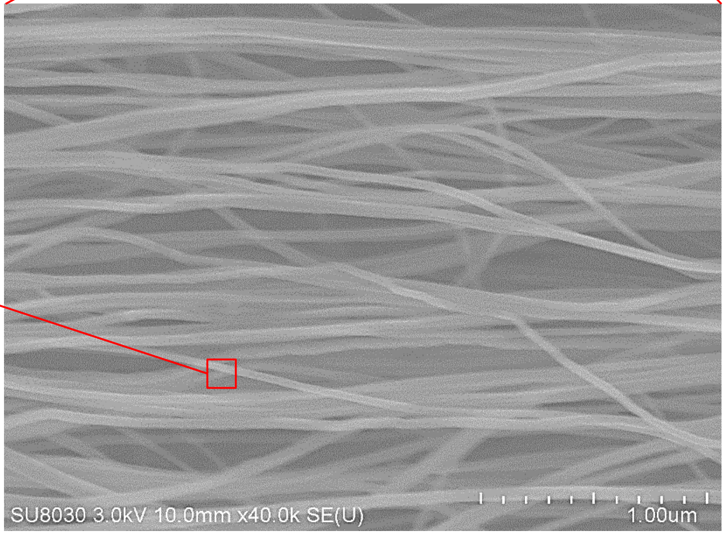
1.2. Advanced Materials

Nanomaterials - Carbon nanotubes (CNTs)



Tran Huu Nam, Ken Goto, et al. "Improved mechanical properties of aligned multi-walled carbon nanotube/ thermoplastic polyimide composites by hot stretching." Journal of Composite Materials 53.9 (2019): 1241-1253.





Tran Huu Nam, Ken Goto, et al. "Effects of high-temperature thermal annealing on properties of aligned multi-walled carbon nanotube sheets and their composites." *Composite Interfaces* 27.6 (2020): 569-586.

1.3. Composite Materials

- What is a composite?
- What are the advantages and drawbacks of composites over monolithic materials (such as aluminum or steel)?
- What factors influence mechanical properties of a composite material?
- How do we classify composites?
- What are the common types of fibers and matrices?
- How are composite materials manufactured?
- What are the mechanical properties of composite materials?
- Give applications of composite materials.
- How are composites recycled?
- What terminology is used for studying mechanics of composites?

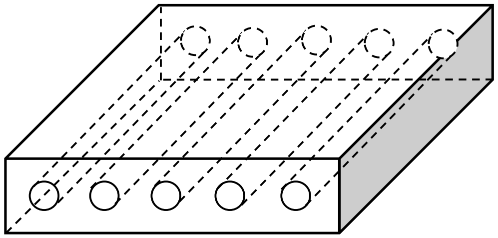
1.3. Composite Materials

What is a composite?

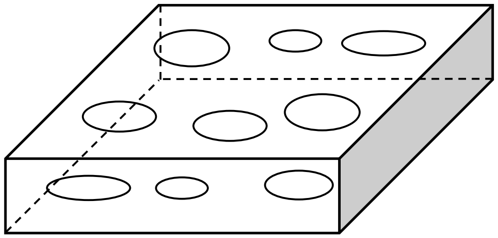
- A composite is a structural material that consists of two or more combined constituents that are combined at a macroscopic level and are not soluble in each other.
- The two constituents are a reinforcement and a matrix. The reinforcing phase that provides the strength and stiffness is usually formed of fibers, particles, whickers, or flakes. The continuous phase is the matrix, which is a polymer, metal, or ceramic.

Reinforcement + **Matrix** = **Composite**

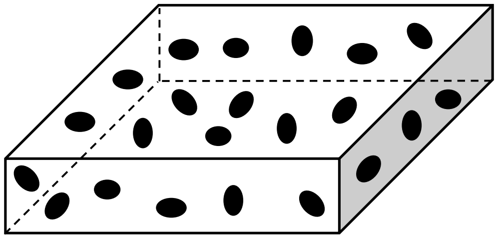
- For example, concrete composite, graphite/epoxy composites.



Fiber composites



Flake composites



Particulate composites

What is an advanced composite material?

- Definition: Advanced Composite Materials are high-structural-strength materials created by combining one or more stiff, high-strength reinforcing fibers with a compatible resin system.
- Advanced composite materials are generally characterized or determined by unusually high strength fibers with unusually high stiffness, or modulus of elasticity characteristics, compared to other composite materials such as reinforced concrete, or even concrete itself.
- Advanced composites exhibit desirable physical and chemical properties that include light weight coupled with high stiffness and strength along the direction of the reinforcing fiber, dimensional stability, temperature and chemical resistance, flex performance, and relatively easy processing.
- Advanced composite materials are refereed to those composite materials developed and used in the aerospace industries. They usually consist of high performance fibers with polymers, metals, or ceramics.

Advantages and disadvantages of composites

- The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part.

- Advantages:
  - Specific strength and stiffness
  - Tailored design
  - Fatigue life
  - Dimensional stability
  - Corrosion resistance
  - Light weight

- Disadvantages:
  - High cost of fabrication
  - Complex mechanical characterization
  - Complicated repair of composite structures
  - High combination of all required properties may not be available

Phases of Composites

- **Reinforcing phase**: fibers, particles, whiskers, or flakes

  Also, dispersed phase, discontinuous phase (metal, ceramic, or polymer).

  Role of reinforcements: Reinforcements give high strength, stiffness and other improved mechanical properties to the composites. Also their contribution to other properties such as the coefficient of thermal expansion, conductivity, etc. is remarkable.

- **Matrix phase**: polymers, metals, or ceramics

  Also, continuous phase, surrounds other phase (metal, ceramic, or polymer)

  Role of matrices: Matrices give shape to the composite part, keep the fibers in place, transfer stresses to the fibers, protect the reinforcement from the environment, such as chemicals & moisture, protect the surface of the fibers from mechanical degradation, act as shielding from damage due to handling, etc.

→ **Interface** between matrix and reinforcement

What are the types of reinforcements?

- **Fiber**: Fiber is an individual filament of the material. The fibers can be in the following two forms: (1) continuous fibers (length to diameter ratio is between 200 and 500) and (2) short/chopped fibers (length to diameter ratio is between 20 and 60). Fibers are generally anisotropic and examples include glass, graphite, carbon and aramids.
- **Particulate:** The reinforcement is in the form of particles which are of the order of a few microns in diameter. Typical examples: Al or Fe particles in rubber; SiC particles in aluminum; and gravel, sand, and cement to make concrete. The composite with reinforcement in particle form is called a particulate composite.
- **Flake**: Flake is a small, flat, thin piece or layer (or a chip) that is broken from a larger piece. Typical flakes: glass, mica, aluminum, and silver.
- **Whiskers**: These are nearly perfect single crystal fibers. These are short, discontinuous, and polygonal in cross-section.

What are the types of matrices?

- **Polymer Matrix**
  - Thermosets
    - Polyester, vinylester
    - Epoxy
    - Polyimide
  - Thermoplastics
    - Polypropylene
    - Polyvinyl chloride
    - Nylon
- **Metal Matrix**
  - Aluminum
  - Titanium
  - Copper
- **Ceramic Matrix**
  - Carbon
  - Silicon Carbide
  - Calcium Alumino Silicate
  - Lithium Alumino Silicate

Important note

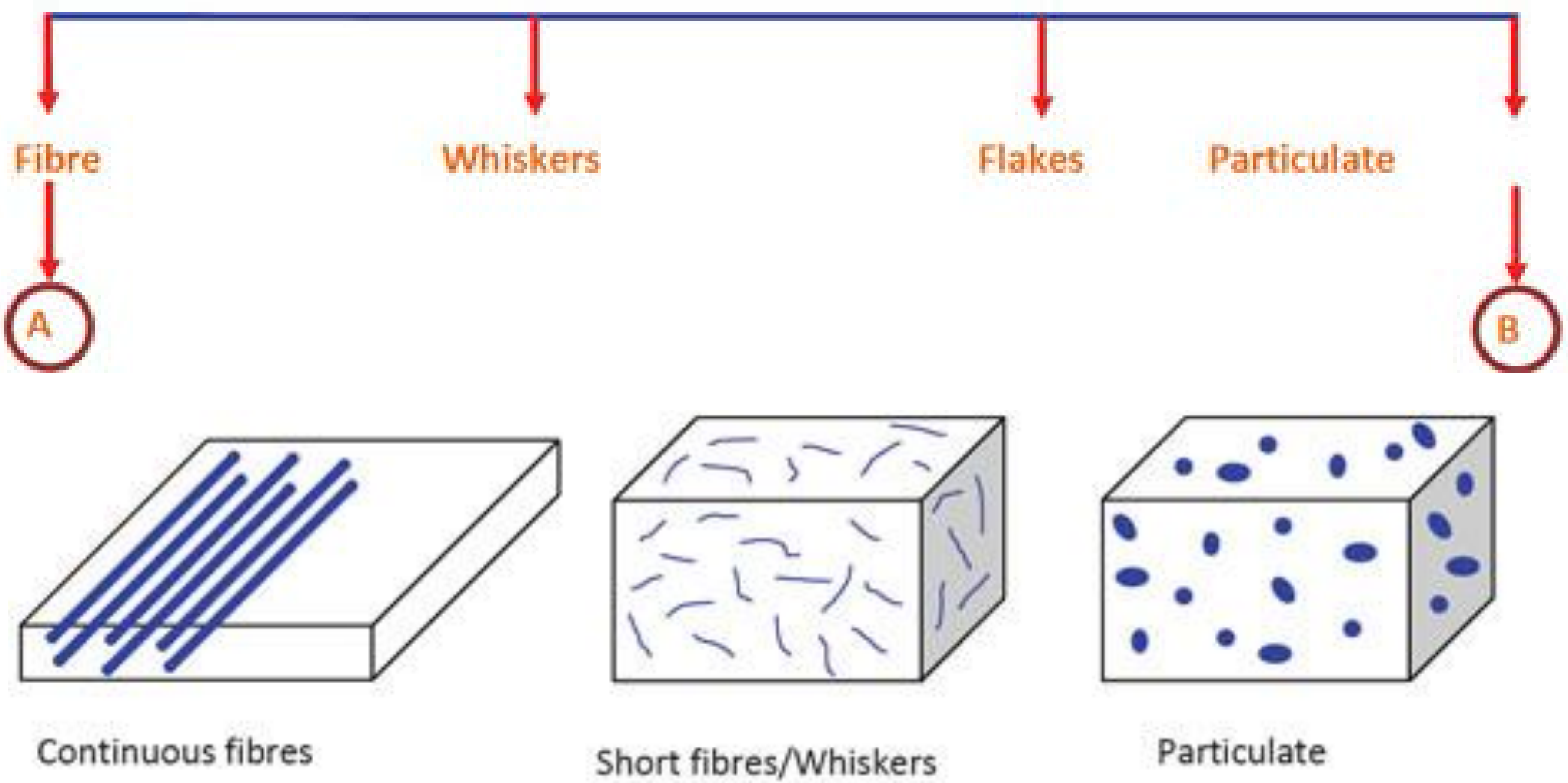
Composite properties are less than those of the fiber because of dilution by the matrix and the need to orient fibers in different directions.

