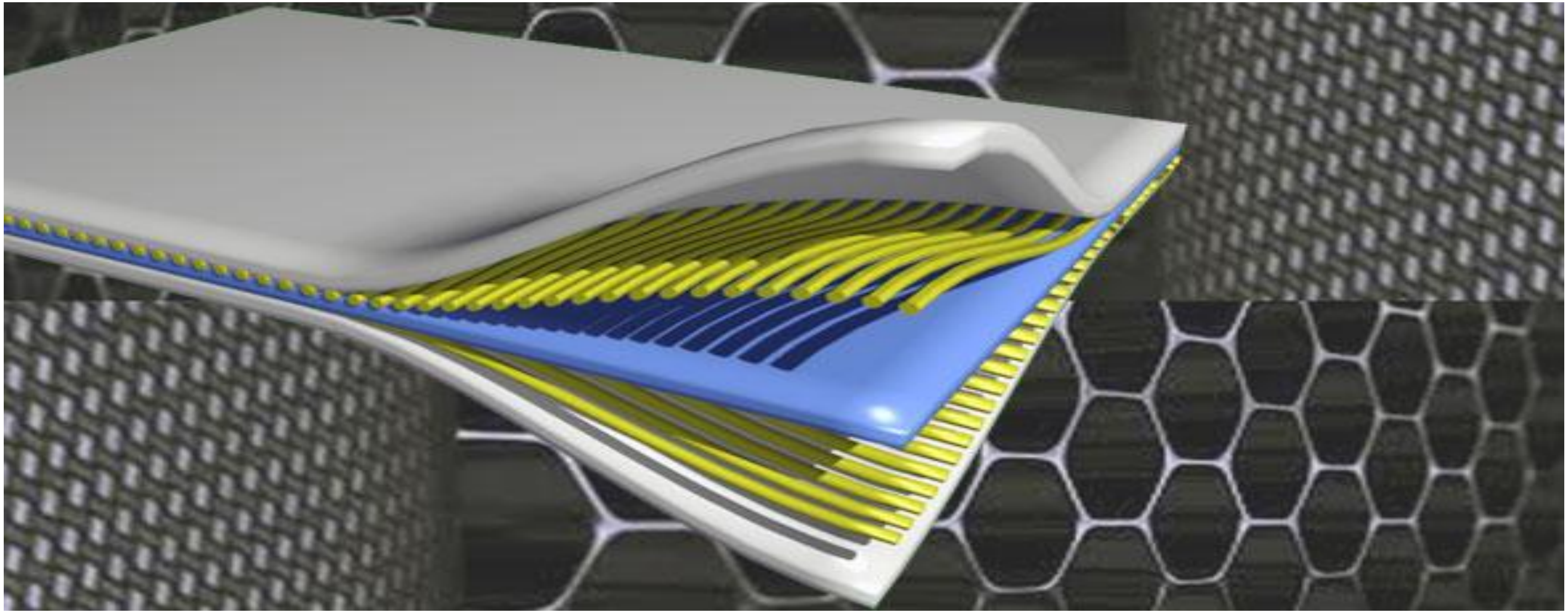
Composite Materials



Dr. Abbas Hasan Faris

Lecture 1

• CHE 3322 Composite Materials

- **Instructor: Dr. Abbas Hsan Faris**

- Office: Chem. & Petrochemical Dept. Building .2nd floor. Room No. 3
- Email: abbashasan@uoanbar.edu.iq
- Course Credits: 2

Course Content:

- Introduction Definition classification behaviors of unidirectional composites
- Analysis of lamina; constitutive classical laminate theory, thermal stresses,
- Classification of reinforcement, Type of fibers, Factors effect of fibers, Mechanical properties of composites, Manufacturing technology, Nano Technology
- Micromechanics
- Factors influencing strength and stiffness failure modes,
- Performance under adverse environment
- •Prediction of strength, stiffness

- **Reference Books/Material:**
- **Composite Materials, Science and Engineering by Krishan K. Chawla**
- **Composite Materials and Applications by Daniel Gay, Suong V. Hoa, Stephen W. Tsai**
- **Any other book on composite materials**
- **Research papers**

- **Grading Policy:**

  - **First Exam: 25%**
  - **Second Exam: 25%**
  - **Assignments: 10% (Individual + Group)**

- • **Absolute 30% for passing. Relative grading after that.**
- • **Assignments should be submitted on the due date, Late submission and copying will be heavily penalized!**
- • **Attendance will be monitored regularly.**

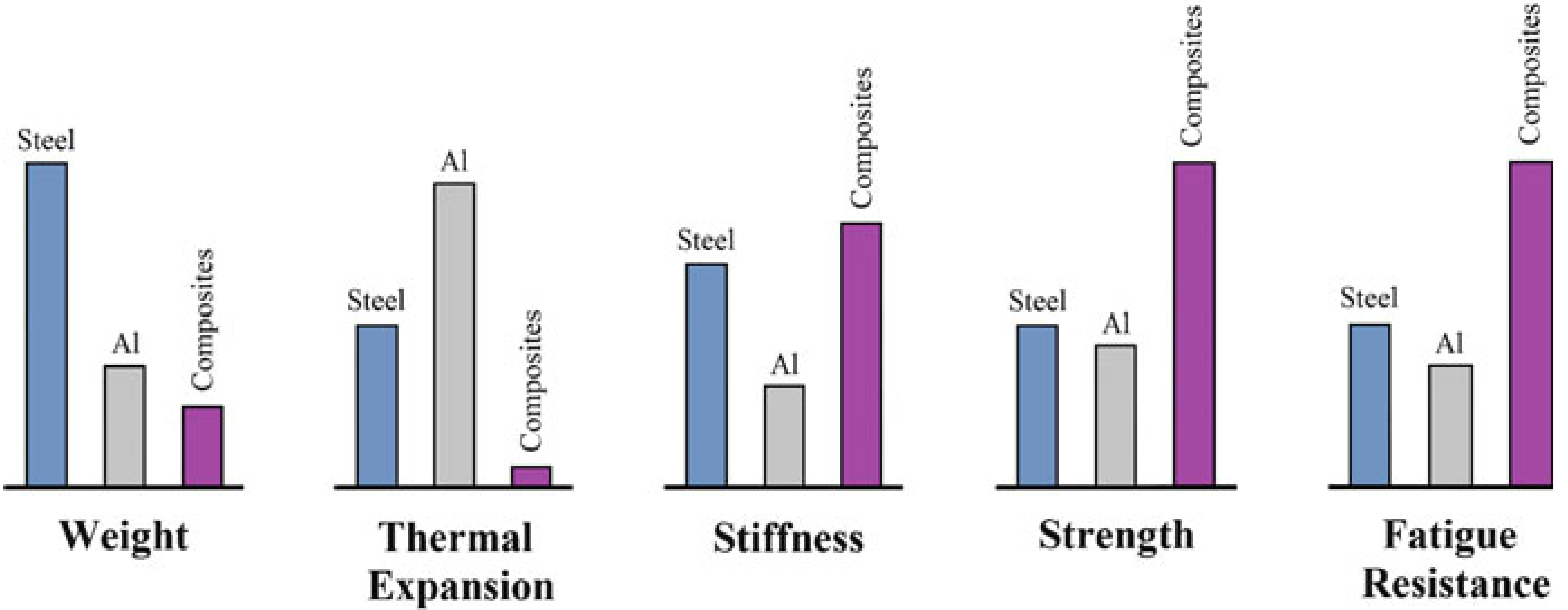
Introduction

- **Composite materials**

- It is an obvious fact **technological development** depends on advances in the field of **materials**. One does not have to be an expert to realize that the most advanced turbine or aircraft design is of no use if **adequate materials** to **bear** the **service loads** and **conditions** are not available. Whatever the **field** may be, the **final limitation** on **advancement** depends on **materials**. **Composite materials in this regard represent nothing but a giant step in the ever-constant work of improving materials.**

- The **idea** of composite materials is not a **new or recent** one. Nature is full of examples wherein the concept of composite materials is used. The **coconut palm leaf,** for example, is essentially used as a concept of fiber reinforcement. **Wood** has represented a composite : **cellulose fibers in a lignin matrix**. The cellulose fibers have **high tensile strength** but are **very flexible** (low stiffness), while the lignin matrix joins the fibers and provides the **stiffness**. **Bone** is yet another example of a **natural composite** that supports of various members of the body. It consists of short and soft collagen **fibers embedded** in a **mineral matrix** called **apatite**.

- Since the **early 1960s**, there has been an **increasing demand** for **stiffer** and **stronger** materials yet **lighter** ones in fields as diverse as **aerospace**, **energy**, and **civil construction**. The **demands made on materials** to improve overall **performance** are **so great and diverse** that **no one material** can **satisfy** them. This naturally led to a resurgence of the **old concept** of **combining different materials** in an **integral-composite material** to satisfy the user requirements.



Comparison between conventional monolithic materials and composite materials (1978).

- Therefore, we must **agree** on an operational definition of **composite material** for our purposes in this text. We shall **call a material** that **satisfies** the **following conditions** a **composite material**:

- **1. It is manufactured (i.e., naturally occurring composites, such as wood, are excluded).**

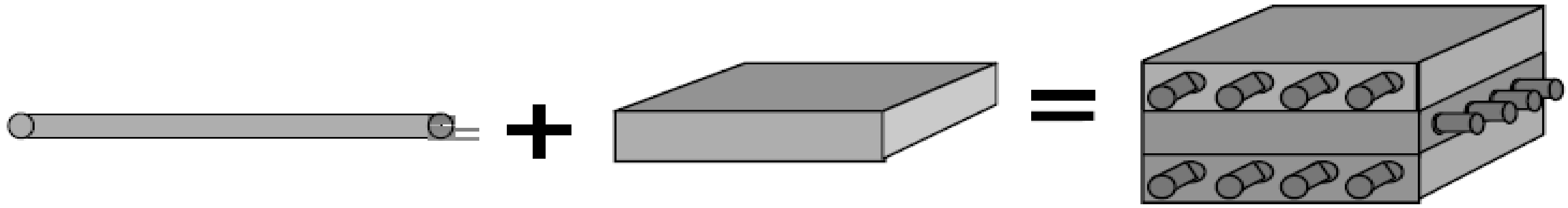
- **2. It consists of two or more phases that are physically and/or chemically distinct, suitably arranged, or distributed with an interface separating them.**

- **3. It should have characteristics that are not depicted by any of the components in isolation.**

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. So that the properties of the composite are different (usually better) from those of the individual constituents.

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.

Composition of Composites



Fiber/Filament Reinforcement

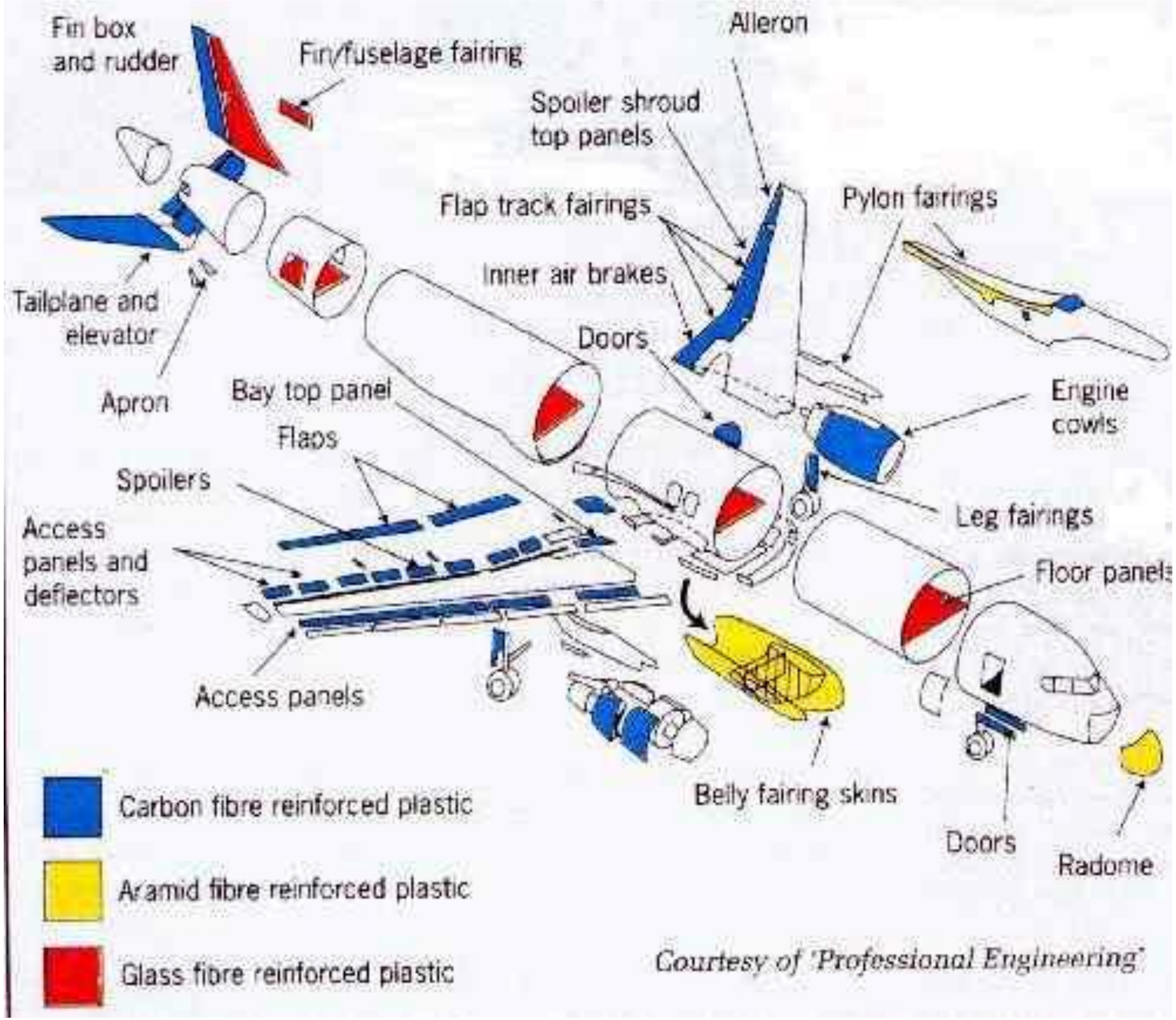
Matrix

Composite

- High strength
- High stiffness
- Low density

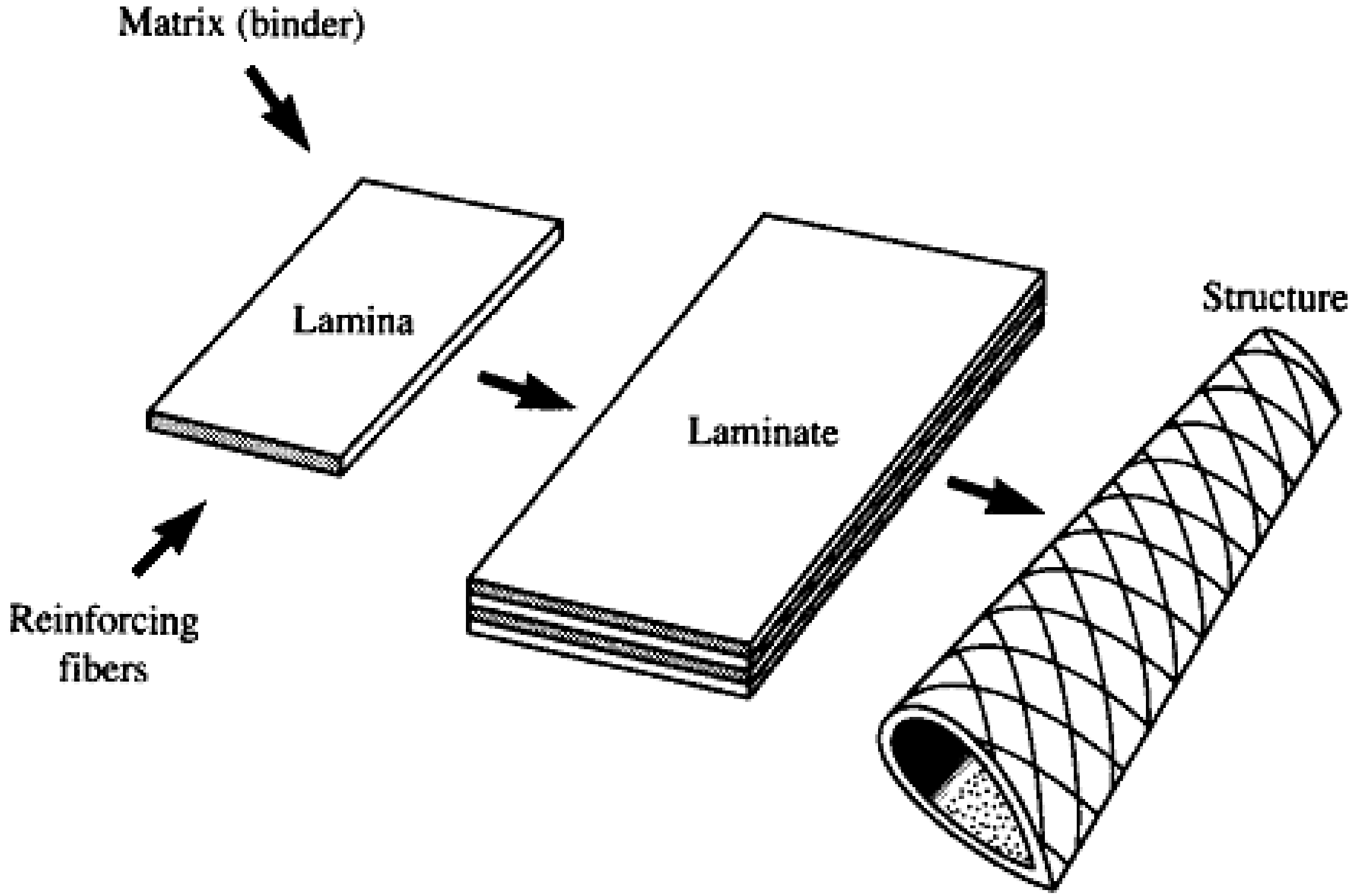
- Good shear properties
- Low density

- High strength
- High stiffness
- Good shear properties
- Low density

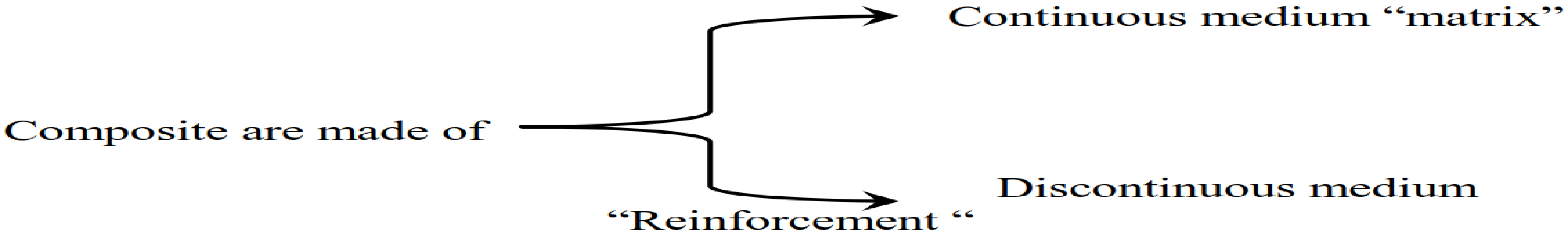


Courtesy of 'Professional Engineering'

- **Applications**:
  – Aerospace industry
  – Chemical industries, electrical constructions.
  – Sporting Goods Industry
  – Automotive Industry
  – Home Appliance Industry



- The important property that recognizes the composite material on metal is the **strength-to-density ratio or strength-to-weight ratio**.