1.3. Composite Materials: Classification

- Composites are classified by the geometry of reinforcement – particulate, flake, whiskers, and fibers – or by the type of matrix – polymer, metal, and ceramic.
- The **first level** of classification is usually made with respect to the matrix constituent. The major composite classes include Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term OCM is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and Carbon Matrix Composites commonly referred to as carbon-carbon composites.
- The **second level** of classification refers to the reinforcement form - fiber reinforced composites, particulate composites, flake composites, and laminar composites. Fiber reinforced composites (FRP) and natural fiber composites (NFCs) can be further divided into those containing discontinuous or continuous fibers. Composites that incorporate nanosized particles into a matrix of standard material are called nanocomposites.

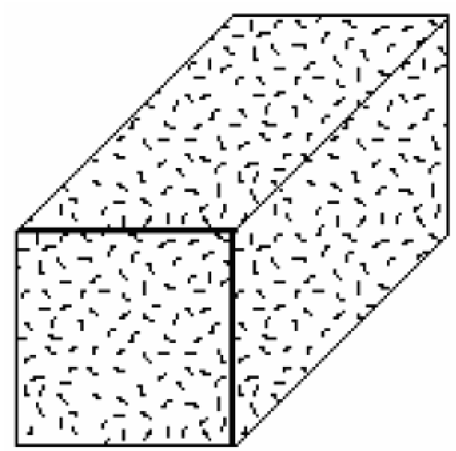
1.3. Composite Materials: Classification

Classification of composites based on reinforcement type

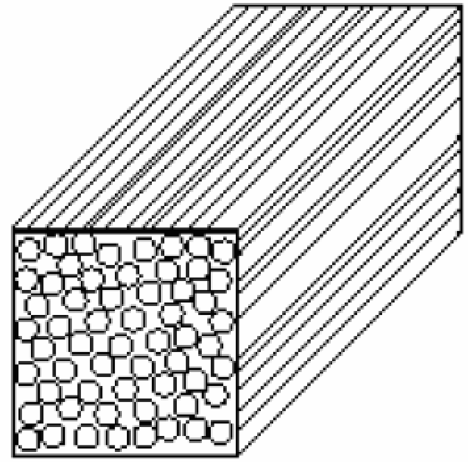


Fiber reinforced composites

- **Fiber reinforced composites** are composed of fibers embedded in matrix material. There are continuous fiber-reinforced composites, discontinuous fiber or short fiber composites.
- **Fibers** are small in diameter and when pushed axially, they bend easily although they have very good tensile properties. These fibers must be supported to keep individual fibers from bending and buckling.



Discontinuous fiber (short fiber) reinforced composites

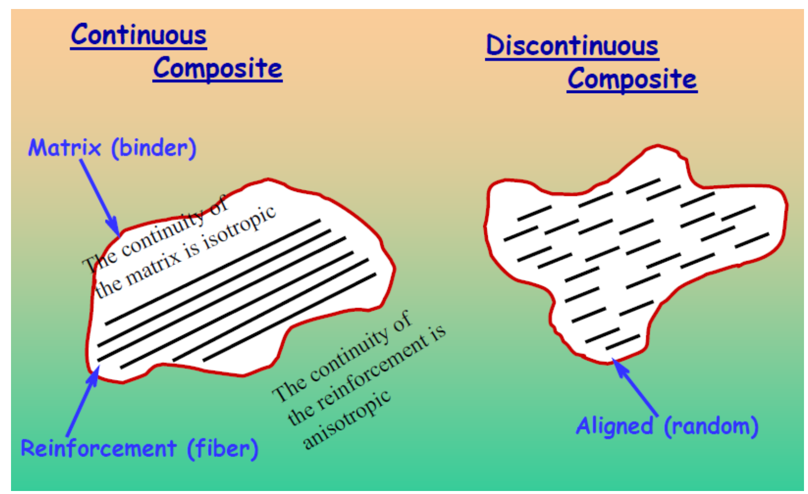


Continuous fiber (long fiber) reinforced composites

1.3. Composite Materials: Classification

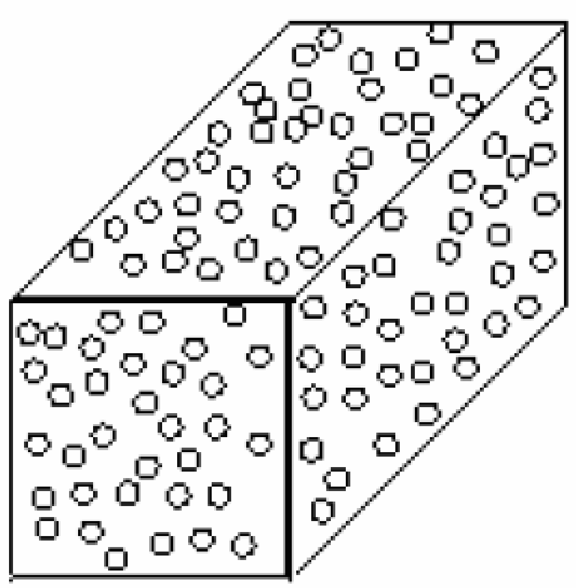
Classification of fiber reinforced composites

- Continuous fiber
  - Unidirectional
  - Woven
    - Bidirectional
    - 3 Dimensional
  - Single layer
  - Multilayer
    - Laminates
    - Hybrids
- Discontinuous fiber
  - Random orientation
  - Preferred orientation



Particulate Composites

- **Particulate Composites** are composed of particles distributed or embedded in a matrix body. The particles may be in powder form. Concrete and wood particle boards are examples of this category.
- **Particles** usually reinforce a composite equally in all directions (called isotropic). Plastics, ceramics and metals are examples of particles.
- **Particles** used to strengthen a matrix do not do so in the same way as fibers. For one thing, particles are not directional like fibers. Spread at random through out a matrix, particles tend to reinforce in all directions equally.

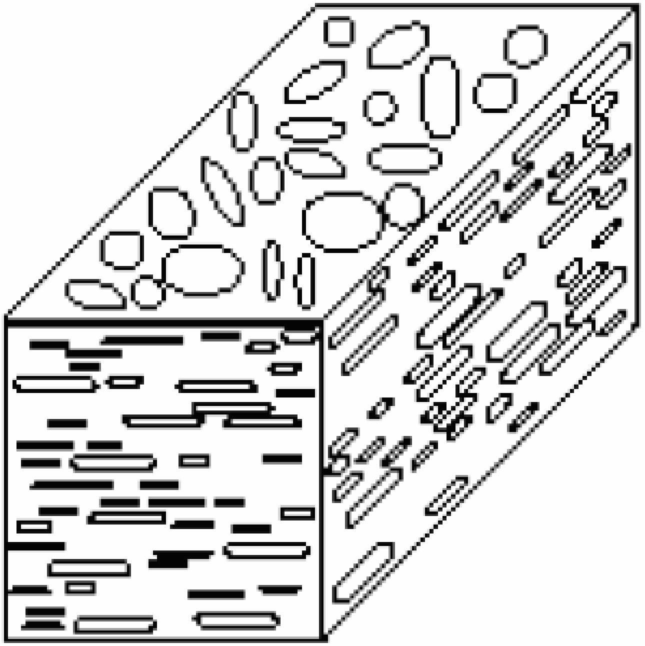


Flake Composites

- **A flake composite** consists of thin, flat flakes held together by a binder or placed in a matrix. Almost all flake composite matrices are plastic resins. The most important flake materials are: aluminum, mica, or glass.

Basically, *flakes* will provide:

- Uniform mechanical properties in the plane of the flakes
- Higher strength
- Higher flexural modulus
- Higher dielectric strength and heat resistance
- Better resistance to penetration by liquids and vapor
- Lower cost



Laminar Composites

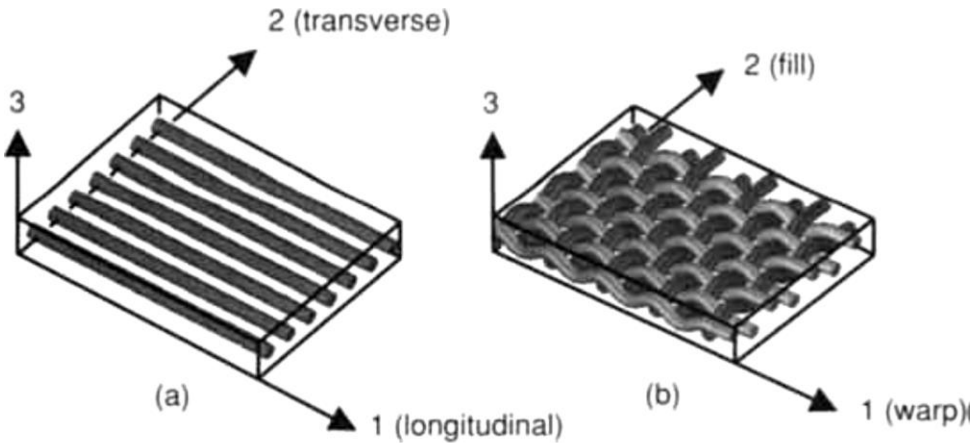
- **Laminar Composites** are composed of layers of materials held together by matrix. Sandwich structures fall under this category.
- **Laminar composites** involve two or more layers of the same or different materials. The layers can be arranged in different directions to give strength where needed. Speedboat hulls are among the many products of this kind.
- Like all composites, **laminar composites** aim at combining constituents to produce properties that neither constituent alone would have.
- In **laminar composites** outer metal is not called a matrix but a **face**. The inner metal, even if stronger, is not called a reinforcement. It is called a **base**.

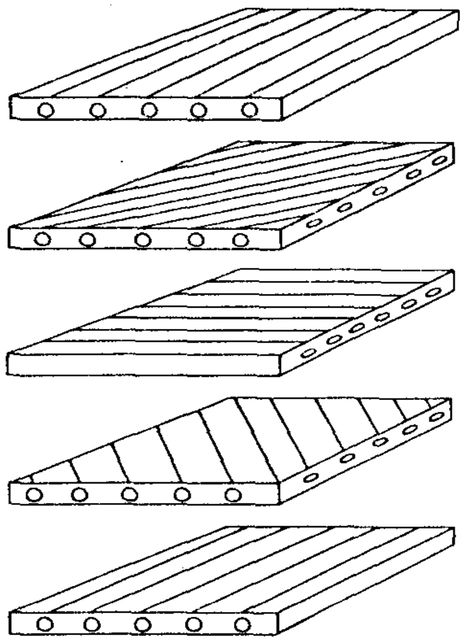
1.3. Composite Materials: Classification

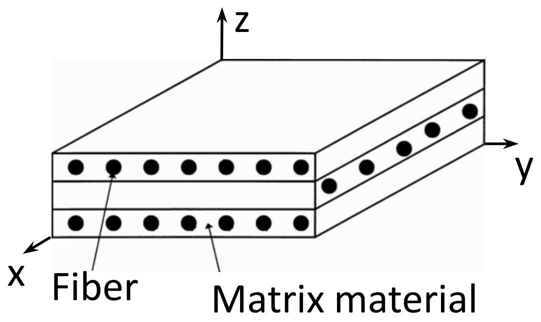
Laminar Composites

- A **lamina** (layer) is any arrangement of unidirectional or woven fibers in a matrix. Usually this arrangement is flat, although it may be curved, as in a shell.

- A **laminate** is a stack of laminae arranged with their main reinforcement in at least two different directions.







1.3.1. Polymer Matrix Composites (PMCs)

- The most common advanced composites are PMCs consisting of a polymer (e.g., epoxy, polyester, urethane, nylon) reinforced by thin diameter fibers (e.g., glass, graphite, aramid (e.g. Kevlar), boron, carbon). For example, graphite/epoxy, Kevlar/epoxy, and boron/epoxy 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.
- Two main kinds of polymer matrices are thermosets (epoxy, silicone, polyurethane, phenolic, etc.) and thermoplastics (polypropylene, polyethylene, polyvinylchloride, polystyrene, polycarbonate, etc.). Thermosets have qualities such as a well-bonded three-dimensional molecular structure after curing. Thermoplastics have one- or two-dimensional molecular structure and they tend to at an elevated temperature and show exaggerated melting point.

1.3.1. Polymer Matrix Composites (PMCs)

Advantages of PMCs

- Reinforcement of polymers by strong fibrous network permits fabrication of PMC characterized by the following properties:
  - High tensile strength;
  - High stiffness;
  - High Fracture Toughness;
  - Good abrasion resistance;
  - Good puncture resistance;
  - Good corrosion resistance;
  - Low cost.

Disadvantages of PMCs

- Low thermal resistance;
- High coefficient of thermal expansion ;
- Low elastic properties in certain directions.

1.3.1. Polymer Matrix Composites (PMCs)

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

(A.K. Kaw. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 2006)

Property	Units	Uni. Graphite /Epoxy	Uni. Glass /Epoxy	Steel	Aluminum
Specific gravity	--	1.6	1.8	7.8	2.6
Young's modulus	Gpa	181.0	38.6	206.8	68.95
Ultimate strength	Mpa	1500	1062	648.1	275.8
Coefficient of thermal expansion	μm/m/^{o}C	0.02	8.6	11.7	23

- ✓ Specific gravity of a material is the ratio between its density and the density of water.

1.3.1. Polymer Matrix Composites (PMCs)

Various fibers used in PMCs

The most common fibers used are carbon, glass, graphite, aramid (e.g. Kevlar), and boron. Typical properties of these fibers compared with bulk steel and aluminum.

Property	Units	Graphite	Aramid	Glass	Steel	Aluminum
Specific Gravity	___	1.8	1.4	2.5	7.8	2.6
Young's modulus (axial)	GPa	230	124	85	206.8	68.95
Transverse modulus	GPa	22	8	85	206.8	68.95
Axial Tensile Strength	MPa	2067	1379	1550	648.1	275.8
Axial Compressive Strength	MPa	1999	276	1550		
Axial Coefficient of Thermal Expansion	μm/m /°C	-1.3	-5	5	11.7	23

(A.K. Kaw. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 2006)

Glass fiber is isotropic, while aramid and graphite are transversely isotropic.

Glass fiber types

- E-glass (fiberglass) - electrical applications
- S-glass - strength applications
- C-glass - Corrosion resistant
- D-glass - Low dielectric applications
- A-glass - Appearance applications
- AR-glass - Alkali resistant

Comparison of properties of E-glass and S-glass

Property	Units	E-glass	S-glass
Specific Gravity	―	2.54	2.49
Young's modulus	GPa	72.4	85.5
Ultimate Tensile Strength	MPa	3447	4585
Coefficient of Thermal Expansion	μm/m/°C	5.04	5.58

(A.K. Kaw. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 2006)

1.3.1. Polymer Matrix Composites (PMCs)

Various polymers used in PMCs

- These polymers include polyesters, phenolics, epoxies, polyamide, and others.
- Each polymer has its advantages and drawbacks:
  - 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, chemical and dimensional stability, low contractility, etc. The inherent disadvantages of epoxy resin are its poor impact damage resistance, brittle toughness, and low heat resistance (less than 170°C).

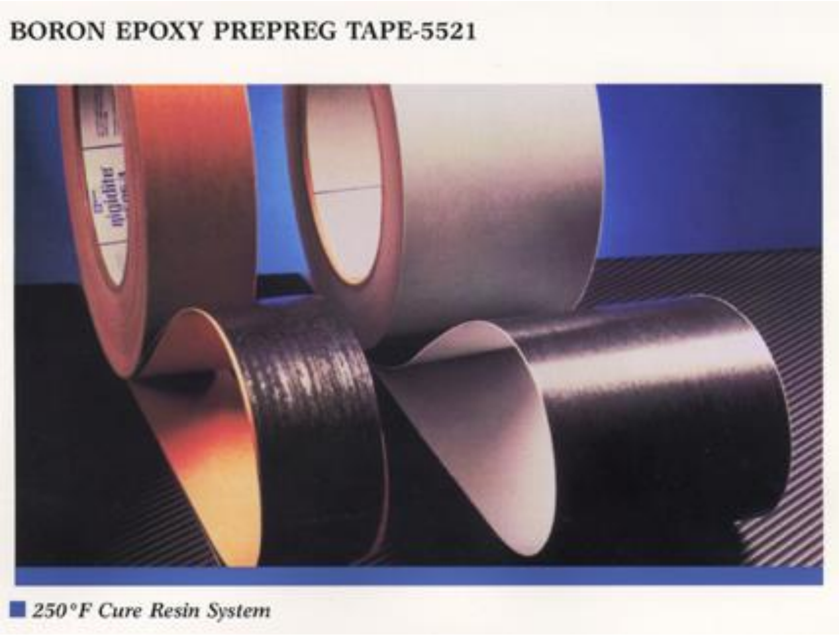
1.3.1. Polymer Matrix Composites (PMCs)

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

- Although epoxy is costlier than several 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

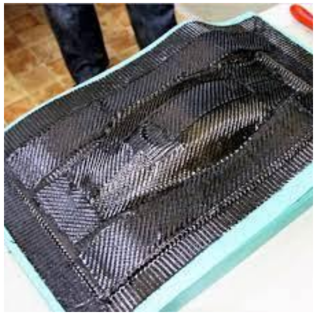
What are prepregs?