Composite is made of

A- Continuous medium "matrix"

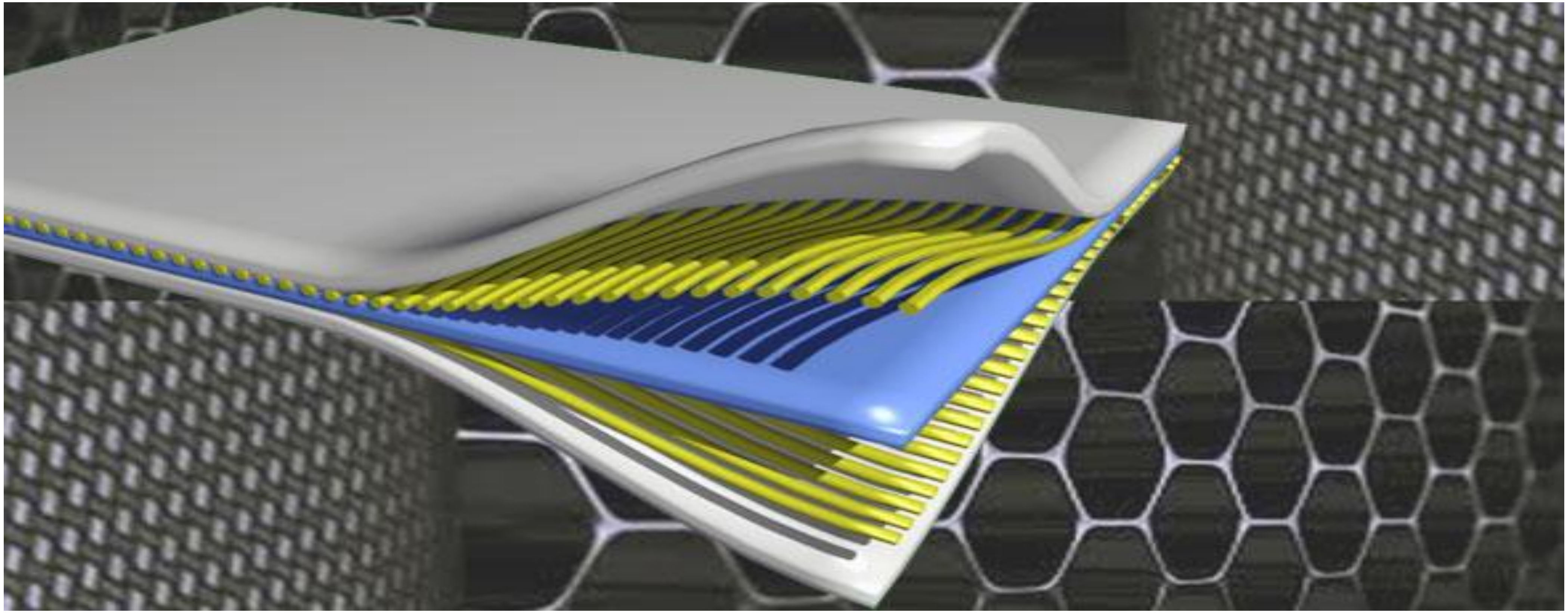
B- Discontinuous medium "Reinforcement" (which is usually harder and stronger one)

Therefore the properties of the composite depend on the properties of the matrix and reinforcement materials, their distribution, and interaction.

Interface: Zone across which matrix and reinforcing phases chemically, physically, and mechanically interact

- The **simplest composite** materials are composed of just **two phases**.
- •The first is termed the **matrix**, which is continuous and surrounds the other phase which is often called the **dispersed phase (Reinforcement phase)**.
- **Reinforcement phase**
- **(a) there is a change in the concentration of the dispersed (fiber) material.**
- **(b) the size of the dispersed phase,**
- **(c) the shape,**
- **(d) the distribution,**
- **and (e) the orientation.**
- **•All these will affect the final performance of the composite.**

Composite Materials



Dr. Abbas Hasan Faris

Lecture 2

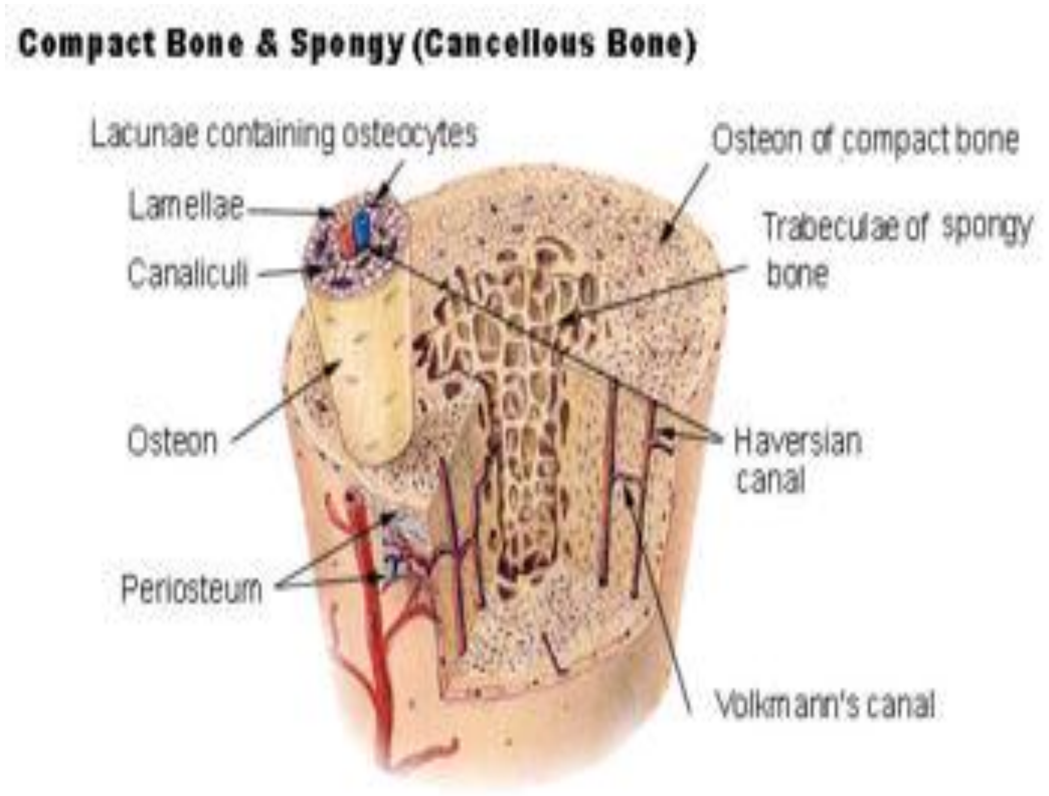
Advanced composites are composite materials that are traditionally used in the aerospace industries. These composites have high performance reinforcements of a thin diameter in a matrix material. Examples are graphite/epoxy, Kevlar /epoxy, and boron / aluminum composites. These materials have now found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

Polymer Matrix Composites

- **What are the most common advanced composites?**
  - **Graphite/Epoxy**
  - **Kevlar/Epoxy**
  - **Boron/ aluminum**

Examples of Natural Composites

- Wood
  - Cellulose Fibers
  - Lignin Matrix
- Bones
  - Collagen Fibers
  - Mineral Matrix



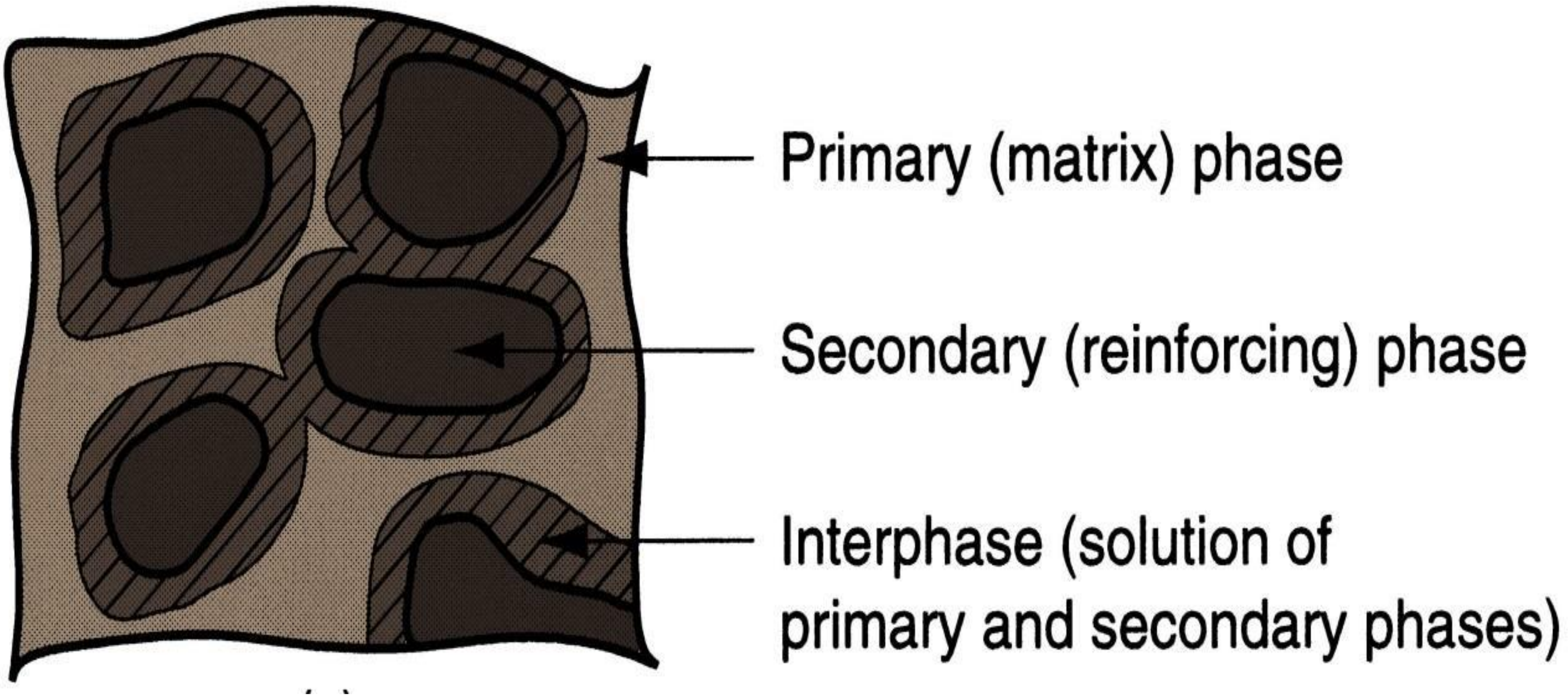
- To manufacturing composite materials should be

- 1. Combination of materials should result in significant property changes
- 2. The content of the constituents is generally more than 10%
- 3. In general, the property of one constituent is much greater (≥5) than the other

- In some cases, a third ingredient must be added to achieve the bonding of primary and secondary phases

- Called interphase, this third ingredient can be thought of as an adhesive.

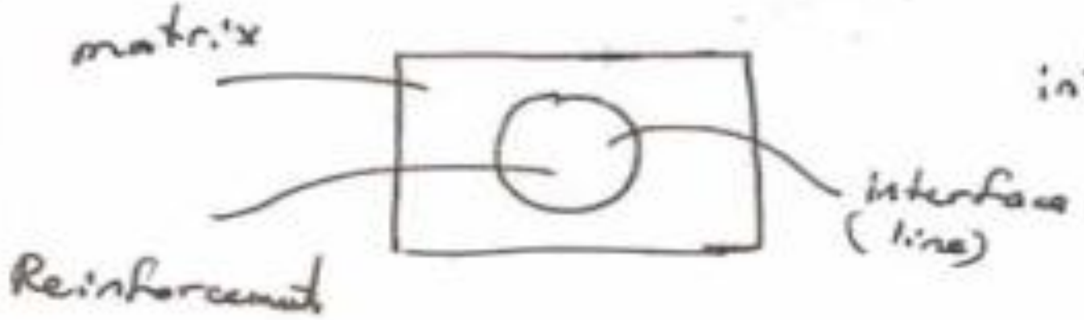
Interphase may be composed of a solution of the primary and secondary phases at their boundary by diffusion



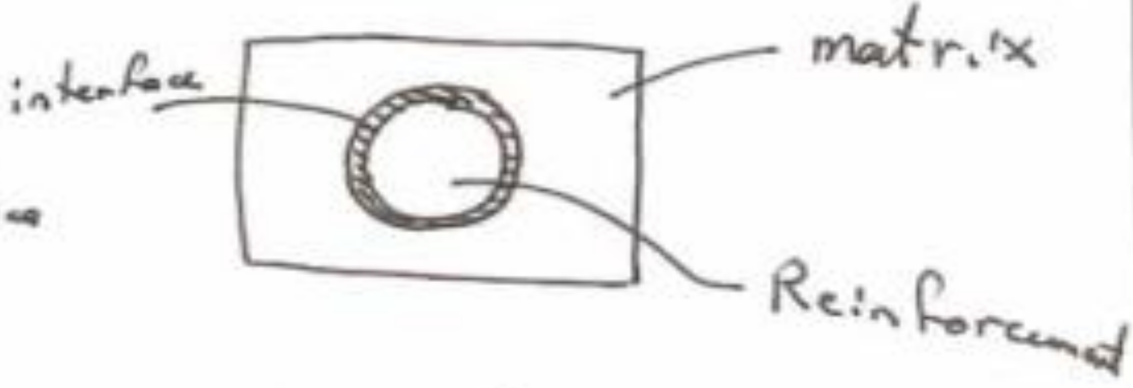
Components of Composite Materials

* matrix
* Reinforcement
* Interface

The interface is a bonding surface or zone between the reinforcement and matrix.



without Coupling Agent



with coupling Agent

- The matrix material must "wet" the reinforcement. Coupling agents are frequently used to improve wettability.
  (wetted reinforcement increase the interface surface area and bonding).

- The applied load is transfer from matrix to the Reinforcement via the interface. This means that the
  يبدي او يعرض
  interface must be large and exhibit strong adhesion between the reinforcement and matrix.

- Coupling Agents form the interphase which have a different mechanical properties from that of matrix and reinforcement.

The General Requirement of the Interphase

- big bond
- chemical stability

} In order to carry the load from the matrix to reinforcement

Therefore the interphase depend on

1- Reinforcement shape.
2- Surface roughness of the reinforcement.
3- treated the surface by Coupling agent (wettability).

- **Why do you need composite materials?**

  - **Enhanced desired properties!**

- **What are these desired properties?**
- Strength
- Stiffness
- Toughness
- Corrosion resistance
- wear resistance
- Reduced weight
- Fatigue life
- Thermal/Electrical insulation and conductivity
- Acoustic insulation
- Energy dissipation
- Attractiveness, cost, ……………………..
- Tailorable properties

-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.

-Corrosion resistance is the resistance to corrosion,

- **Reinforcement** increases the mechanical properties of the composite. It provides **strength** and **stiffness** to the composite **in one direction** as reinforcement carries the **load along the length of the fiber**.
- **Reinforcement** can be **fibers**, **fabric particles**, or **whiskers**. these **reinforcements** are fundamentally used to **increase the mechanical properties of a composite.**
- **The main purpose of the reinforcement is to**
- 1- Provide superior levels of **strength** and **stiffness** to the composite.
- 2- **Reinforcing** materials (graphite, glass, SiC, alumina) may also provide **thermal** and **electrical conductivity**, controlled **thermal expansion**, and **wear resistance** in addition to **structural properties**.
- 3- The most widely used **reinforcement form** in high-performance composites is **fiber tows** (**untwisted bundles of continuous filaments**).
- 4- Fiber monofilaments are used in **PMCs, MMCs, and CMCs**; they consist of a single fiber with a diameter generally ≥100 μm.
- 5- In MMCs, **particulates** and **chopped fibers** are the most commonly used reinforcement morphology, and these are also applied in PMCs.
- 6- Whiskers and platelets are used to a lesser degree in PMCs and MMCs.