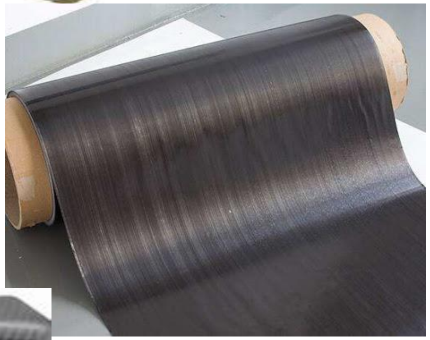
- Prepregs are a ready-made tape composed of fibers in a polymer matrix (see Figure). They are available in standard widths from 3 to 50 in. (76 to 1270 mm).



(A.K. Kaw. Mechanics of Composite Materials. 2nd edition, Taylor & Francis, 2006)

Carbon fiber/epoxy prepreg





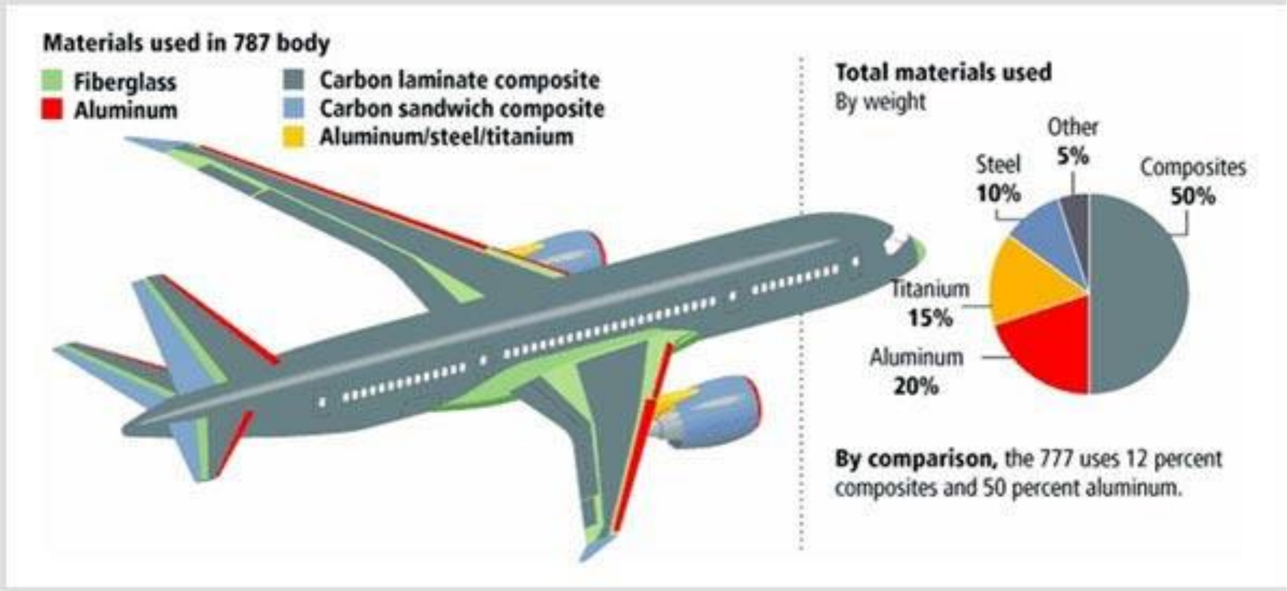
PMCs processing

- Forming processes for thermosetting matrix composites:
  - Pultrusion
  - Resin transfer molding
  - Hand layup and spray up techniques
  - Filament winding
  - Autoclave molding
- Forming processes for thermoplastic matrix composites:
  - Injection molding
  - Diaphragm forming
  - Film stacking
  - Thermoplastic tape laying

Application of Polymer Matrix Composites

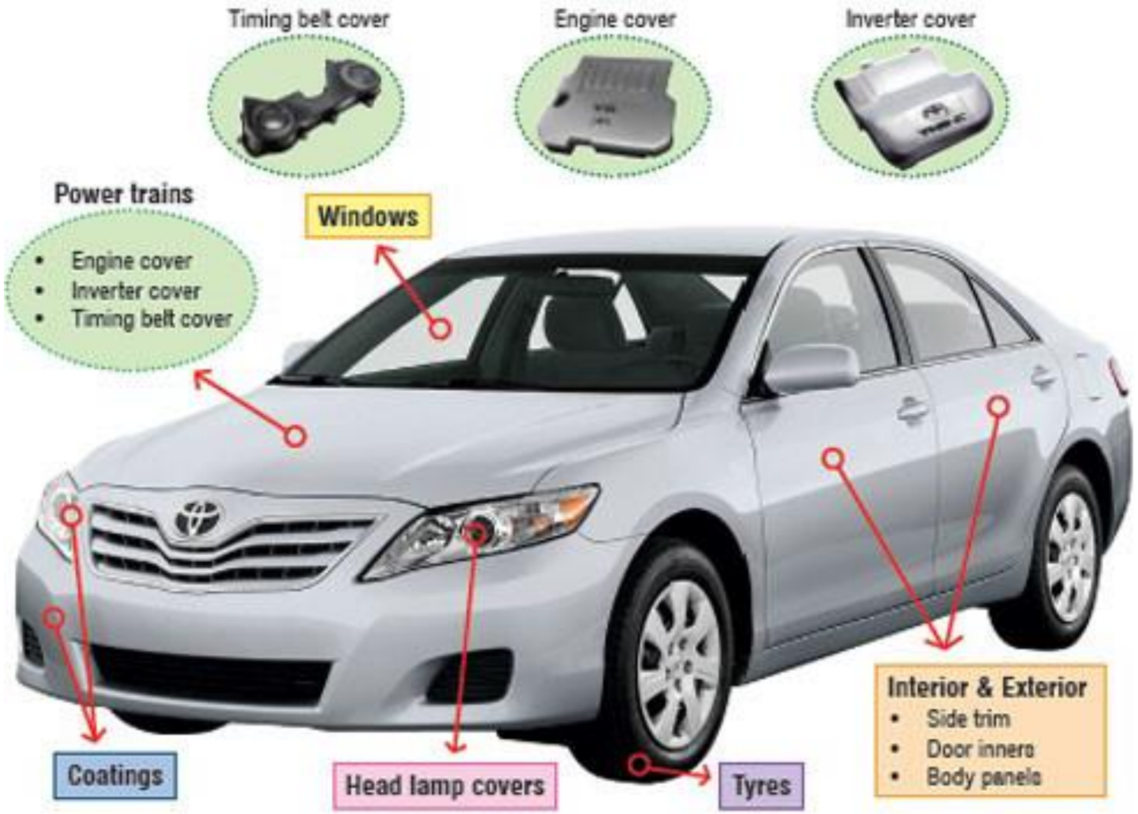
- Aerospace Industry

- The aerospace industry is estimated to consume about 50 percent of advanced composites production in the United States.
- The primary matrix materials used in aerospace applications are epoxies, and the most common reinforcements are carbon, graphite, aramid (e.g. kevlar), and high-stiffness glass fibers.
- Compared with metals, the principal advantages of advanced composites in aerospace are their superior specific strength and stiffness, resulting in weight savings of 10 to 60% over metal designs.



Application of Polymer Matrix Composites

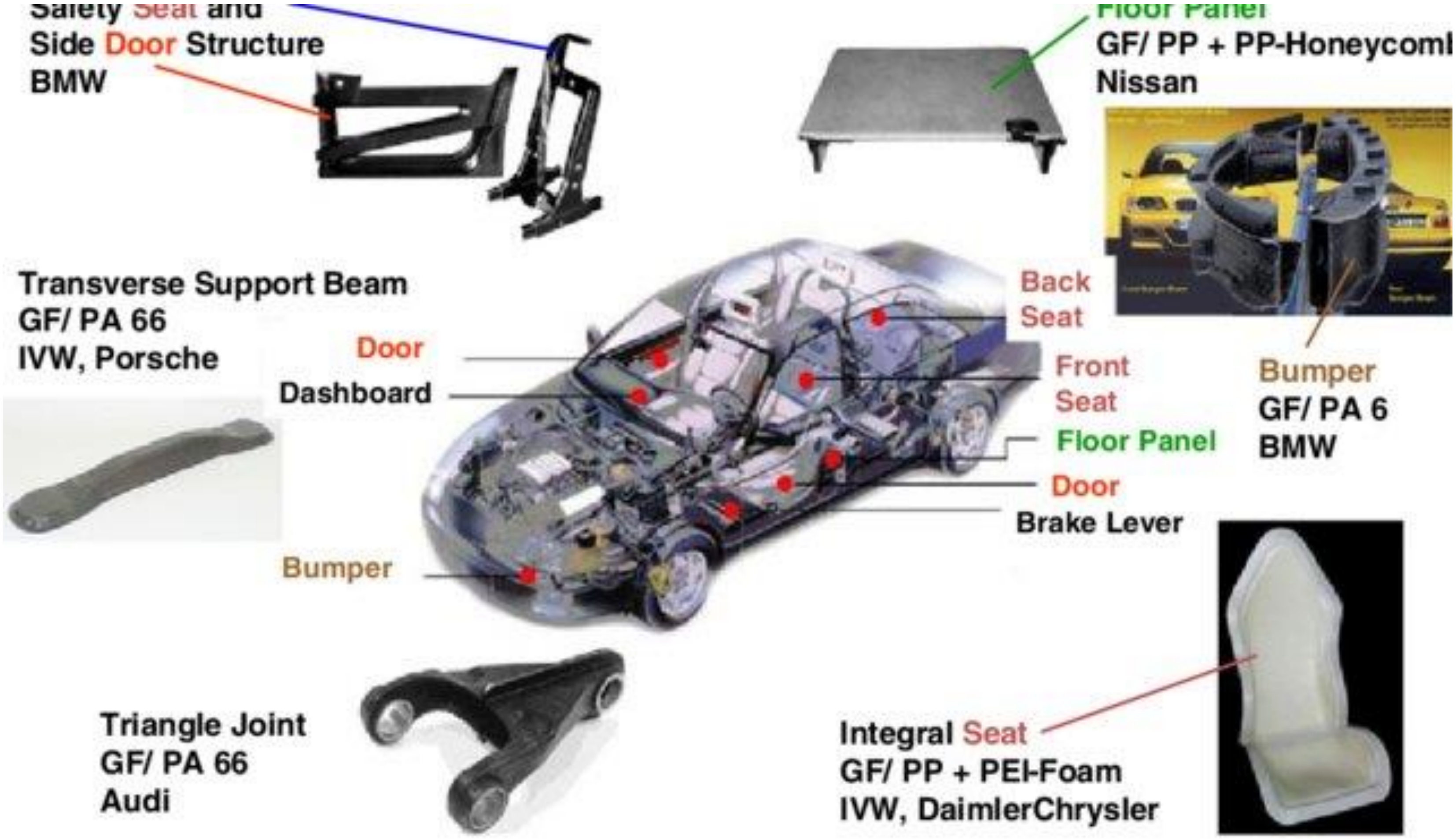
- Automotive Industry
  - The principal motivation for introducing PMCs is cost savings because the industry is mature and highly competitive.
  - Because of greatly improved corrosion resistance PMC automobiles could last 20 or more years compared to the current average vehicle lifetime.