- Regarding the **tensile strength** behavior of the composite, it is given by the **shape**, **concentration**, and **orientation** of reinforcement.

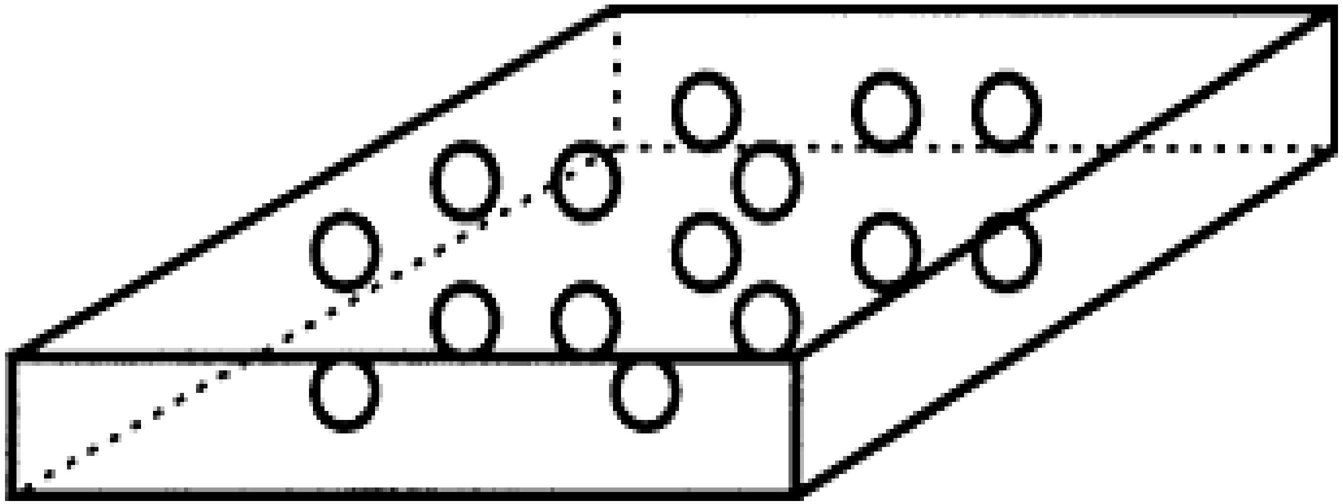
- **The shape** of reinforcement particles can be considered approximately as
- 1. a sphere (the powder form of reinforcement)
- 2. a cylinder (fibers). Their size and distribution then determine the texture of the composite. e.g., glass fibers , carbon fibers, ceramic fibers.
- size of the reinforcing phase, expressed in terms of **volume** or the quantity of **weight**. It is one of the most **important parameters** that **affect the properties of the composite material.**
- **The orientation** of the reinforcing phase affects the isotropy of the system. If the reinforcing particles have the **shape and dimensions in all directions** about **the same** (for example **powders**), the composite behaves basically as an **isotropic material**, **therefore its properties are the same in all directions**. On the contrary systems reinforced with cylindrical reinforcement (fibers) show an **anisotropy** of properties.

- **Simply put this means that the mechanical properties of the material depend on the direction.**

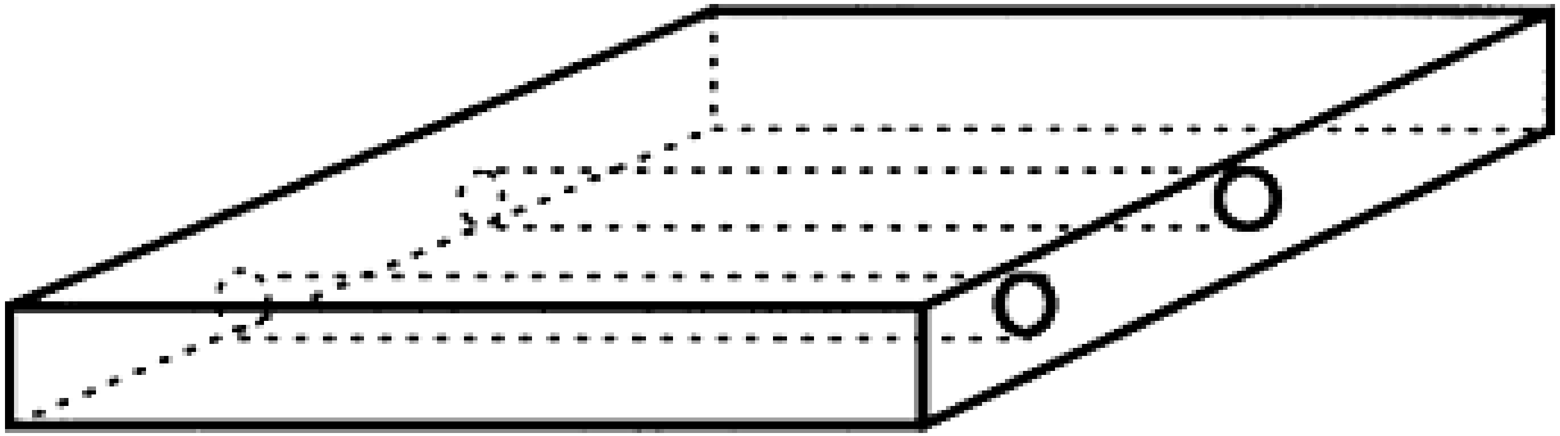
- **Isotropic materials** are materials whose properties remain the same when tested in **different directions**.
- **Isotropic** materials differ from **anisotropic** materials, which display varying properties when tested in **different directions**. Common isotropic materials include glass, plastics, and metals.

- **Isotropic** refers to the properties of a material that is **independent** of the **direction** whereas **anisotropic** is **direction-dependent.** These two terms are used to explain the properties of the material in basic crystallography.

- the **reinforcement** is usually **a fiber or a particulate.**
- **particulate composites** have dimensions that are approximately equal in all directions. they may be spherical, platelets, or any other regular or irregular geometry. particulate composites tend to be much weaker and less stiff than **continuous-fiber** composites, but they are usually much less expensive. particulate reinforced composites usually contain less reinforcement (**up to 40 to 50 volume percent**) due to processing difficulties and brittleness.



Particulate composites

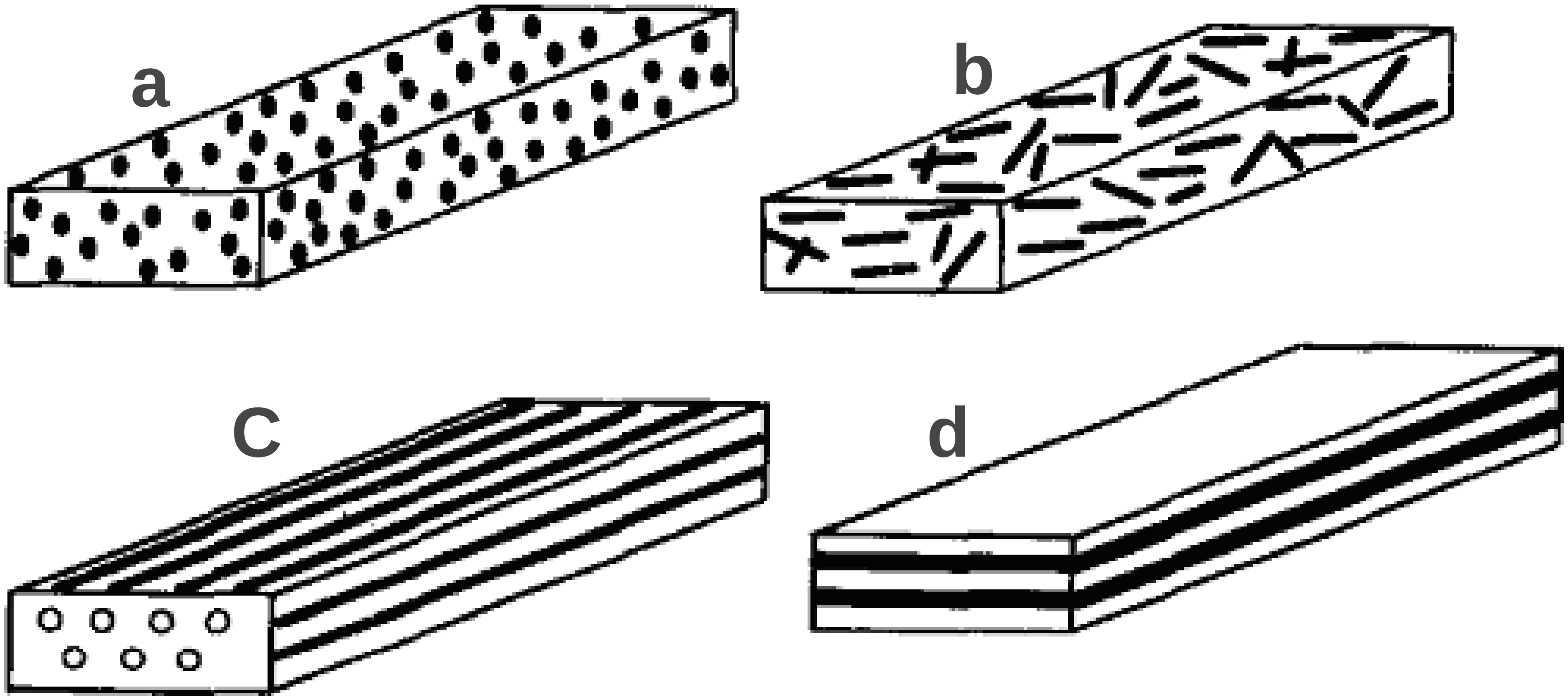


Fiber composites

Reinforcements Types

- **Reinforcing phase, is in the form of:**
- **fibers,**
- **Whiskers,**
- **Sheets &**
- **particles**
- **and is embedded in the other materials (the matrix phase).**

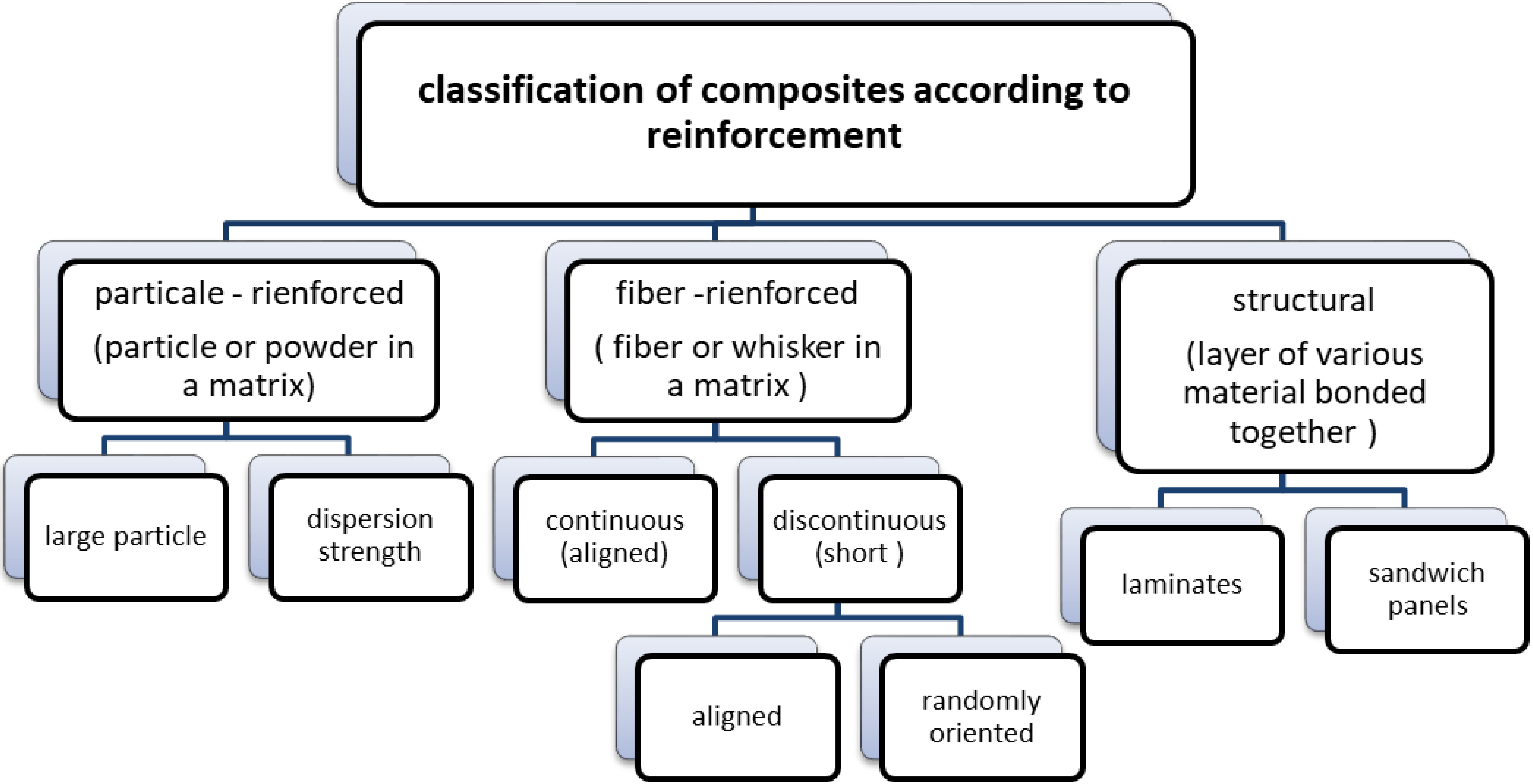
Composites According to Type of Reinforcement a: particles, b: whiskers, c: continuous fibers, d: sheet laminate

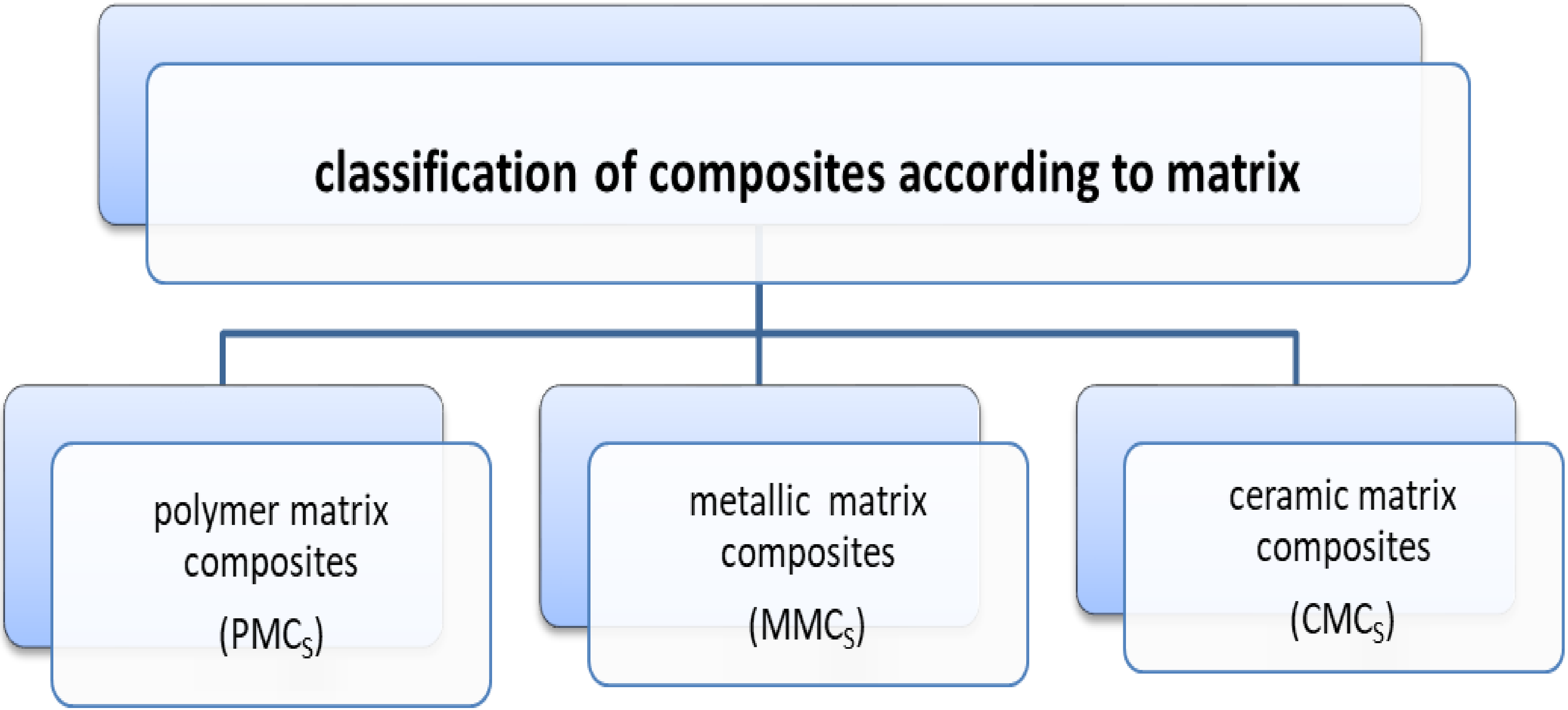


- **The matrix** is basically a homogeneous and monolithic material in which a fiber system of a composite is **embedded**. **Matrix** is **completely continuous**. The matrix provides a medium for **binding and holding reinforcements** together into a solid. It offers **protection** to the **reinforcements** from **environmental damage**, **serves to transfer load**, and provides **finish**, **texture**, **color**, **durability, and functionality**.
- **Matrix :-** It is the material that work to bind the reinforcing material together in order to make a composite material that can carry loads or stresses .
- The matrix combines the individual reinforcement particles, protecting them against external influences. The basic function of the matrix is to transmit the external load onto the reinforced phase.