Application of Polymer Matrix Composites

- Automobile structures

Friedrich, K., & Almajid, A. A. (2013). Manufacturing aspects of advanced polymer composites for automotive applications. Appl. Compos. Mater., 20(2), 107-128.

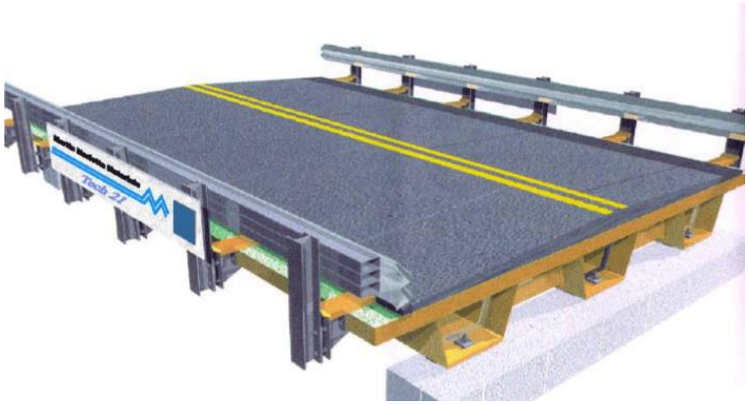


1.3.1. Polymer Matrix Composites (PMCs)

Application of Polymer Matrix Composites

➢ Construction

A potentially high-volume market for PMCs lies in construction applications especially in Buildings, Bridges, Housing, Cables Lampposts, Smokestacks, Highway culverts, etc.

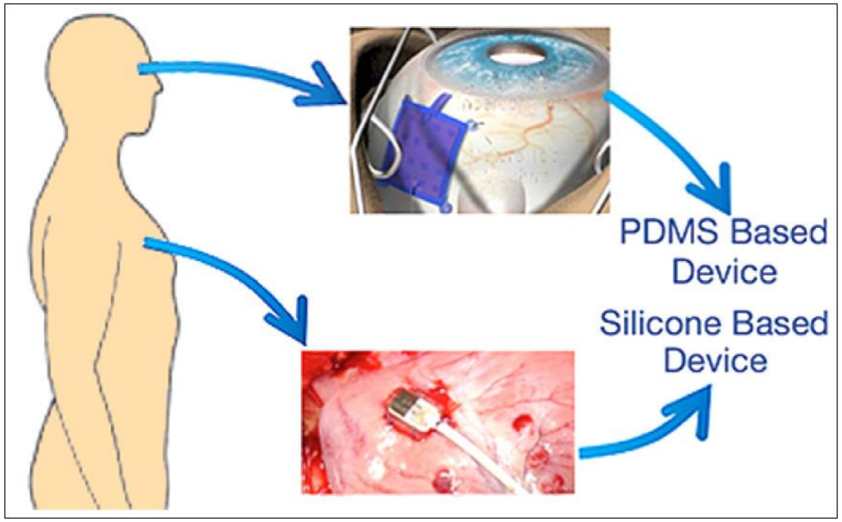


The smith road bridge all-composites bridge, Ohio, USA

1.3.1. Polymer Matrix Composites (PMCs)

Application of Polymer Matrix Composites

- Other applications
  - Medical devices
  - Ships, boats
  - Bikes
  - etc.

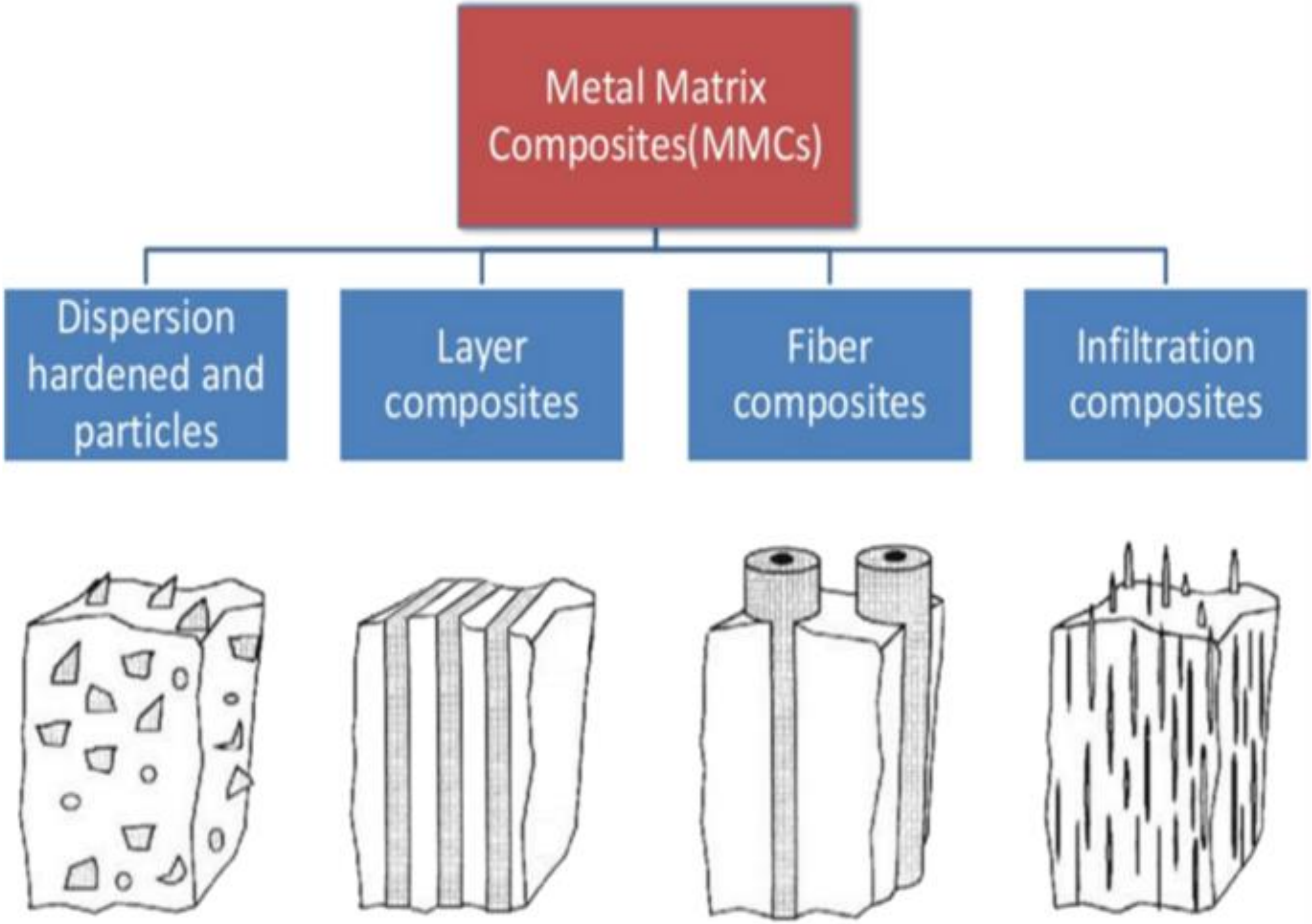


Here is an example of a composite in this frame (courtesy TREK) of the bike made of CFRP – carbon fiber reinforced composites.

1.3.2. Metal Matrix Composites (MMCs)

What are metal matrix composites?

- Metal matrix composites (MMCs) have a metal matrix.
- Examples of matrices in such composites include aluminum, magnesium, and titanium. Typical fibers include carbon and silicon carbide.



1.3.2. Metal Matrix Composites (MMCs)

Advantages of MMCs

- Low coefficient for thermal expansion
- Fire resistance, wear resistance.
- Higher transverse stiffness , strength & modulus
- No moisture absorption
- Higher electrical and thermal conductivities
- Better radiation resistance
- Some reinforcing fibers are inexpensive
- Casting is low cost and net shaped process

Disadvantages of MMCs

- Some fabrication processes are complex and expensive
- Higher cost
- Machining difficult
- Complex fabrication methods
- Reinforcing material may reduce ductility and fracture toughness
- Fiber-matrix interactions at high temperature degrade fibers

Typical mechanical properties of metal matrix composites

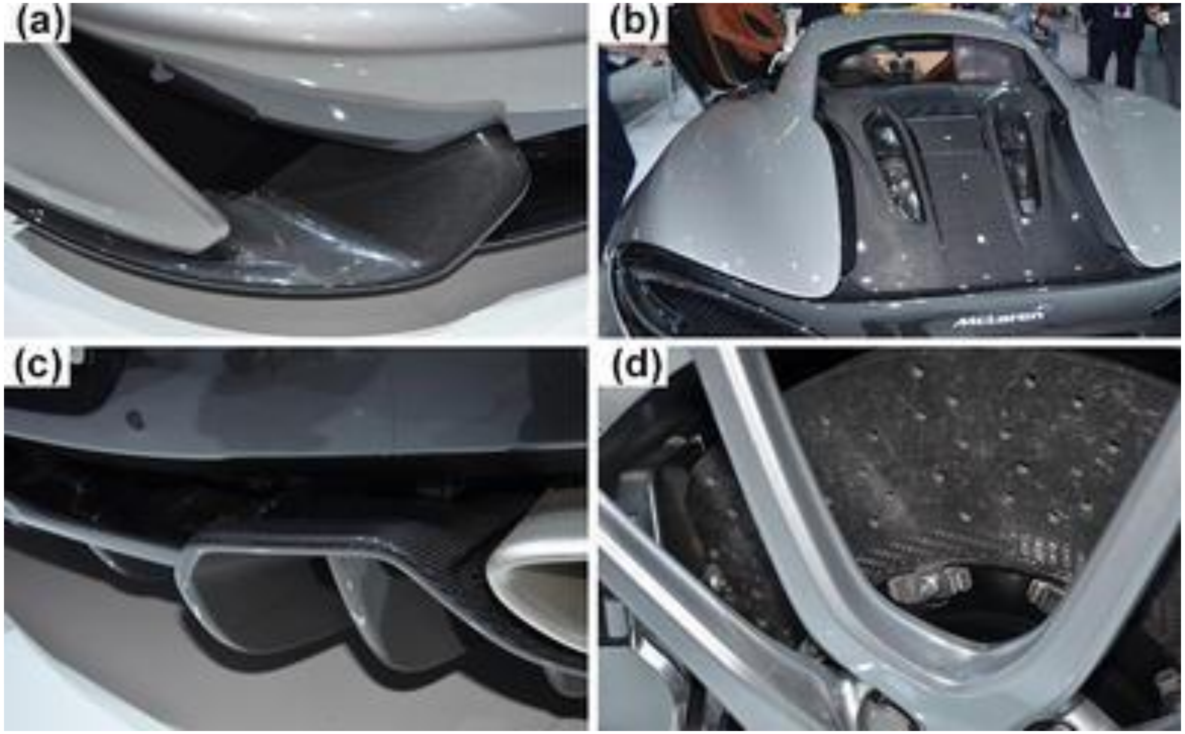
Property	Units	SiC/ Aluminum	Graphite/ Aluminum	Steel	Aluminum
Specific Gravity	———	2.6	2.2	7.8	2.6
Young's modulus	GPa	117.2	124.1	206.8	68.95
Ultimate Tensile Strength	MPa	1206	448.2	648.1	234.40
Coefficient of Thermal Expansion	μm/m/°C	12.4	18	11.7	23

1.3.2. Metal Matrix Composites (MMCs)

Applications of metal matrix composites

- Automobile
  - High temperature engine components
  - Brake drum and rotors
  - Bumpers and Fenders

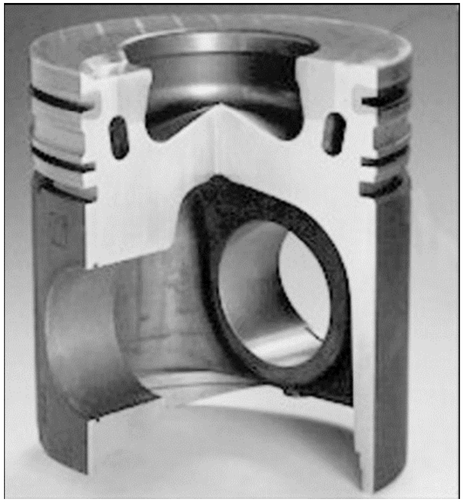
Carbon composite parts in McLaren 570S displayed at 2015 New York International Auto Show (a) front air splitter, (b) engine cover, (c) rear diffuser and (d) brake disk



Applications of metal matrix composites

- Automobile

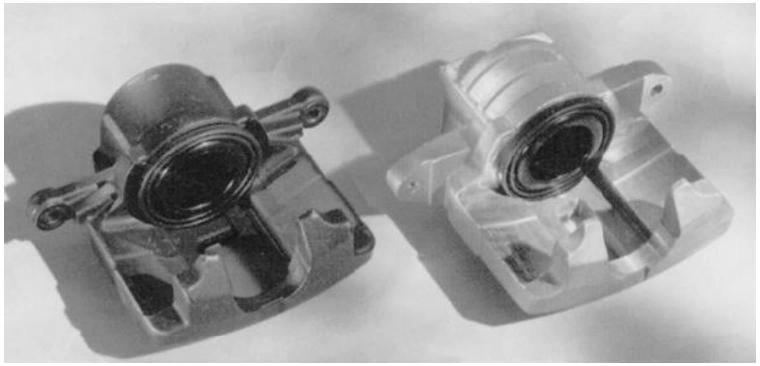
BRAKE ROTOR



DIESEL PISTON

CYLINDER HEAD

Honda has used aluminum metal matrix-reinforced ceramic composite cylinder liners in some of their engines, including the B21A1, H22A and H23A, F20C and F22C



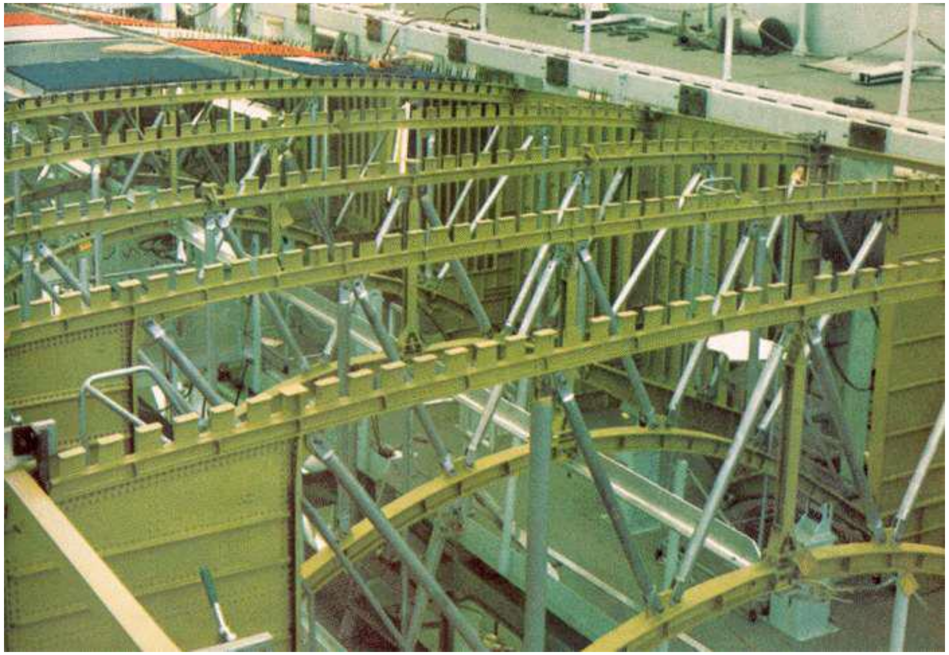
DISC BRAKE CALIPER

Applications of metal matrix composites

- Aerospace

The F-16 Fighting Falcon uses monofilament silicon carbide fibers in a titanium matrix for a structural component of the jet's landing gear.

12Mid-fuselage structure of space shuttle orbiter showing boron-aluminum composite tubes



1.3.3. Ceramic Matrix Composites (CMCs)

What are ceramic matrix composites?

- Ceramic matrix composites (CMCs) have a ceramic matrix such as calcium aluminosilicate (CAS) or lithium aluminosilicate (LAS) reinforced by fibers such as carbon or silicon carbide.
- Ceramic materials are in general brittle, and, according to the fracture mechanics, the strength is governed by the flaw size and the fracture toughness.
- General approaches for producing strong ceramics are to reduce the maximum size of processing flaws or to enhance the fracture toughness.
- Ceramic matrix composites may be classified into two categories: Toughened Ceramics Reinforced with Particulates/Whiskers and Continuous-fiber Composites

1.3.3. Ceramic Matrix Composites (CMCs)

Advantages of CMCs

- Excellent wear and corrosion resistance in a wide range of environments and temperature
- Higher strength to weight ratio
- Higher strength retention at elevated temperature
- Higher chemical stability
- Non-catastrophic failure, High hardness, Lightweight

Disadvantages of CMCs

- Processing routes for CMCs involve high temperatures
- CMCs are designed to improve toughness of monolithic ceramics, the main disadvantage of which is brittleness.
- High processing temperature results in complexity in manufacturing and hence expensive processing.
- Difference in the coefficients of thermal expansion between the matrix and the reinforcement lead to thermal stresses on cooling from the processing temperatures.