- Fo the matrix,
- 1. a good bond strength with the reinforcing phase material (i.e. perfect wettability without chemical interaction at the interface of the matrix and reinforcement) is required.
- 2. Among other requirements for the matrix, a low weight is commonly included. In comparison with the reinforcement phase, a matrix has generally lower strength and greater plasticity.
- It is also called “medium “, it is may be metal , polymer or ceramic.

- **Classification of the composite materials**




classification of composites according to matrix
polymer matrix composites (PMC$_S$)
metallic matrix composites (MMC$_S$)
ceramic matrix composites (CMC$_S$)

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.

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**. Composites offer several other advantages over conventional materials.

These may include improved **strength, stiffness, fatigue and impact resistance, thermal conductivity, corrosion resistance ,etc.**

- **Advantages and disadvantages of composites**

The advantage of composites as structural materials is to obtain a material of higher strength, toughness, and stiffness, but also a higher resistance compared to conventional materials. In addition, with a suitable combination of components, we can also obtain a composite of specific properties (thermal, electrical, optical). The disadvantage of composite materials, **in comparison with traditional materials, is their difficult workability and relatively higher price.**

Stiffness is how well a material resists deformation.

Toughness is the ability of a material to absorb energy before failure.

- Thus, to measure the mechanical advantage, the (E/ρ) ratio is calculated and is called the **specific modulus** (ratio between **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 (σult) and the density of the material (ρ), that is,

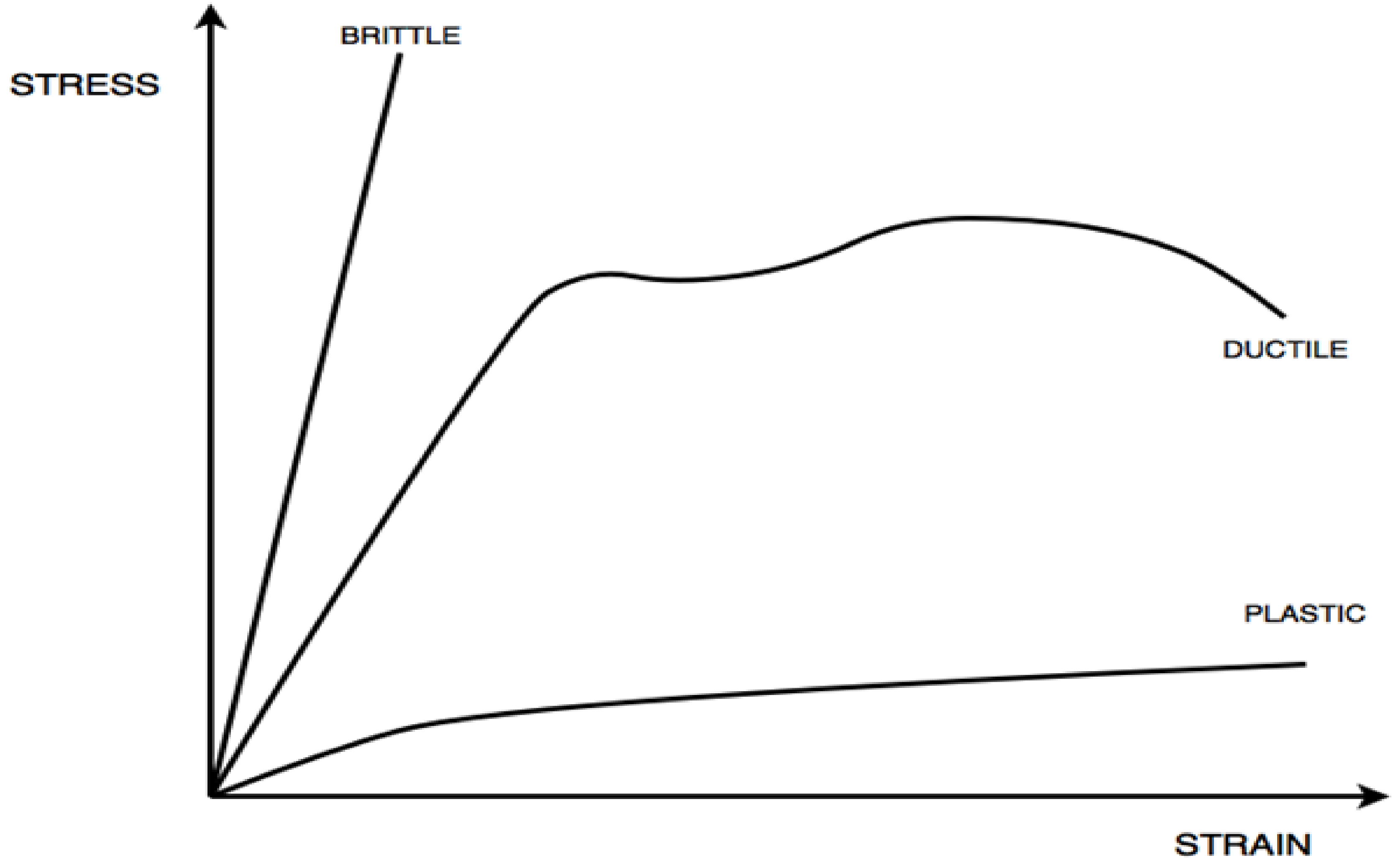
$$\text{Specific modulus} = \frac{E}{\rho},$$

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

- Young's modulus is the slope of the linear part of the stress-strain curve for a material under tension or compression. E ...

- The Young's modulus (E) is a property of the material that tells us how easily it can **stretch and deform** and is defined as the ratio of tensile stress (σ) to tensile strain (ε). Where stress is the amount of force applied per unit area ($\sigma = F/A$) and strain is extension per unit length ($\varepsilon = dl/l$).

- The basic difference between **stress** and **strain** is that stress is the deforming force per unit area, While **strain** is the **apparent change** in the shape, volume, or length of an object caused due to stress is called strain. The strain has no unit.


STRESS
BRITTLE
DUCTILE
PLASTIC
STRAIN

Why Composites over Metals?

How is the mechanical advantage of composite measured? •

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

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

where

E = Young's Modulus

ρ = Density

σ_{ult} = Ultimate Strength

Specific Strength vs. Year

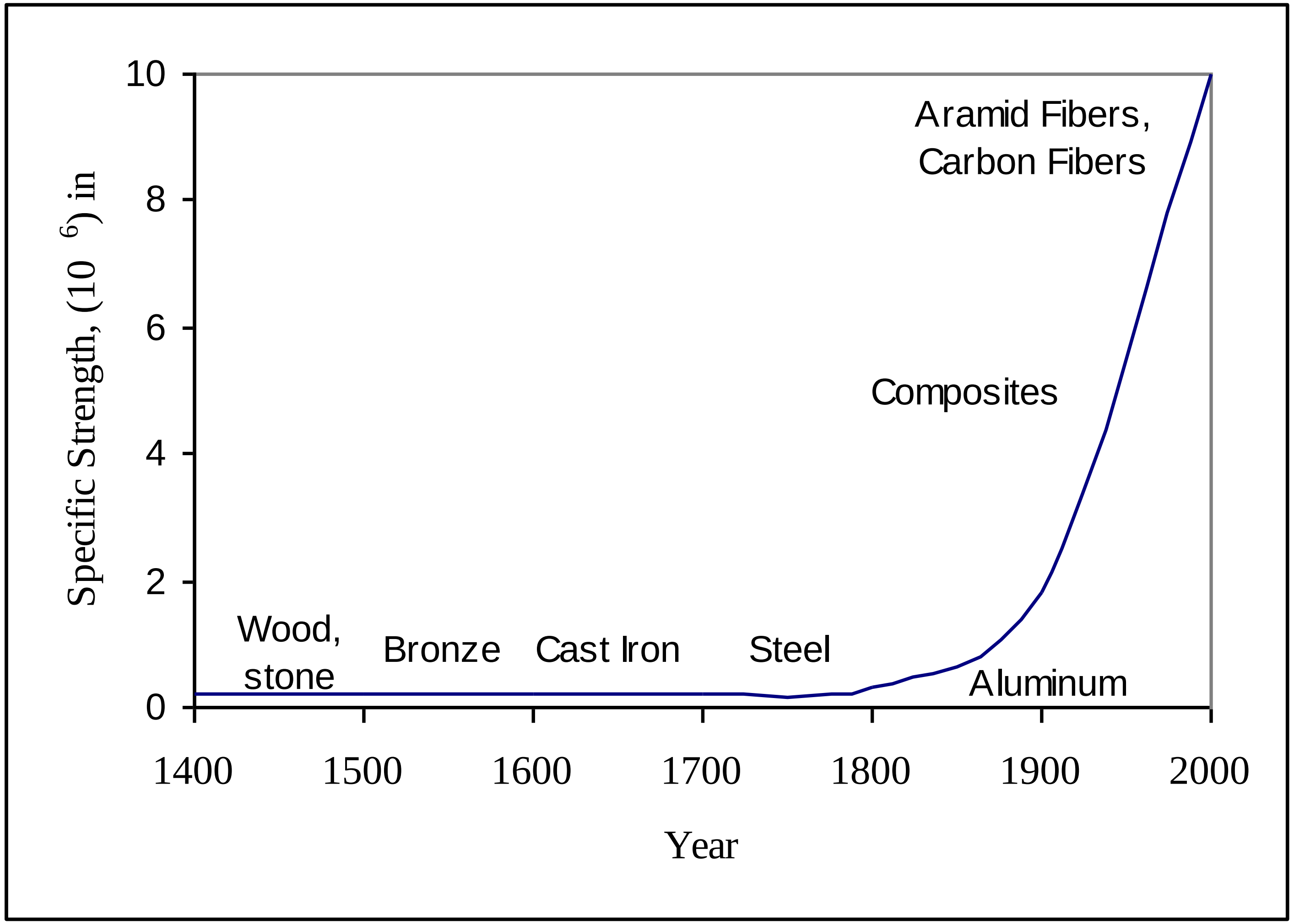


Table 1.1. Specific modulus and strength of typical fibers, composites and bulk metals

Material	Specific Gravity	Young's Modulus	Ultimate Strength	Specific Modulus	Specific Strength
Units		**GPa**	**MPa**	**GPa-m^3/kg**	**MPa-m^3/kg**
Graphite	**1.8**	**230**	**2067**	**0.13**	**1.1**
Unidirectional Graphite/Epoxy	**1.6**	**181**	**1500**	**0.11**	**0.94**
Cross-Ply Graphite/Epoxy	**1.8**	**96**	**373**	**0.060**	**0.23**
Quasi-Isotropic Gr/Epoxy	**1.8**	**70**	**276**	**0.043**	**0.17**
Steel	**7.8**	**207**	**648**	**0.026**	**0.083**
Aluminum	**2.6**	**69**	**276**	**0.026**	**0.106**

Composites Have Distinct Advantages Over Metals. Too, There Are Drawbacks Or Limitations In Using Them.

Drawbacks And Limitations In Use Of Composites Include:

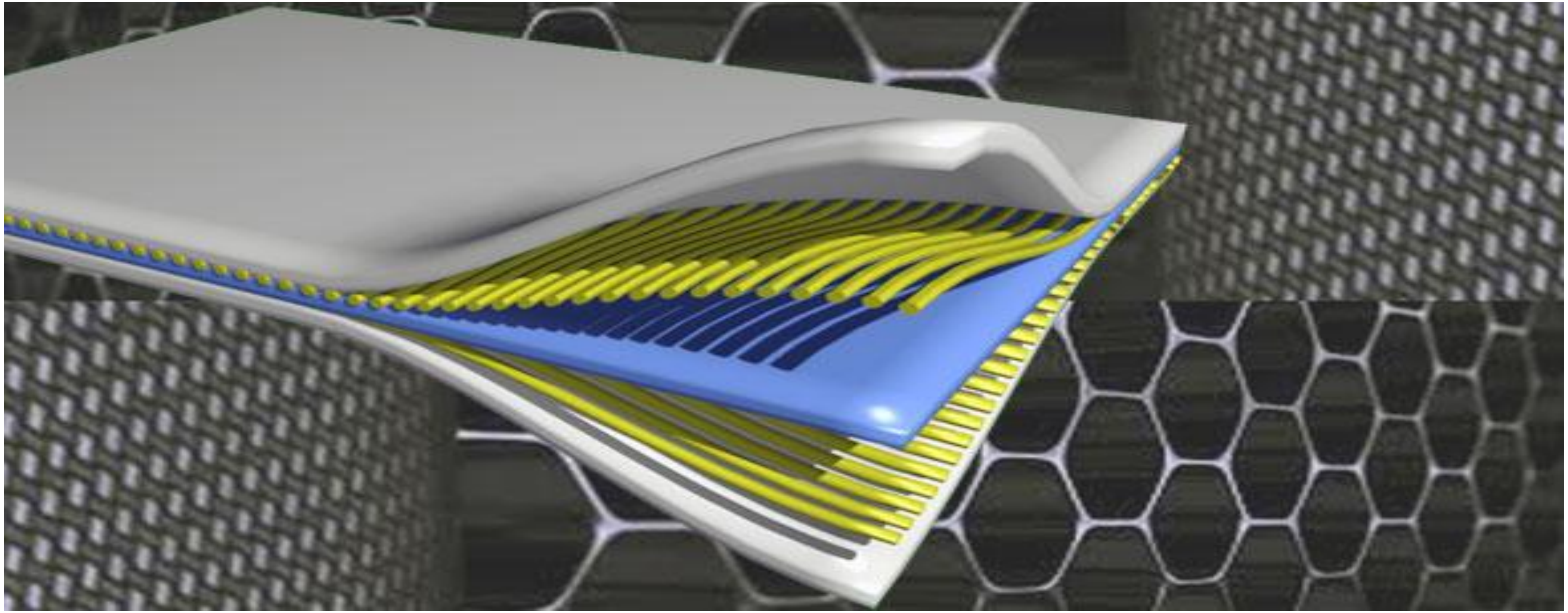
- **High cost of fabrication of composites is a critical issue. For example, a part made of graphite/epoxy composite may cost up to 10 to 15 times the material costs.**
- **Mechanical characterization of a composite structure is more complex than that of a metal structure.**

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.

- **Repair of composites is not a simple process compared to that for metals. Sometimes critical flaws and cracks in composite structures may go undetected.**
- **Composites do not have a high combination of strength and fracture toughness compared to metals.**
- **Composites do not necessarily give a higher performance in all the properties used for material selection.**

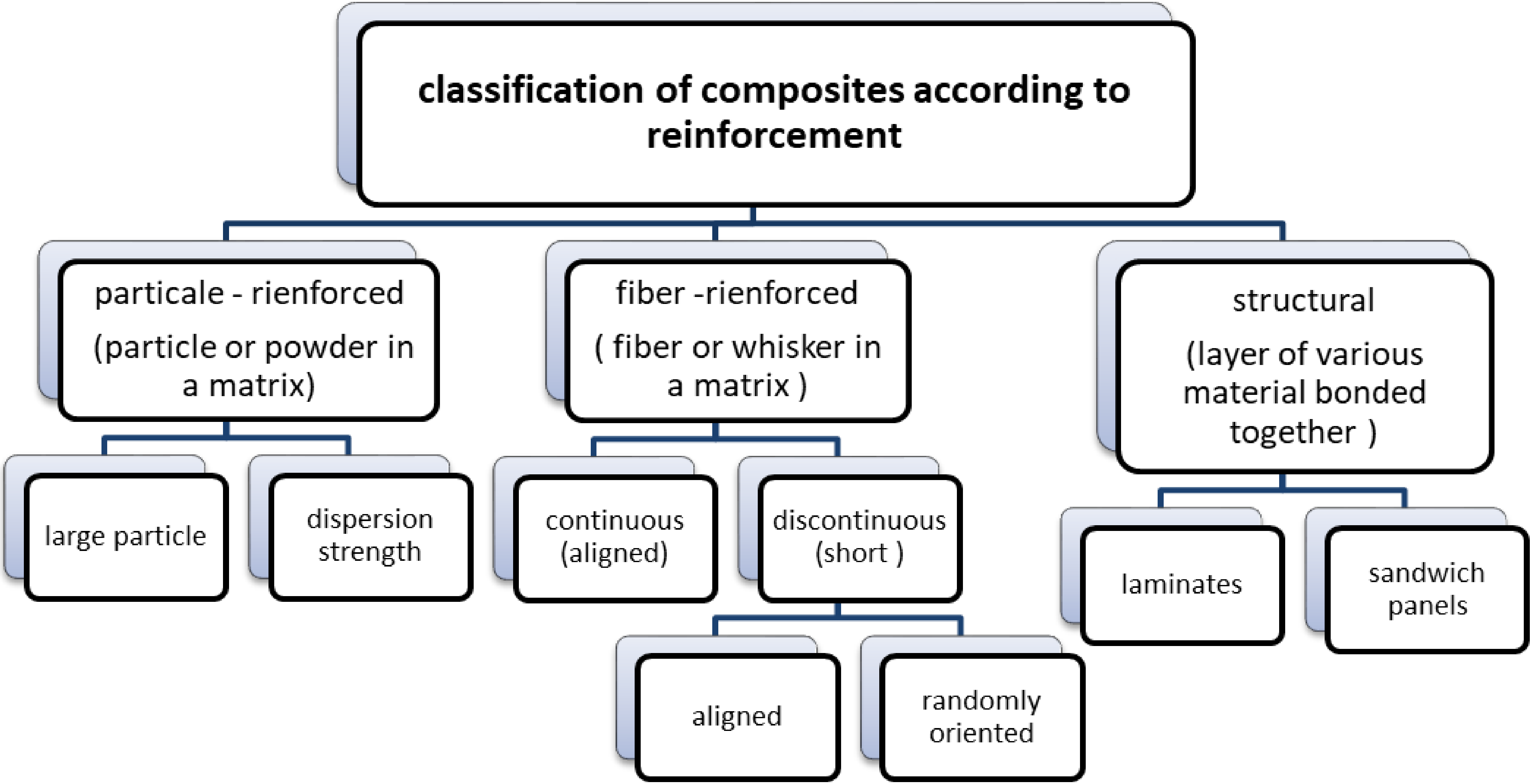
Composite Materials



Dr. Abbas Hasan Faris

Lecture 3

- **Classification of the composite materials**



• **Composite: Constituents**

• There are two main constituents of composites:

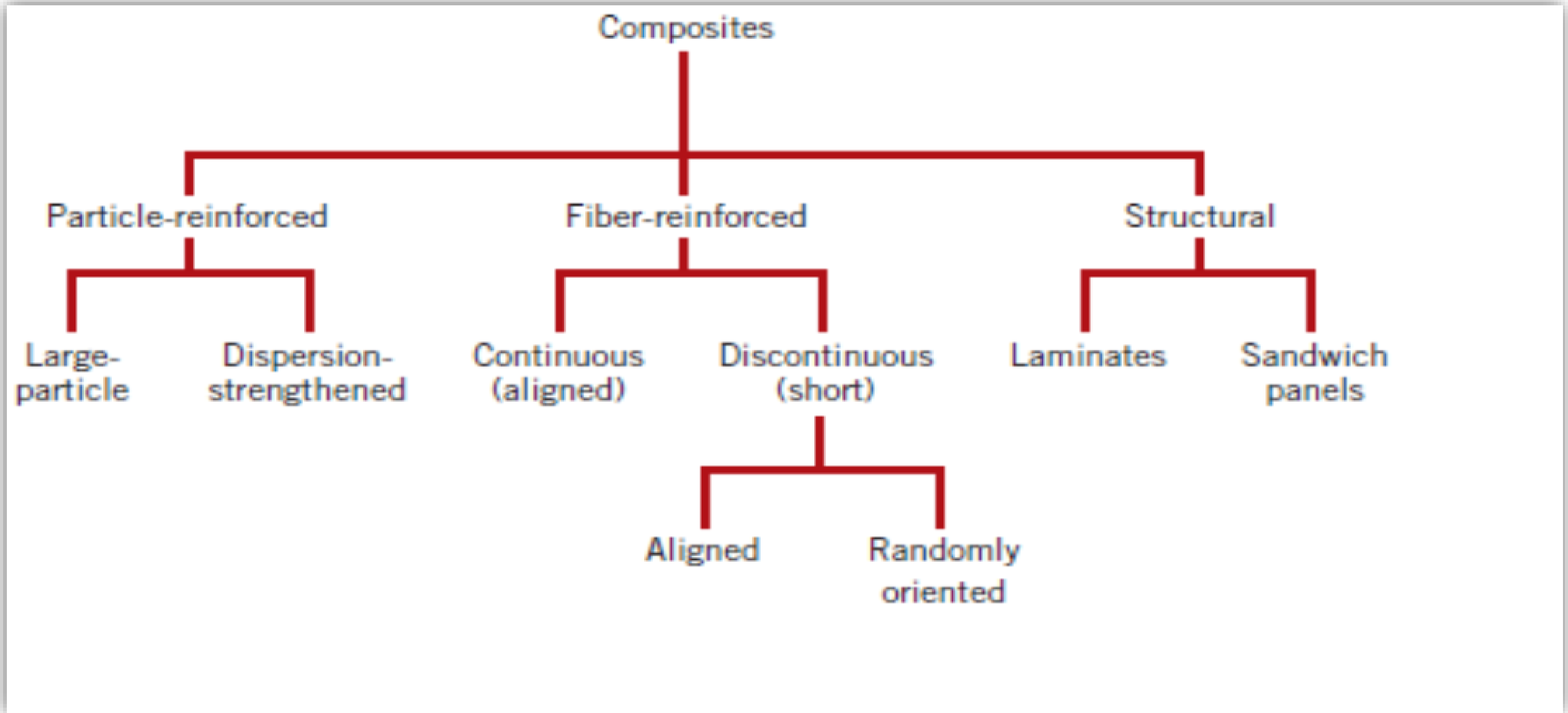
1- Reinforcement

2- Matrix

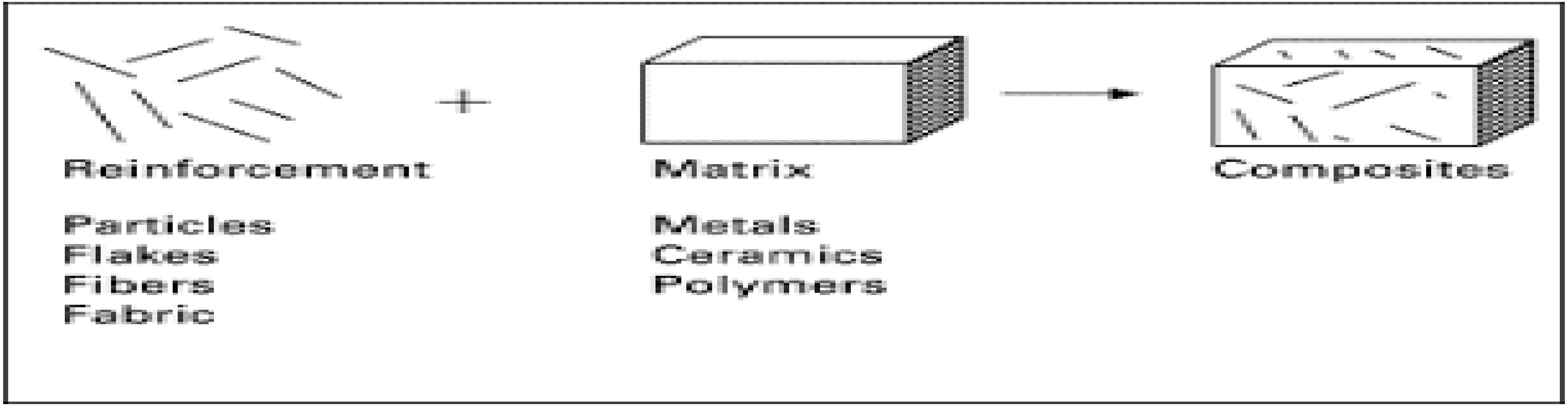
Reinforcing materials:- It is the materials that make **reinforce** the matrix. It has different forms may be **fibers, particles, flakes, fillers, and woven** made from glass, carbon, Kevlar or steel…….etc

The reinforcing phases are mainly divided according to the geometry of their individual particles into:

- Reinforcement phase :The **reinforcing phase provides strength** and **stiffness**. In most cases, the reinforcement is **harder, stronger, and stiffer than the matrix**. The reinforcement is usually fiber or particulate.



- The purpose of reinforcement is to **enhance matrix properties**. Reinforcements for composite materials can be in the form of **fibers, particles, or flakes**. Each has its own unique application, **although fibers are the most common in composites and have the most influence on properties.**



:Difference between Matrix and reinforcement

MATRIX	REINFORCEMENT
• This constituent is continuous and in greater quantity.	• This may be continuous or discontinuous.
• Based up on matrix composite is of 3 types. PMC,CMC,MMC.	• Based up on reinforcement type it can be fiber reinforced or particulate reinforced.
• Matrix transfers the load.	• Reinforcement bears the load.
• It protects individual fiber from surface damage due to abrasion and oxidation.	• The reinforcing phase provides strength, stiffness. In most cases these are stronger and harder than matrix.
• Example: aluminium, epoxy, polyester etc.	• Example: carbone, aramide, nylon, jute etc.

- If the reinforcement is **similar in all dimensions**, it is a **particulate** reinforced composite
- If its **shape is needle-shaped single crystals**, it is **whisker-reinforced** composite
- If the reinforcement is cut into **continuous filament**, it is **chopped fiber** reinforced composite
- If the fiber is continuous, it is **fiber composite**.
- **It can be broadly classified as:**

  (1) Particle reinforced composites

  (2) Fiber reinforced composites

- Particulate composites have dimensions that are approximately equal in all directions. They may be spherical, or any other regular or irregular geometry. Particulate composites tend to be much **weaker and less stiff than continuous fiber** composites, but they are usually much **less expensive**. Particulate reinforced composites usually contain less reinforcement (up to 40 to 50 volume percent) due to processing difficulties and brittleness.

- •Points to further note are the following;

  - **In particle reinforcement**, the particles are generally equiaxial; that is approx. the same in all directions, **but for fiber** reinforcement there is a **large difference** in fiber length to fiber diameter, **where l >> d.**

Fiber has a **length** that is **much greater** than its **diameter**. the length-to-diameter (l/d) ratio is known as the **aspect ratio** and can vary greatly.

•This has profound effects on the overall composite property, particularly the load bearing properties of the final composite.

K_{IC}= fracture toughness

σ_y, = yield stress

TS = Tensile strength

E = Elastic modulus

- Dispersed phase:
  - -- Purpose:
    - MMC: increase σ_y, *TS*, creep resist.
    - CMC: increase K_{Ic}
    - PMC: increase *E*, σ_y, *TS*, creep resist.
  - -- Types: particle, fiber, structural

- Microstructures of metal and ceramics composites, which show particles of one phase **spread** in the other, are known as **particle reinforced composites**. Square, triangular and round shapes of reinforcement are known, but the dimensions of all their sides are observed to be more or less equal.

- Particles in composites are typically used not only to improve the **mechanical properties**, but often (also) to improve or modify properties such as **heat resistance, electrical conductivity, damping of vibrations, hardness, resistance to high temperatures, etc**. Dispersions usually consist of powders with particles of various shapes (spherical, pyramidal, lamellar, etc.).

and various sizes. There are usually used powders of inorganic compounds such as oxides (MgO, ZnO, BeO, Al_2O_3, ZrO_2, etc.), carbides (SiC, TiC, B_4C, Al_4C_3, etc.), nitrides (Si_3N_4, BN), borides, or silicates (kaolin, mica, glass beads, etc.).

Glass is often used for **weight reduction** in the form of solid or hollow glass beads.

Reinforcements

Ceramics

- **Silicon Carbide (SiC)**
- **Aluminum Oxide (Al_2O_3)**
- **Titanium Carbide (TiC)**
- **Boron Carbide (B_4C)**

Other

- **Graphite (C)**
- **Titanium Diboride (TiB_2)**

Metal Filaments

- **Boron**
- **Steel**
- **Tungsten**

The **Reinforcement** (**Secondary Phase**) Function is to reinforce the **primary phase** Imbedded phase is most commonly one of the following shapes: **Fibers Particles Flakes** In addition, the second phase can take the form of an **infiltrated phase** in a skeletal or porous matrix Example: a **powder** metallurgy part infiltrated with **polymer**

- **Particulate composite:-** Consist of one or more materials suspended in a matrix of another material. The particles can be either **metallic or non-metallic**.
- According to their size, we distinguish the particles as follows:
- **1- Large particles reinforced**
- **2- Dispersion strength composite**
- **A classic example of polymers as a particulate composite material is carbon black in rubber (in the manufacturing of tires). A carbon black improves strength, stiffness, wear resistance.**
- **1- Large particle reinforced composite:** Have particles with a diameter of (1µm)or more and a volume concentration **(25-50) %** or more of the composite.
- One of their applications is cermet or (cemented carbides), a composite involving **ceramic particles in a metal matrix** that are widely used for the tips of cutting tools.
- Where particle-matrix interactions cannot be treated on an atomic or molecular level **(microscopic).** An example of a large-particle composite is concrete, which is composed of cement (the matrix), and sand and gravel (the particulates).

- •The first example of particle composites is the large particle composites. These are known as such **because the interactions between the matrix phase and particle phase cannot be examined on a molecular, atomic level**.
- •Here the particle phase is generally tougher than the matrix and, in addition to acting as a cheap filler material, tends to **resist** localized deformations.
- •Portland cement is an example of a large particle reinforced composite
- •The composite's **mechanical properties are increased** with **increasing particulate content**; increasing this increases the interfacial area between the particulate and the matrix.

- **2- Dispersion strengthened composite:** The strength of metal can be increased by small particles dispersed throughout the matrix. The diameter of particle (0.1μm)and volume concentration (1-15)% of the composite. For example the dispersion of aluminum – copper compound throughout of alloy. To produce composite for general application, like a **piston, connecting rod** for automotive application.
- **recognizable by a scanning electron microscope (SEM).**

- Also, one way of introducing a dispersion of small particles throughout a metal uses **sintering**. Like dispersion of aluminum oxide (AL2O3) about (14%) throughout an aluminum matrix.
- Where the tensile strength is :
- 90 MPa for aluminum, WHILE 400 MPa for sintered aluminum

- •Dispersion strengthened composites have **much smaller particle sizes** whose interactions with the matrix can be seen at the molecular level.
- •These **particle-matrix interactions** at the molecular level increase the overall strength of the composite.
- •The small particles also resist dislocation motion throughout the composite in a similar manner to the pinning of precipitate-hardened metals.
- •For dispersed strengthened composites, the matrix supports the load whilst small particles act to stop crack propagation through the matrix material.
- •We can see examples of particulate composites with all three material types (metals, polymers, and ceramics).

- **3. Nanoparticles** under 10-5 mm (below 10 nm), recognizable by a **transmission electron microscope (TEM)**.
- **For effective reinforcement**, the particles should be **small** and **evenly distributed** throughout the matrix(. It is therefore necessary when producing the composite by adding dispersion particles to the melt to (often) use intensive mixing.
- The volume fraction of the two phases influence the behavior; **mechanical properties are enhanced with increasing particulate content.**

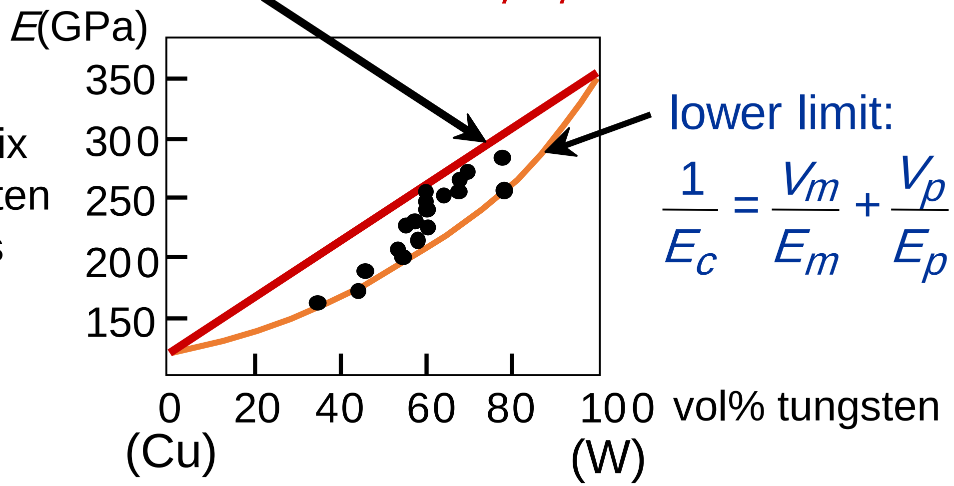
Classification: Particle-Reinforced (iii)

Particle-reinforced | Fiber-reinforced | Structural

- Elastic modulus, E_c, of composites:
  - -- two "rule of mixture" extremes:

upper limit: $E_c = V_m E_m + V_p E_p$

Data:
Cu matrix
w/tungsten
particles



lower limit:

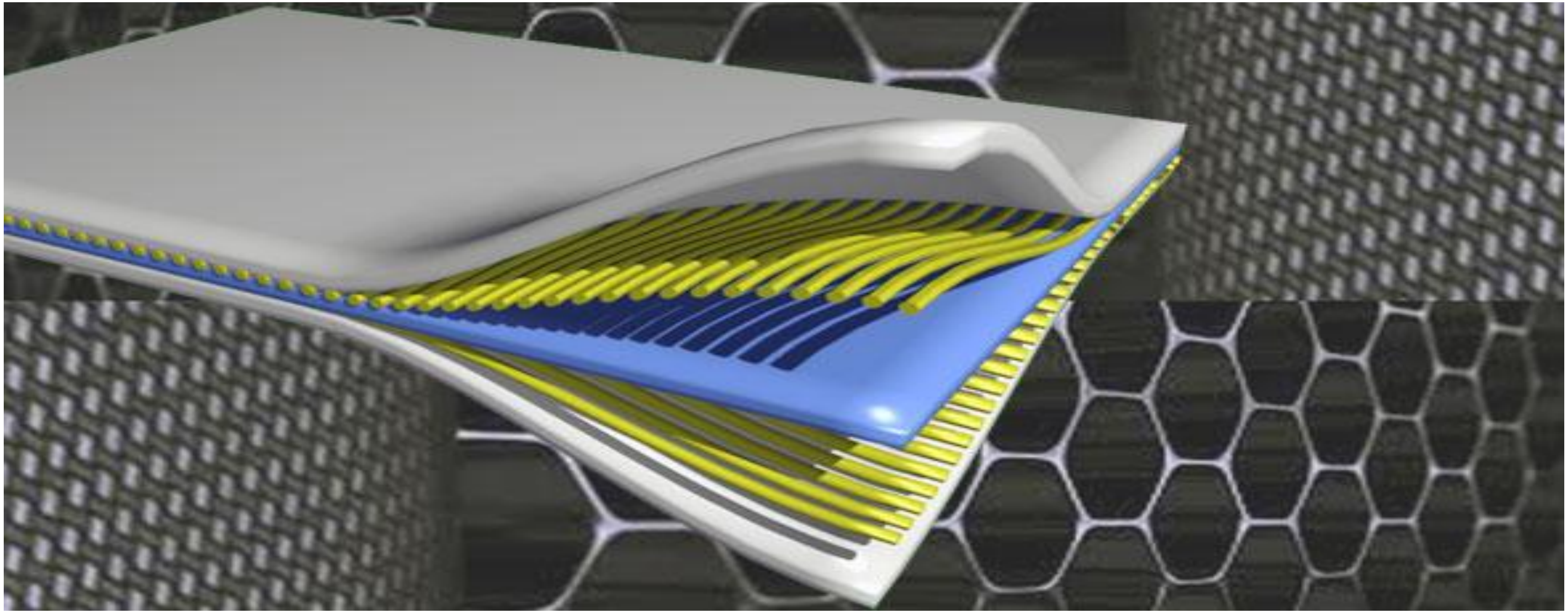
$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$

Adapted from Fig. 16.3, *Callister & Rethwisch 8e*. (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

- Application to other properties:
  - -- Electrical conductivity, σ_e: Replace E's in equations with σ_e's.
  - -- Thermal conductivity, k: Replace E's in equations with k's.