1.3.3. Ceramic Matrix Composites (CMCs)

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

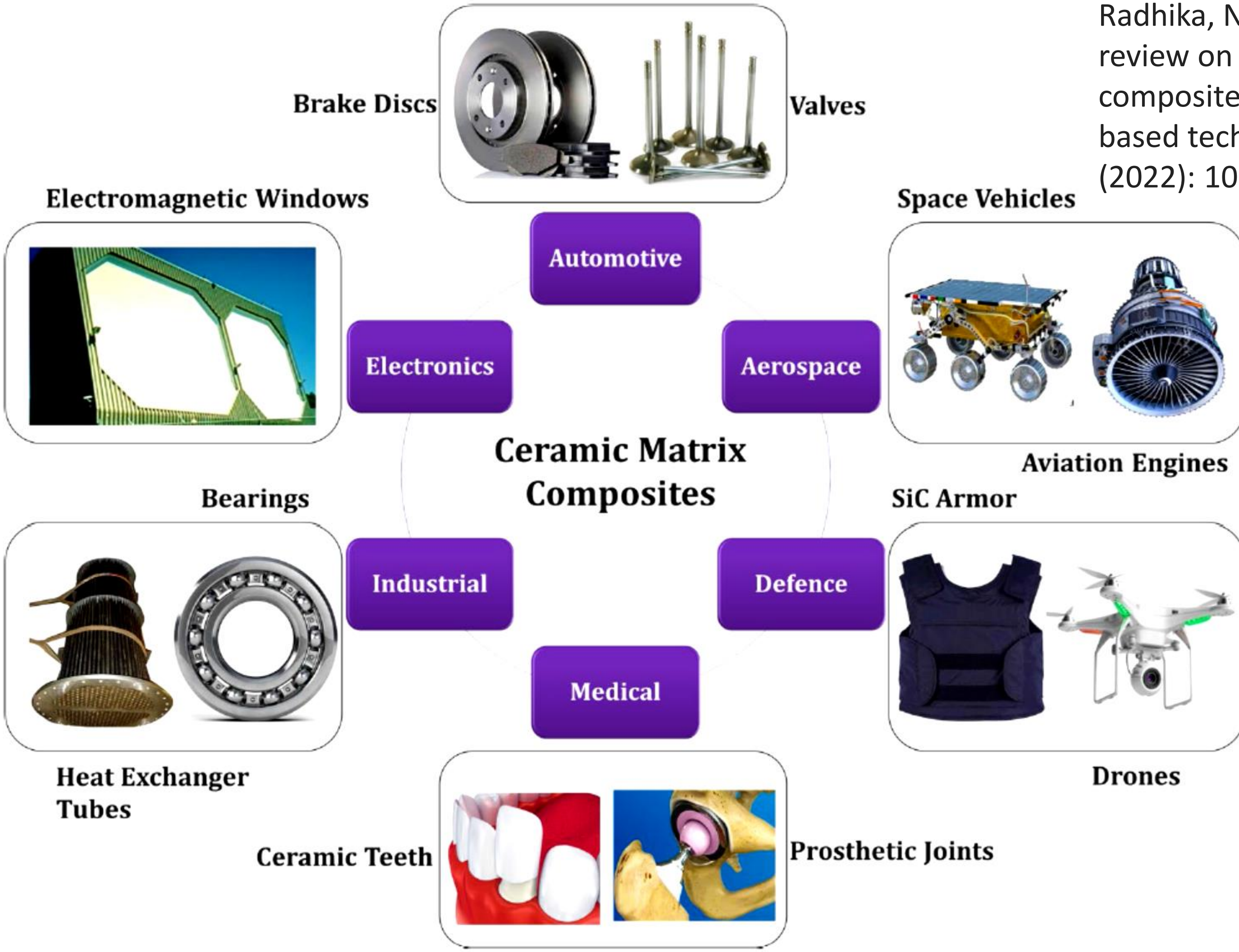
Typical mechanical properties of some ceramic matrix composites

Property	Units	SiC/LAS	SiC/CAS	Steel	Aluminum
Specific Gravity	———	2.1	2.5	7.8	2.6
Young's modulus	GPa	89.63	121	206.8	68.95
Ultimate Tensile Strength	MPa	496.4	400	648.1	234.4
Coefficient of Thermal Expansion	μm/m/°C	3.6	4.5	11.7	23

1.3.3. Ceramic Matrix Composites (CMCs)

Applications of ceramic matrix composites

Radhika, N., and M. Sathish. "A review on Si-based ceramic matrix composites and their infiltration based techniques." *Silicon* 14.16 (2022): 10141-10171.

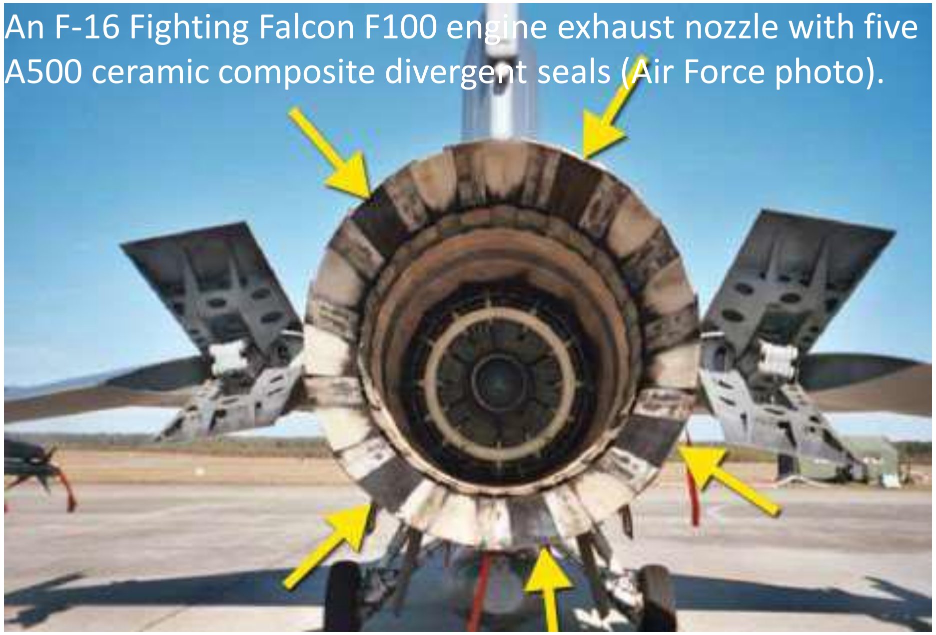


1.3.3. Ceramic Matrix Composites (CMCs)

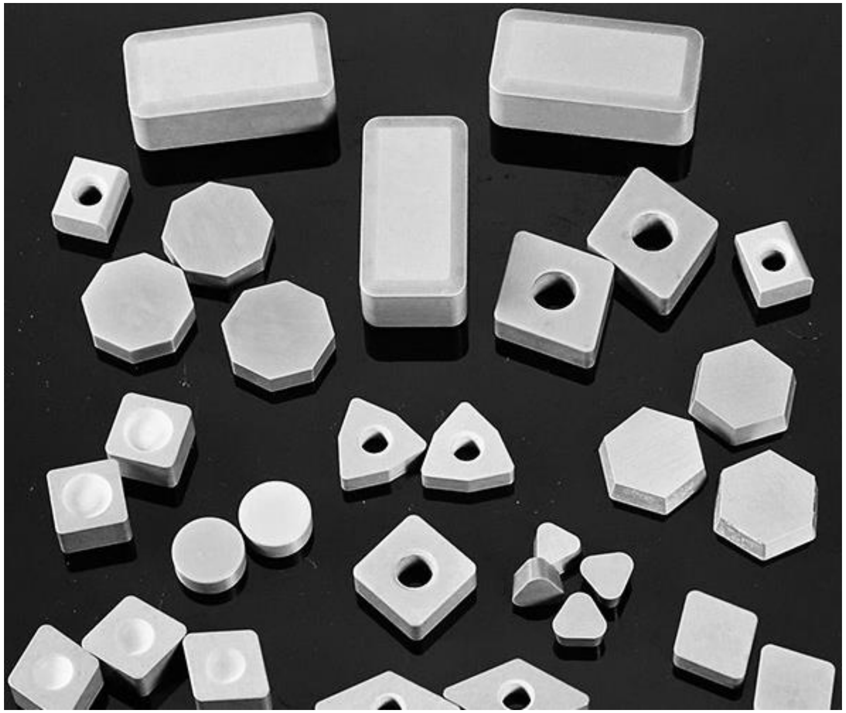
Applications of ceramic matrix composites

CMCs are finding increased application in high-temperature areas in which metal and polymer matrix composites cannot be used.

- Cutting tools
- Application in aerospace



An F-16 Fighting Falcon F100 engine exhaust nozzle with five A500 ceramic composite divergent seals (Air Force photo).



N. Kumar. A seminar presented on application and properties of ceramics matrix composite. Jadavpur University Kolkata, 2016.

1.3.3. Ceramic Matrix Composites (CMCs)

- Aerospace, space structures

LEAP Turbofan engine for the Boeing 737 MAX

Oxide CMC exhaust nozzle of a 1.60-m diameter and 1.14-m diameter × 2.34-m conical center body with titanium end cap inspection portal. Credit: Steyer; *IJACT*.