- •The properties of the composite reinforced with **large particle** filler can be predicted using the 2 rules of **mixture equations**.
- •Let’s consider using for example the **elastic modulus**.
- •The **anticipated upper and lower values** for **E** can be obtained from two fairly simple equations.
- •**The upper value** is given by E subscript c (E_c,) the elastic modulus of the composite equals the product of the **matrix volume and elastic modulus plus the product of the particle volume and elastic modulus**. We can see from this equation that the greater the volume fraction of the particle the greater E subscript c.
- •**The lower limit** of E subscript c is given by a similar, **proportional equation** here in blue. Interestingly this equation is expressed in reciprocal terms.
- •Again the overall effect of a greater volume of particles is to produce a stiffer composite.
- •When experimental data for a Cu matrix reinforced with tungsten particles is plotted as seen here we see excellent agreement with the theory as the values all fall between the two limits.

Composite Materials



Dr. Abbas Hasan Faris

Lecture 4

- **Fiber- reinforcement composite:-** A composite in which the dispersed phase is in the form of **fiber** (i.e., a filament that has a large length-to-diameter ratio). for example, **straw-reinforced clay bricks**.
- Fiber reinforcement of material is **very effective** because many materials (but not all) are **much stronger and stiffer** in **fiber** form than they are in bulk form.

- Fibers allow one to obtain the **maximum tensile strength and stiffness** of a material, but there are disadvantages. Fibers alone cannot support **longitudinal compressive loads** and their **transverse** mechanical properties are generally **not as good** as the corresponding **longitudinal** (fiber direction) properties. Thus, there is often the need to **place fibers in different directions** depending upon the **particular loading application**.

A fibrous reinforcement is characterized by its length being much greater than its cross-sectional dimension. However, the ratio of length to the cross-sectional dimension, known as the aspect ratio, can vary considerably. In single-layer composites long fibres with high aspect ratios give what are called *continuous* fibre reinforced composites, whereas *discontinuous* fibre composites are fabricated using short fibres of low aspect ratio (block C). The orientation of the discontinuous fibres may be random or preferred (Figures 1.4 (b) and (c)). The frequently encountered preferred orientation in the case of a continuous fibre composite (Figure 1.4(d)) is termed *unidirectional* and the corresponding random situation can be approximated to by *bidirectional* woven reinforcement (Figure 1.3, block D).

Multilayered composites are another category of fibre reinforced composites. These are classified as either laminates or hybrids (block E). *Laminates* are sheet constructions which are made by stacking layers (also called plies or laminae and usually unidirectional) in a specified sequence. A typical laminate may have between 4 to 40 layers and the fibre orientation changes from layer to layer in a regular manner through the thickness of the laminate, e.g., a 0/90° stacking sequence results in a *cross ply* composite.

Hybrids are usually multilayered composites with mixed fibres and are becoming commonplace. The fibres may be mixed in a ply or layer by layer and these composites are designed to benefit from the different properties of the fibres employed. For example, a mixture of glass and carbon fibres incorporated into a polymer matrix gives a relatively inexpensive composite, owing to the low cost of glass fibres, but with mechanical properties enhanced by the excellent stiffness of carbon. Some hybrids have a mixture of fibrous and particulate reinforcement.

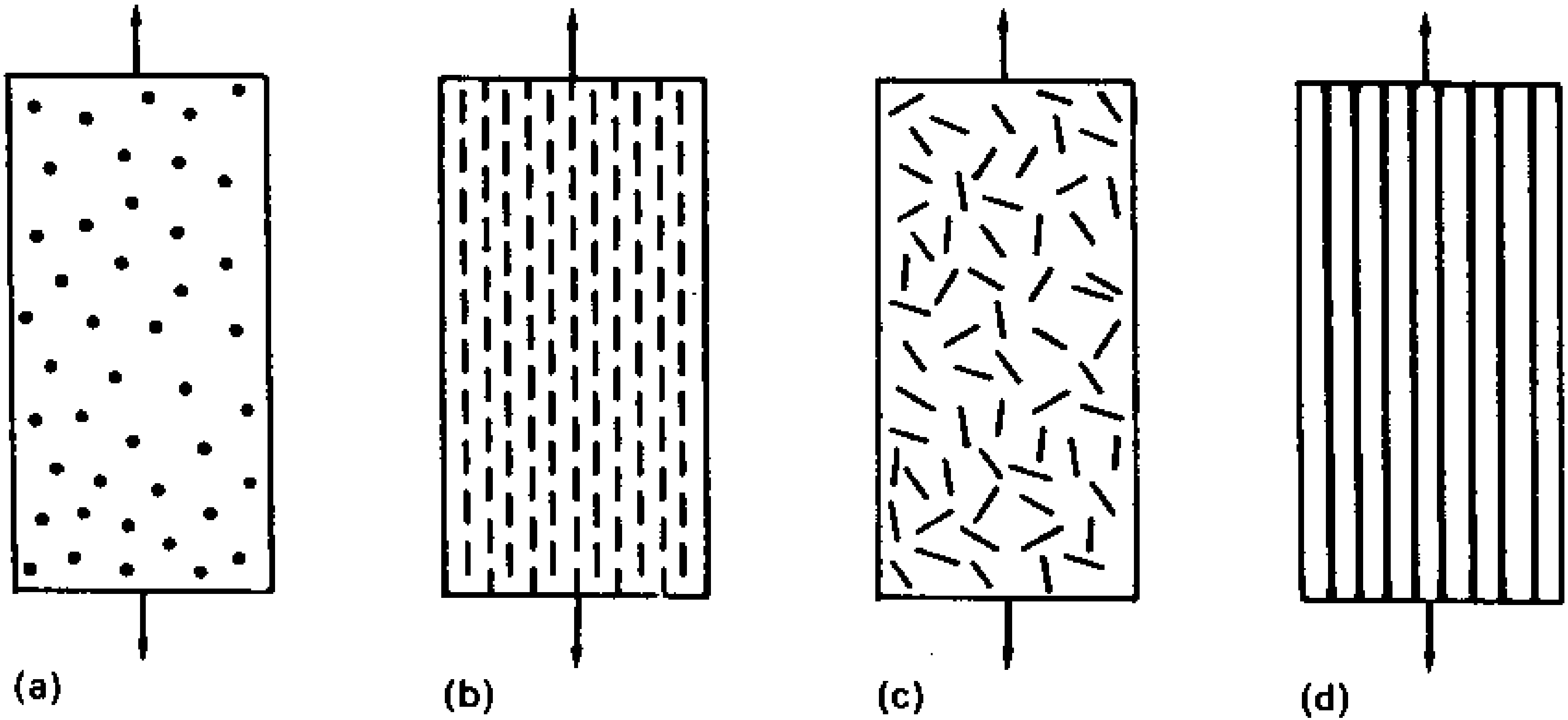
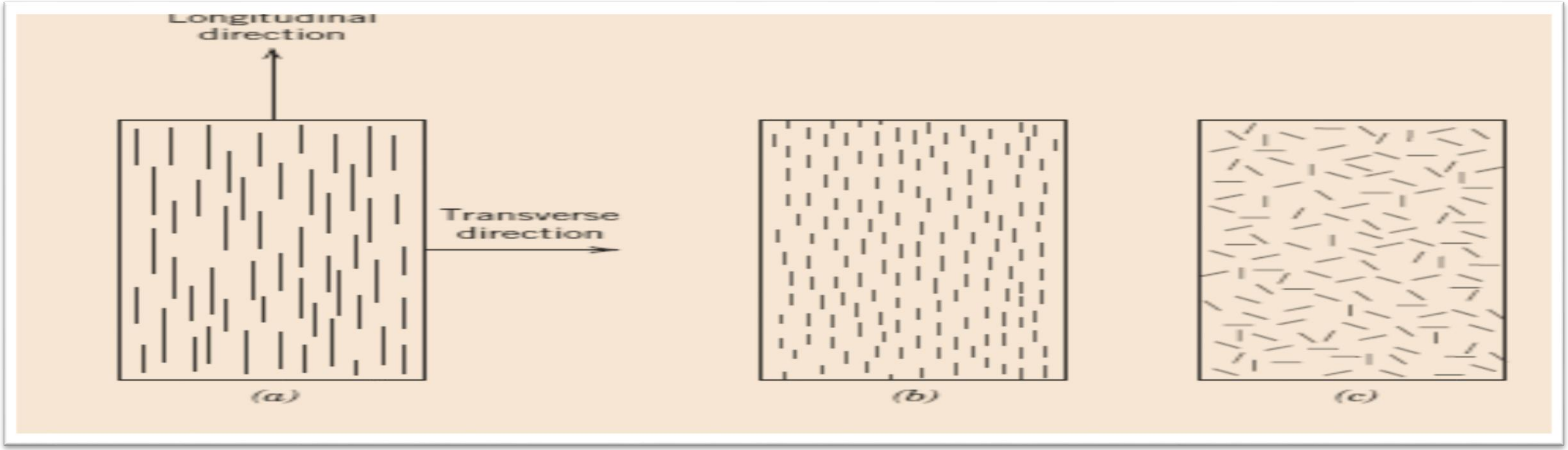


Figure 1.4 Examples of composites: (a) particulate, random; (b) discontinuous fibres, unidirectional; (c) discontinuous fibres, random; (d) continuous fibres, unidirectional.

- **Fibers** are the **most common** in composites and have the **most influence on properties**. Fiber has a **length** that is **much greater** than its **diameter**. The length-to-diameter **(l/d)** ratio is known as the aspect ratio and can **vary greatly**. Continuous fibers have long aspect ratios, the large aspect ratio of the fiber gives rise to effective shear stress transfer between the matrix and the reinforcement, while discontinuous fibers have short aspect ratios. Continuous-fiber composites normally have a preferred orientation, while discontinuous fibers generally have an aligned (preferred) or random orientation. As shown in figure



- Technologically, the most important composites are those in which the dispersed phase is in the form of a **fiber**. Design goals of fiber-reinforced composites often **include high strength and/or stiffness on a weight basis**. These characterizations are expressed in terms of **specific strength and specific modulus parameters**, which correspond, respectively, to the ratios of tensile strength to specific gravity and modulus of elasticity to specific gravity. Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that use low-density fiber and matrix materials.

- The main reasons for using fibers of thin diameter are the following:
- The 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 a strength of 100 ksi (689 MPa), while a wire made from this steel plate can have a strength of 600 ksi (4100 MPa). Figure 1.6 shows how the strength of a carbon fiber increases with the decrease in its diameter.

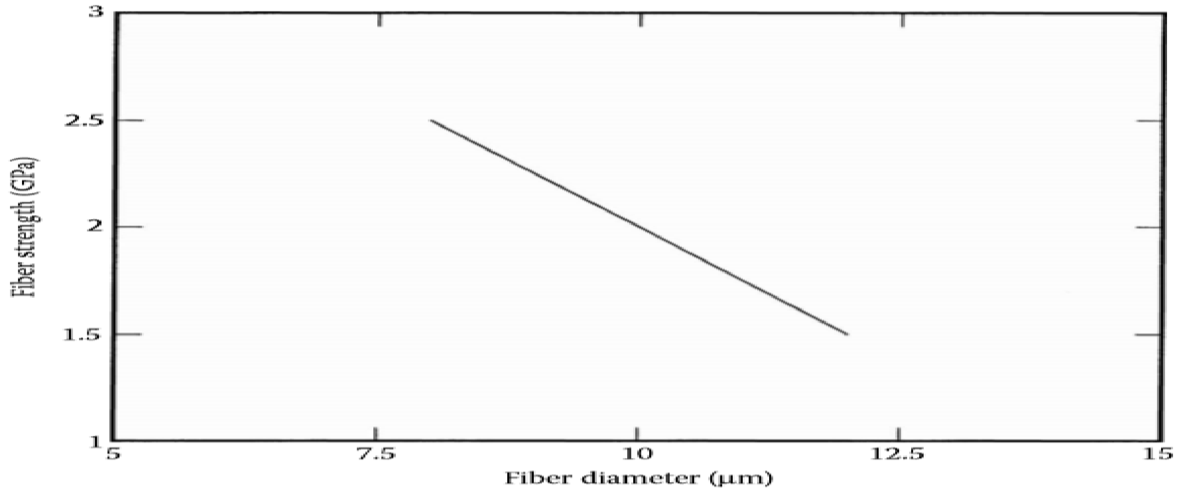


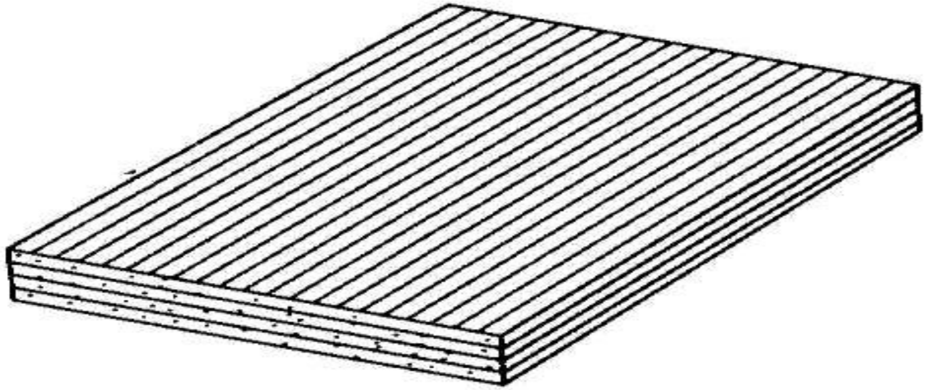
FIGURE 1.6
Fiber strength as a function of fiber diameter for carbon fibers. (Reprinted from Lamotte, E. De, and Perry, A.J., *Fibre Sci. Technol.*, 3, 159, 1970. With permission from Elsevier.)

- Fibers able to **bend without breaking** are required in the 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.

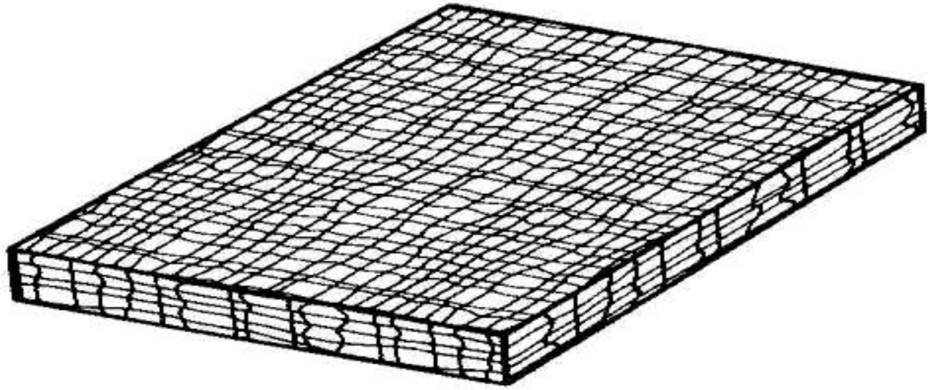
- Flexibility is defined as the **inverse of bending stiffness** and is proportional to the inverse of the product of the elastic modulus of the fiber and the fourth power of its diameter.

❖ Types of Fiber-Reinforced Composites

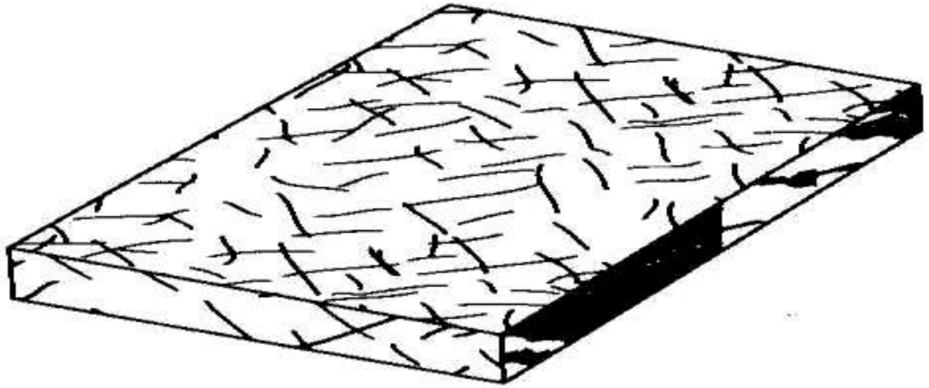
- One generally finds four types of fiber-reinforced composites as shown below . They differ in how the fibers are utilized to make the composite (**orientation** and **length of fibers**).