- Hot Fluid Channel

- A set of nozzle

- Turbine Blade

N. Kumar. A seminar presented on application and properties of ceramics matrix composite, 2016.

1.3.4. Carbon–Carbon Composites

What are Carbon–Carbon Composites?

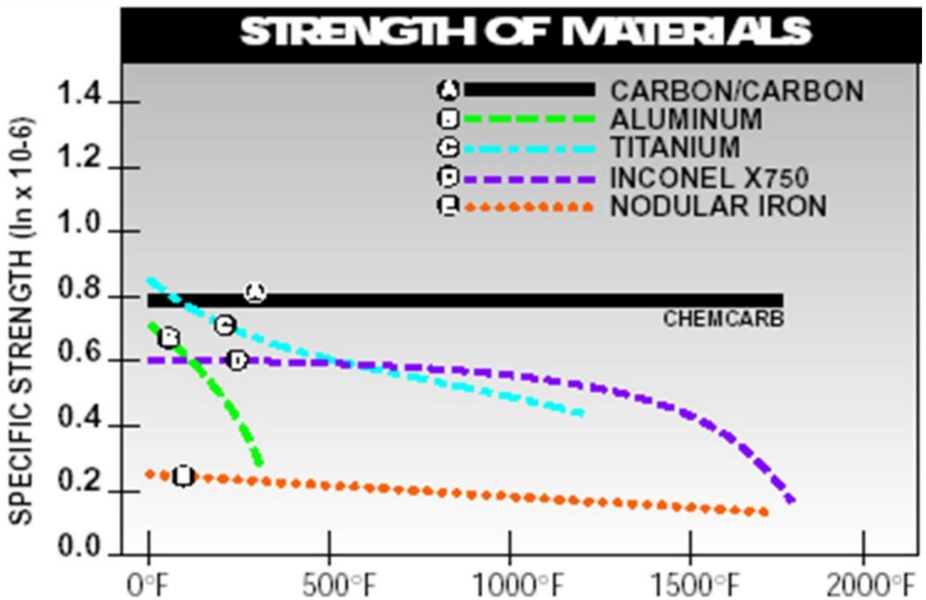
- Carbon–carbon composites (C-C composites) use carbon fibers in a carbon matrix. These composites are used in very high-temperature environments of up to 6000°F (3315°C).
- Carbon-Carbon Composites are the woven mesh of carbon-fibers.
- Carbon-carbon composites are used for their high strength and modulus of rigidity.
- Carbon-carbon composites are light weight material which are 20 times stronger and 30% lighter than graphite fibers.
- Carbon-carbon composites' structure can be tailored to meet requirements.

1.3.4. Carbon–Carbon Composites

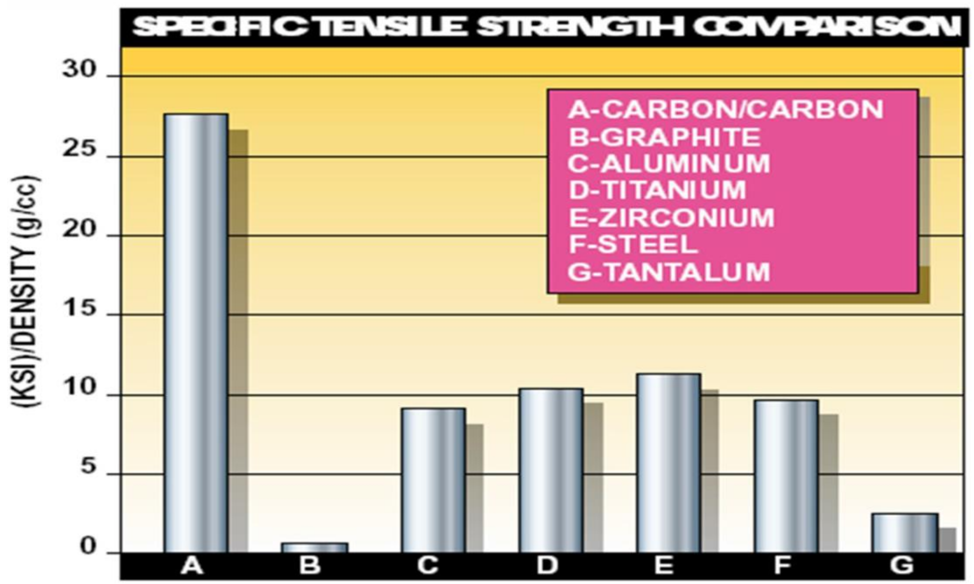
Properties of carbon–carbon composites?

- Excellent thermal shock resistance (Over 2000 ^{o}C)
- Low coefficient of thermal expansion
- High modulus of elasticity (200 GPa)
- High thermal conductivity (100 W/m*K)
- Low density (1830 Kg/m^3)
- High strength
- Low coefficient of friction (in fiber direction)
- Thermal resistance in non-oxidizing atmosphere
- High abrasion resistance
- High electrical conductivity
- Non-brittle failure

Properties of carbon–carbon composites?



CHEMCARB composites retain their physical properties even at temperatures exceeding 3,700°F.



For its density, CHEMCARB composites offer outstanding tensile strength, exceeding that of many metals.

http://www.hitco.com/products/corrosion/chemical/index.html

1.3.4. Carbon–Carbon Composites

Advantages

- Gradual failure
- Withstand high temperatures
- Low creep at high temperatures
- Low density
- High thermal conductivity
- Low and tailorable CTE
- Great strength to weight ratio
- High modulus, thermal conductivity, and electrical conductivity
- Good thermal shock resistance, abrasion resistance, and fracture toughness
- Excellent high temperature durability in inert or vacuum environment
- Good corrosion resistance

Disadvantages

- High fabrication cost
- Porosity
- Poor oxidation resistance – formation of gaseous oxides in oxygen atm.
- Poor inter-laminar properties.

1.3.4. Carbon–Carbon Composites

Applications of C-C Composites

- High performance braking system
- Refractory material
- Hot-pressed dies (brake pads)
- Turbo-jet engine components
- Heating elements
- Missile nose-tips
- Rocket motor throats
- Leading edges(Space Shuttle, Agni missile)
- Heat shields
- X-Ray targets
- Aircraft brakes
- Reentry vehicles
- Biomedical implants
- Engine pistons
- Electronic heat sinks
- Automotive and motorcycle bodies

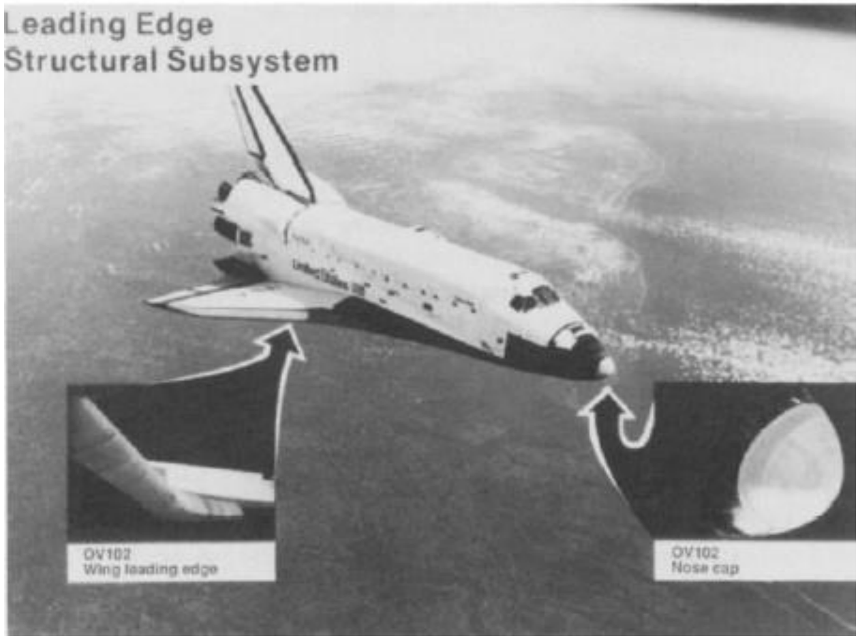
Applications of C-C Composites

- Aircraft, F-1 racing cars and train brakes

http://www.fibermaterialsinc.com/frSW.htm

http://www.futureshuttle.com/conference/ThermalProtectionSystem/Curry_73099.pdf

- Space shuttle nose tip and leading edges
- Rocket nozzles and tips



http://www.fibermaterialsinc.com/frSW.htm

How is a composite structure analyzed mechanically?

- **The approach to analyze the mechanical behavior of composite structures is as follows**

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.

1.4. Mechanics Terminology

How is a composite structure analyzed mechanically?

- **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.

1.4. Mechanics Terminology

What is a homogeneous body?

A homogeneous body has properties that are the same at all points in the body.

Are composite materials isotropic and/or homogeneous?

Most composite materials are neither isotropic nor homogeneous.

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.

1.5. Summary

- ✓ This chapter introduced composite and advanced materials and mentioned the advantages and disadvantages of composite materials over monolithic materials.
- ✓ Fiber and matrix factors were discussed to understand their influence on the properties of the composites.
- ✓ The classification of the composites based on the matrix materials — polymer, metal, and ceramics —was presented. In addition, carbon–carbon composites were also examined.
- ✓ The properties and applications of composite materials were described.
- ✓ Discussion the mechanics terminology used in studying the mechanics of composite materials.

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