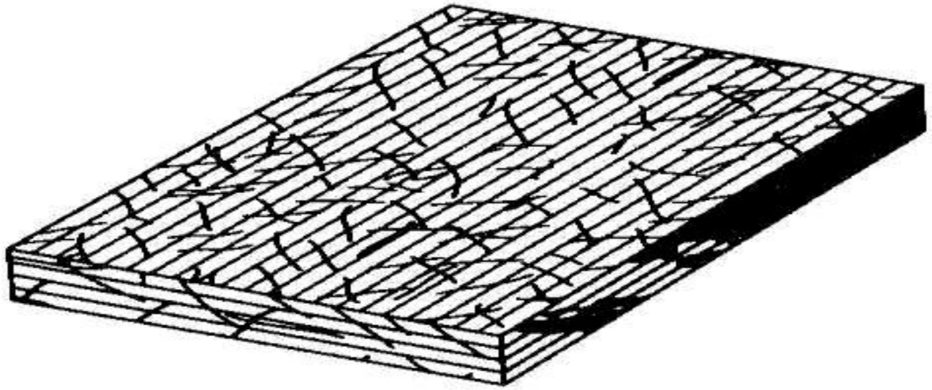
(a) Continuous fiber composite



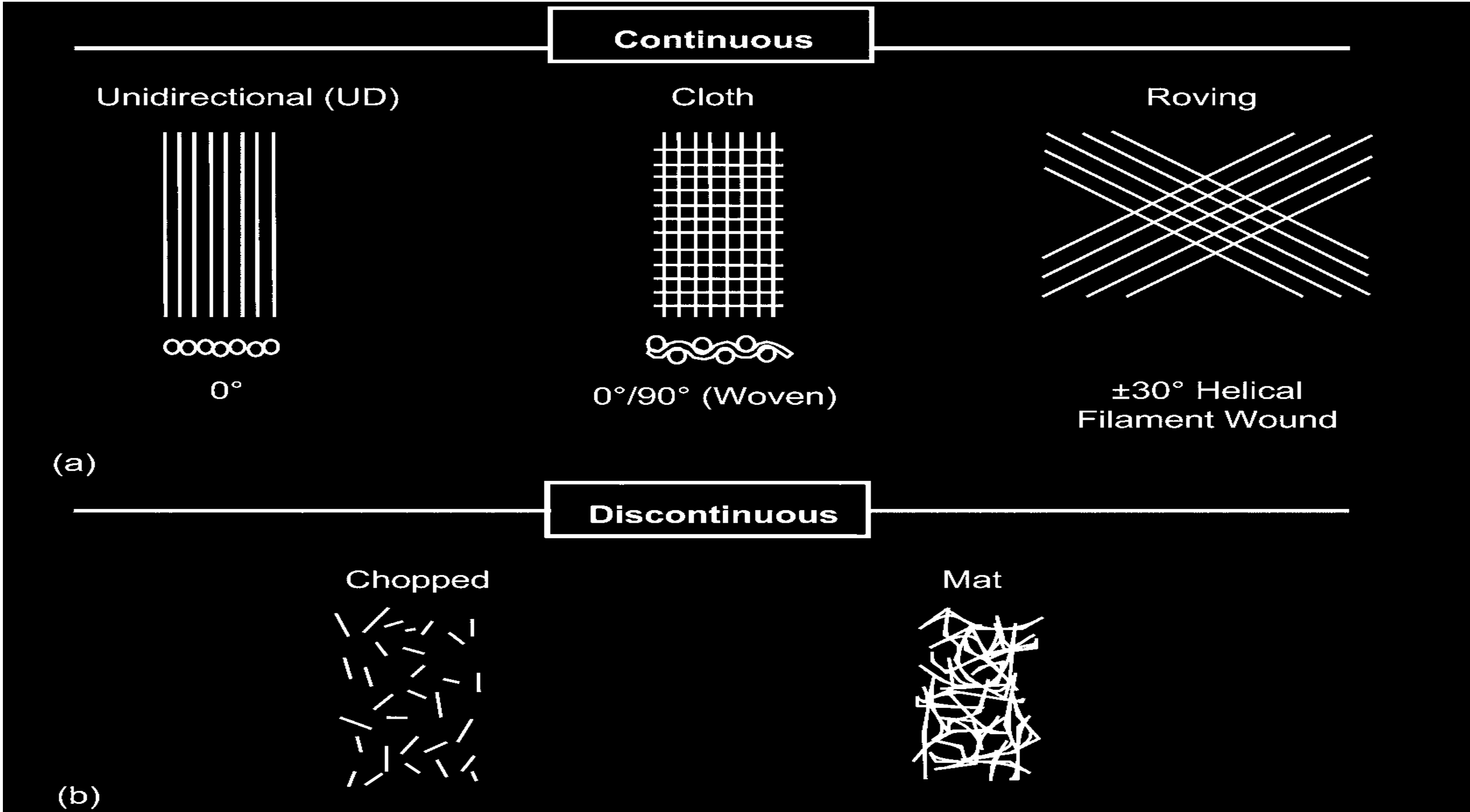
(b) Woven fiber composite



(c) Chopped fiber composite



(d) Hybrid composite


Continuous
Unidirectional (UD)
Cloth
Roving
0°
0°/90° (Woven)
±30° Helical
Filament Wound
(a)
Discontinuous
Chopped
Mat
(b)

1- Continuous fiber composites are generally "laid-up" in plies (or laminae) with each ply having fibers oriented in the same direction. A layer of fibers all oriented in the same direction is embedded in a homogeneous material (called the matrix) to make a single ply or laminae. For example, glass-epoxy has a layer of glass fibers running more-or-less parallel within an epoxy resin matrix material.

2- Woven fiber composites are **similar to ordinary cloth** used in the textile industry. The woven fiber may be 2-D (fibers interwoven in 2 directions) or 3-D (fibers interwoven in 3 directions). Woven fiber composites do not generally have distinct laminae and are not nearly as susceptible to delamination; however, **strength and stiffness** are sacrificed due to the fact that the fibers are not as straight (because of the weaving) as in the continuous fiber laminate.

•

3- Chopped fiber composites have fibers that are relatively short and have a random orientation and distribution of fibers. Chopped fiber composites generally have mechanical properties that are considerably **poorer** than those of continuous fiber composites. However, they are cheaper to manufacture and are used in high-volume applications.

4- Hybrid composites generally consist of mixed chopped and continuous fibers; or mixed fiber types such as glass/graphite.

The mechanical characteristics of FRC depend on the following

1. Properties of fiber

2. Interfacial bond between fiber and matrix

3. Fiber length like longer gives continuous, shorter length gives discontinuous or random. Reinforcement efficiency of continuous is higher than short fibers.

4. Fiber orientation and concentration, if it is orderly orientation and continuous it is highly anisotropic or discontinuous or random orientation,

- **Continuous fibers** have **long aspect ratios**, while **discontinuous fibers** have **short aspect ratios.** Continuous-fiber composites normally have a **preferred orientation**, while discontinuous fibers generally have a **random orientation**. examples of continuous reinforcements include **unidirectional woven cloth**, and **helical winding**, while examples of discontinuous reinforcements are **chopped fibers** and **random mat** . Continuous-fiber composites are often made into laminates by stacking single sheets of continuous fibers in different orientations to obtain the desired strength and stiffness properties with fiber volumes as high as 60 to 70 percent.
- As the fibers become **smaller in diameter**, the chances of an **inherent defect** in the material are **reduced**.

Fibers produce high-strength composites because of their **small diameter**; they contain far fewer defects (normally surface defects) compared to the material produced in bulk.

- As a general rule, the **smaller the diameter** of the fiber, **the higher its strength**, but often the **cost increases** as the diameter becomes smaller. In addition, smaller-diameter high-strength fibers have **greater flexibility** and are more amenable to fabrication processes such as weaving or forming over radii. typical fibers include glass, aramid, and carbon, which may be continuous or discontinuous.

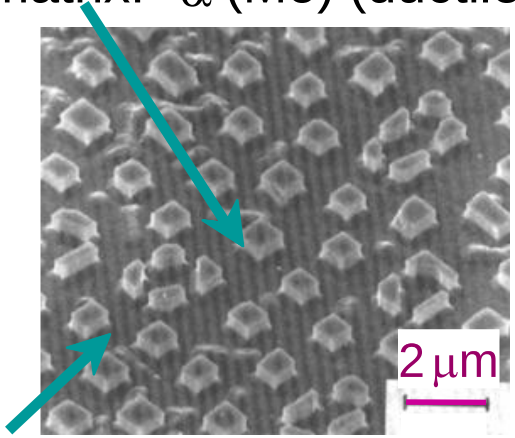
Classification: Fiber-Reinforced

Particle-reinforced | **Fiber-reinforced** | Structural

- Aligned Continuous fibers
- Examples:

-- Metal: $\gamma'(Ni_3Al)$-α(Mo)
by eutectic solidification.

matrix: α (Mo) (ductile)



fibers: γ' (Ni_3Al) (brittle)

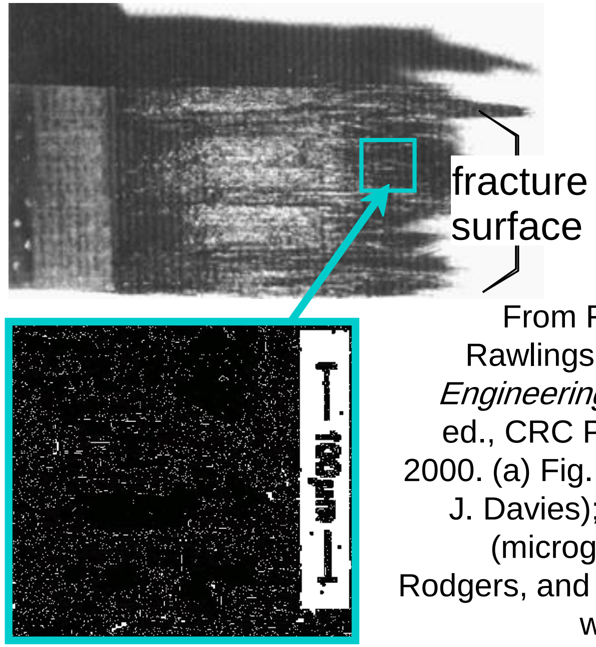
From W. Funk and E. Blank, "Creep deformation of Ni_3Al-Mo in-situ composites", *Metall. Trans. A* Vol. 19(4), pp. 987-998, 1988. Used with permission.

-- Ceramic: Glass w/SiC fibers
formed by glass slurry

E_{glass} = 76 GPa; E_{SiC} = 400 GPa.

(a)

(b)

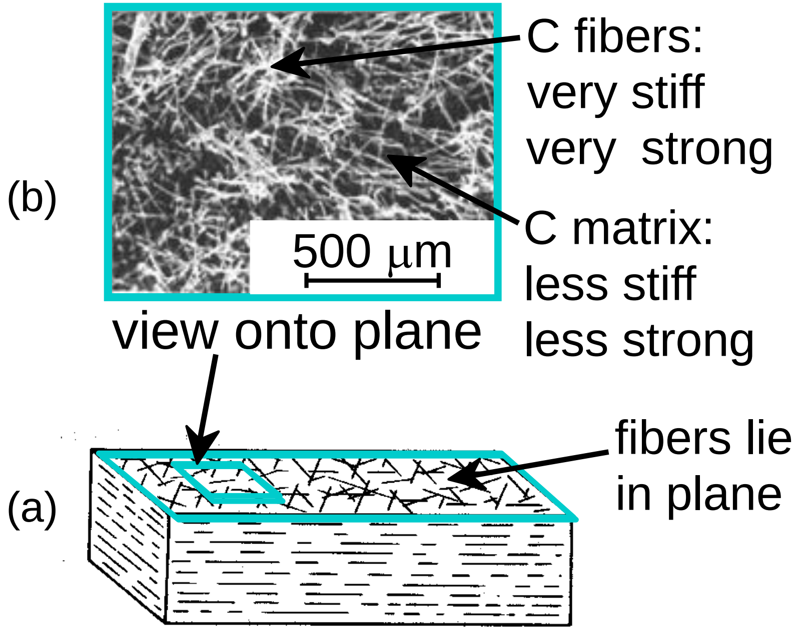


From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.22, p. 145 (photo by J. Davies); (b) Fig. 11.20, p. 349 (micrograph by H.S. Kim, P.S. Rodgers, and R.D. Rawlings). Used with permission of CRC Press, Boca Raton, FL.

Classification: Fiber-Reinforced

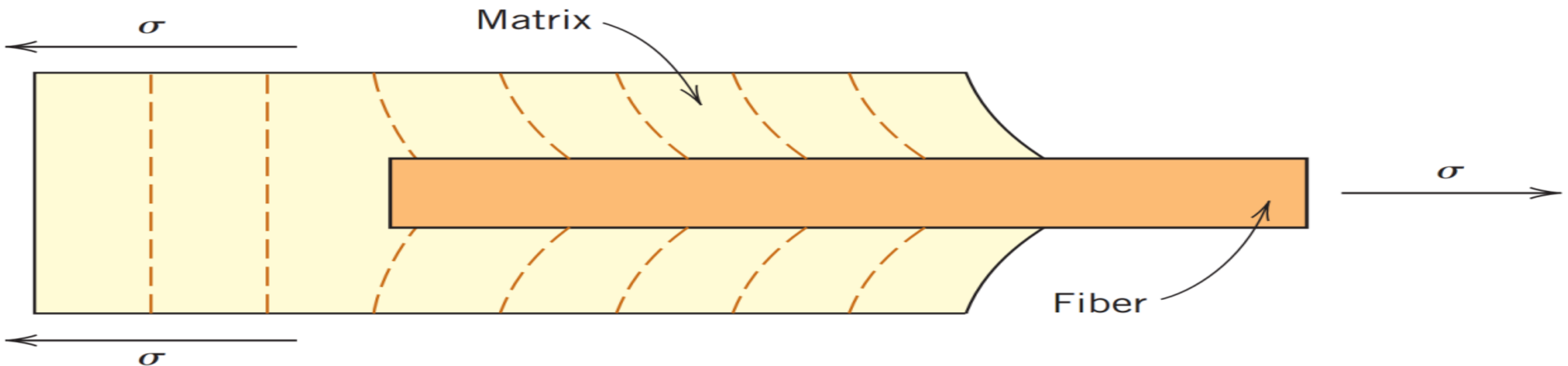
Particle-reinforced | **Fiber-reinforced** | Structural

- Discontinuous fibers, random in 2 dimensions
  - Example: Carbon-Carbon
    - -- fabrication process:
    - - carbon fibers embedded in polymer resin matrix,
    - - polymer resin pyrolyzed at up to 2500ºC.
    - -- uses: disk brakes, gas turbine exhaust flaps, missile nose cones.
  - Other possibilities:
    - -- Discontinuous, random 3D
    - -- Discontinuous, aligned

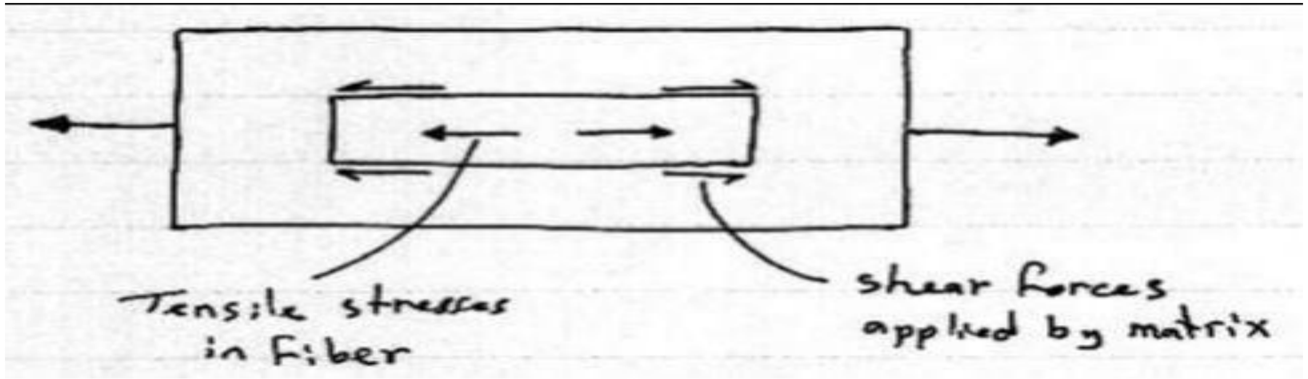


Adapted from F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151. (Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.

- **INFLUENCE OF FIBER LENGTH**
- The mechanical characterization of a fiber-reinforced composite depend not only on the **properties of the fiber** but also on the **degree** to which an **applied load** is transmitted to the fibers by the **matrix phase**. Important to the extent of this **load transmittance** is the magnitude of the **interfacial bond** between the fiber and matrix phases. Under **applied stress**, this **fiber-matrix bond** ceases at the **fiber ends**, yielding a **matrix deformation** pattern as shown in the figure below.
- Fig. the deformation pattern in the matrix surrounding a fiber that is subjected to an applied tensile load

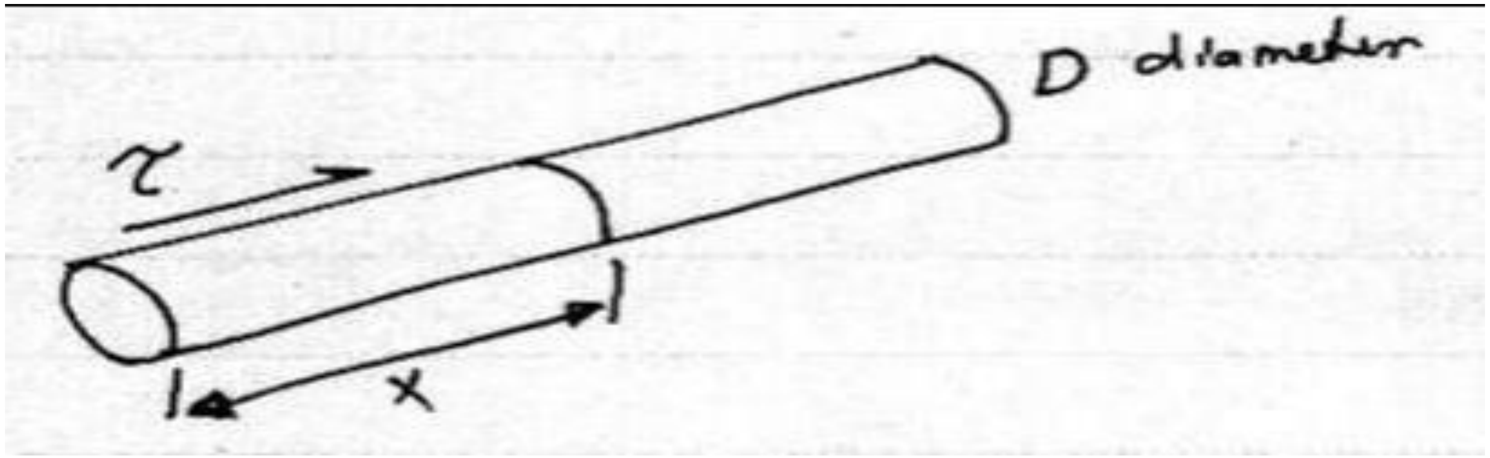


- When a **load is applied** to a **composite,** it is applied to the **matrix** and transferred to the **fibers** by some **combination of shear and tensile stresses** acting across the interface.



The main difference between shear stress and tensile stress is that tensile stress refers to cases where a deforming force is applied at right angles to a surface, whereas shear stress refers to cases where a deforming force is applied parallel to a surface.

- Consider the interfacial shear stress acting on a single fiber in a matrix in the following figure.



If (τ) is the average interfacial shear stress, then the shear force acting on a section of the fiber length (x) and of uniform cross-sectional diameter (D) is the :

Shear force =shear stress * area

$$= \tau * \pi D x$$

- This shear force is equal to normal force on the fiber, therefore
- The stress increases from zero at the end of a fiber, i.e. When (x=0), to its maximum possible value when (X= 0.5* Lc).

$$\sigma_f * \frac{1}{4}\pi D^2 = \tau * \pi D x$$

$$\sigma_f = \frac{4\tau x}{D}$$

Hence , the maximum value of the tensile stresses is given by:

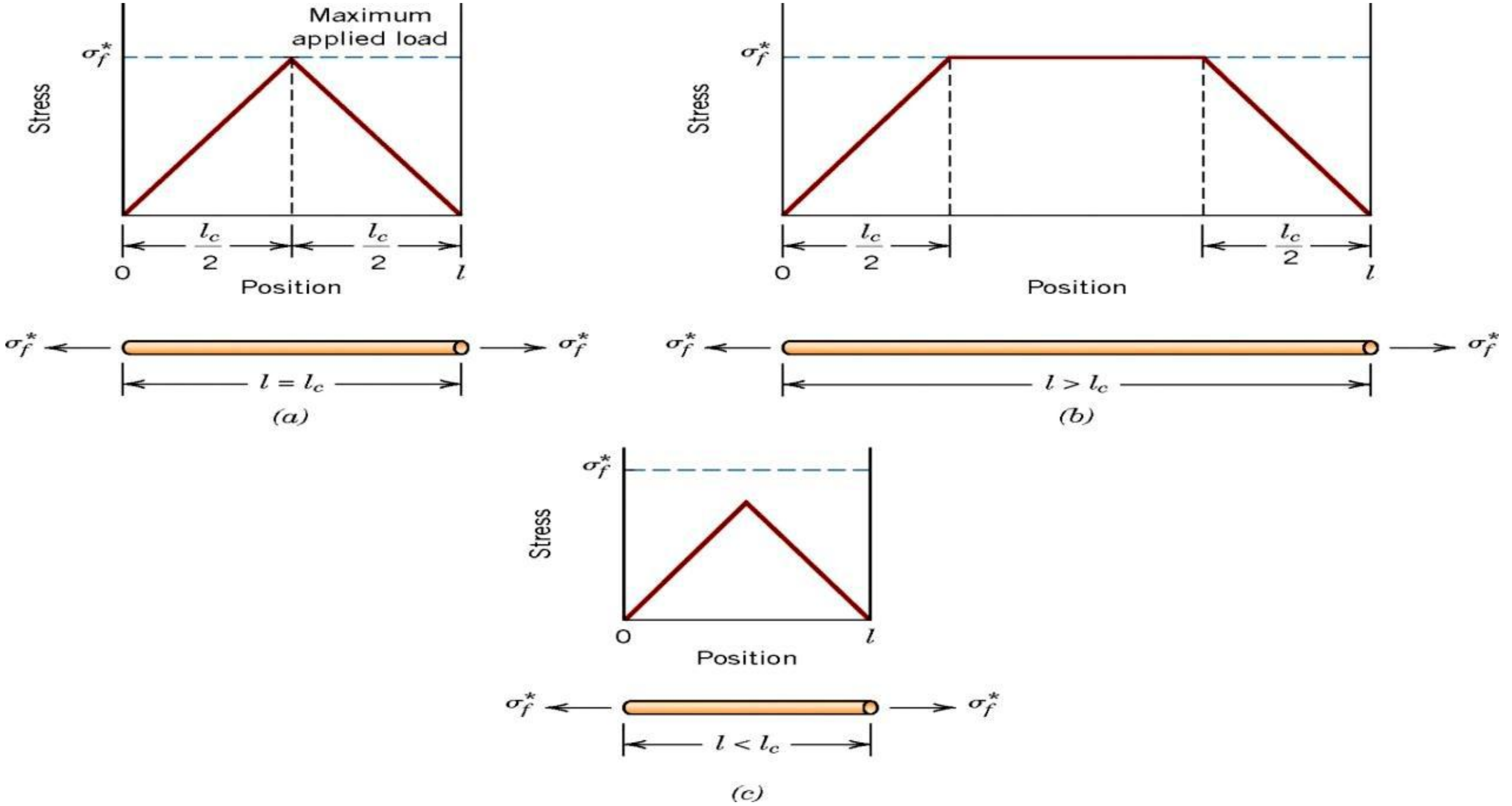
$\boldsymbol{Maximum\ \sigma f = 2 * \tau * Lc}$

- Then the **critical fiber length (Lc),** for any given fiber **diameter (D)** can be determined:

$$L_c = \frac{\sigma_f * D}{2 * \tau}$$

- **(τ) is the average interfacial shear stress**
- **(D)cross-sectional diameter**
- **(σf) ultimate (or tensile) strength**
- Some critical fiber length is necessary for **effective strengthening and stiffening** of the composite material.
- This critical length lc is dependent on the fiber **diameter** (d) and its ultimate (**or tensile**) strength (σ_f), and on the **fiber–matrix bond strength** (or the **shear strength** of the matrix.

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$



Maximum
applied load
σ_f^*
Stress
$\frac{l_c}{2}$
$\frac{l_c}{2}$
0
l
Position
σ_f^*
σ_f^*
$l = l_c$
(a)
σ_f^*
Stress
$\frac{l_c}{2}$
$\frac{l_c}{2}$
0
l
Position
σ_f^*
σ_f^*
$l > l_c$
(b)
σ_f^*
Stress
0
l
Position
σ_f^*
σ_f^*
$l < l_c$
(c)

- 1. **l = lc** , the maximum fiber load is achieved only at the **axial center** of
- the fiber.
- 2. **l > lc** , as fiber length increases, the fiber reinforcement becomes more effective. Therefore, fiber normally have **length > 15lc** .
- 3. **l < lc** , the matrix deforms around the fiber such that there is no **stress transference** and **little reinforcement by the fiber**

- **Critical fiber length—dependence** on fiber strength and diameter, and fiber–matrix bond strength/matrix shear yield strength load is achieved only at the axial center of the fiber. As fiber length (l) increases, the fiber reinforcement becomes more effective a stress–axial position profile for l > lc when the applied stress is equal to the fiber strength.

$$lc = \sigma_f d/2 \tau_c$$

where

- d = fiber diameter
- τ_c = fiber-matrix bond strength (shear strength of fiber-matrix interface)
- σ_f = fiber yield strength (fiber ultimate tensile strength)

Classification: Fiber-Reinforced

Particle-reinforced | **Fiber-reinforced** | Structural

- Critical fiber length for effective stiffening & strengthening:

fiber ultimate tensile strength

fiber diameter

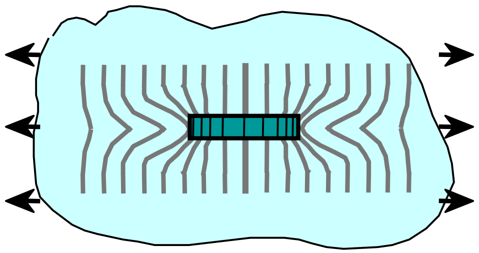
$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

shear strength of fiber-matrix interface

- Ex: For fiberglass, common fiber length > 15 mm needed
- For longer fibers, stress transference from matrix is more efficient

Short, thick fibers:

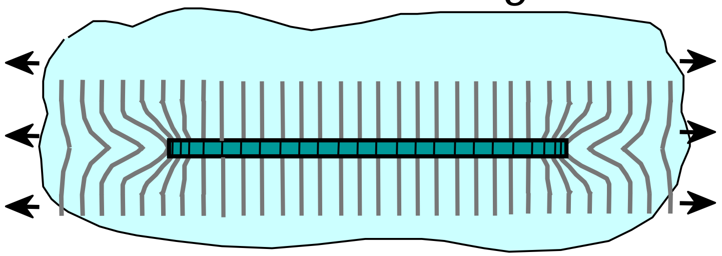
$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$



Low fiber efficiency

Long, thin fibers:

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$



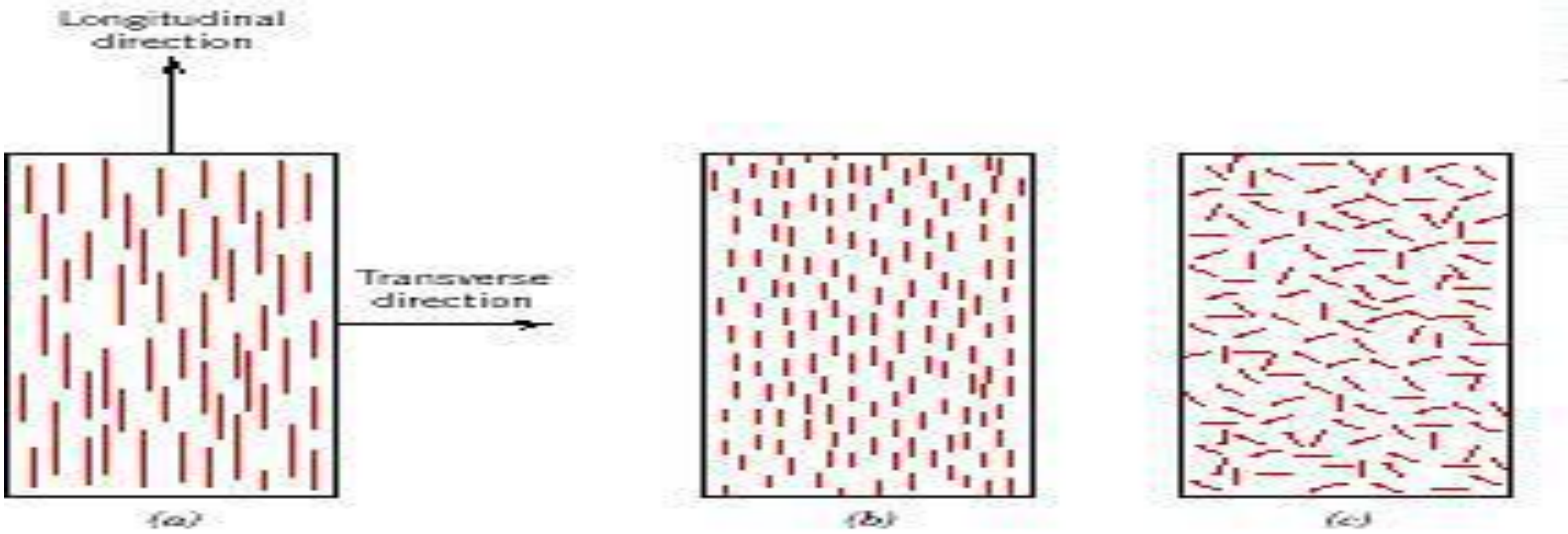
High fiber efficiency

- **Example (1)** A glass fiber polyester composite contains (60%) by volume of fibers. The fibers being of length (3mm) with diameter (0.005mm). If the failure stress for the fibers is (1500 MPa), the shear strength (25 MPa), and the matrix has a tensile strength of (50 MPa) . Determine Critical length of the fiber.

- **Solution**

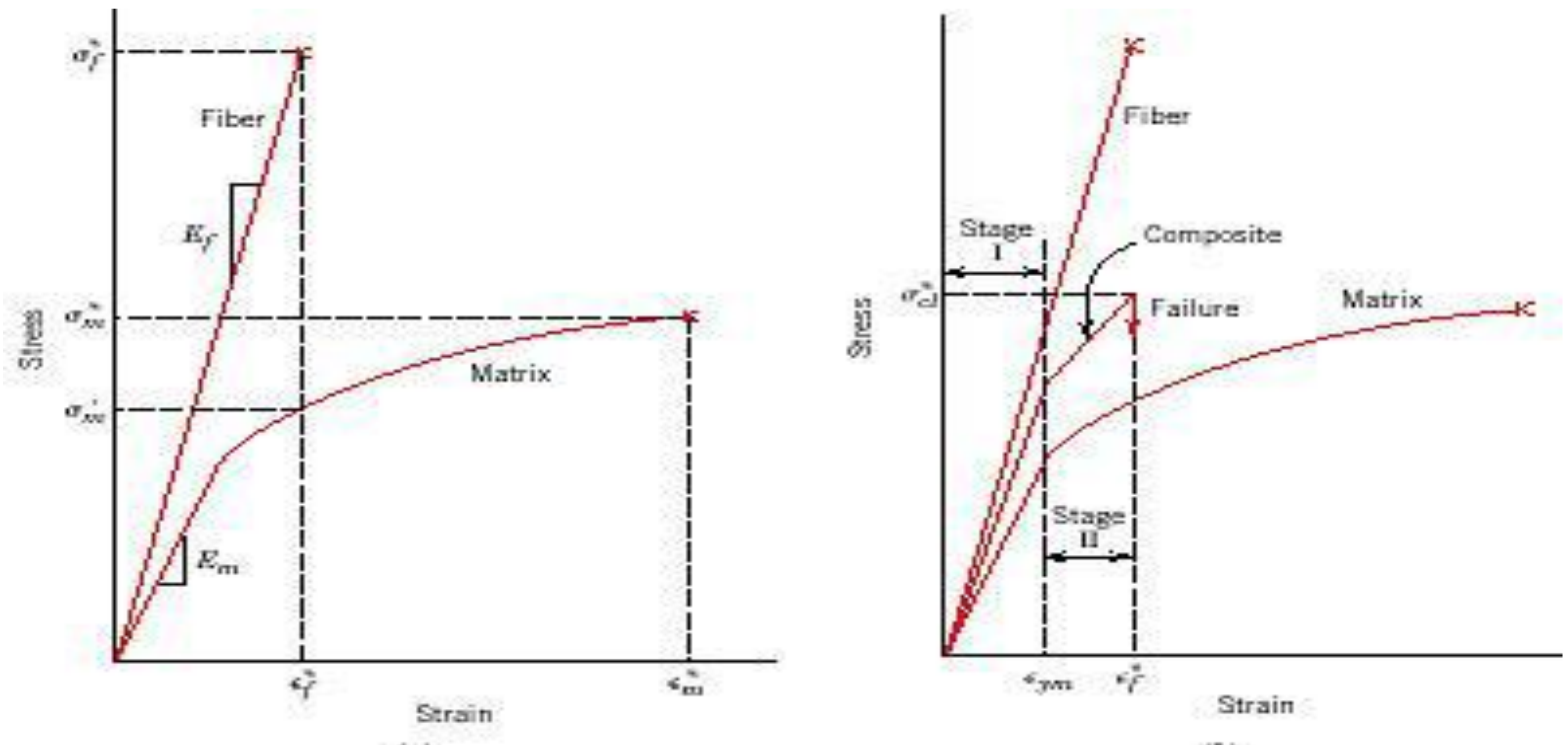
$$Lc = \frac{\sigma_f * D}{2\tau} = \frac{1500 * 0.005}{2 * 25} = 0.15mm$$

- **INFLUENCE OF FIBER ORIENTATION AND CONCENTRATION**
- The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. With respect to orientation, two extremes are possible:
- (1) a parallel alignment of the longitudinal axis of the fibers in a single direction.
- (2) a totally random alignment.
- (3) some combination



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

Continuous fibers are normally aligned whereas discontinuous fibers may be aligned randomly oriented or partially oriented. Better overall composite properties are realized when the fiber distribution is uniform .



Stress
Fiber
E_f
E_m
Matrix
σ_f^*
σ_m^*
σ_m'
ϵ_f^*
ϵ_m^*
Strain
Stage I
Composite
Failure
Stage II
σ_{cl}^*
ϵ_{ym}

(a)
(b)

- The effects of arrangement or orientation of the fibers on composite properties
- Stage I - elastic deformation with intermediate
- Stage II - matrix yields
- Failure - Non-catastrophic. When fibers fracture, you now have a new fiber length and a matrix is still present.

- **Four fiber factors contribute to the mechanical performance of a**
- **composite are :**
- **1- 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.
- **2- • Shape:** The most common shape of fibers is circular because handling and manufacturing them is easy. Hexagon and square-shaped fibers are possible, but their advantages of strength and high packing factors do not outweigh the difficulty in handling and processing.

3- 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.

4- 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.

• Effect of fiber orientation on the tensile strength of E-glass fiber-reinforced epoxy composites.

- **Glass is a common reinforcement**
- - it is easily drawn into fibers
- - it is cheap and readily available
- - it is easy to process into composites
- -it can produce very strong, very light composites (high specific strength) it is usually chemically inert (does not degrade in environments)
- **When fibers are aligned**
- 1- properties of the material are highly anisotropic modulus in direction of alignment is a function of the volume fraction of the modulus of the fiber and matrix
- 2- modulus perpendicular to the direction of alignment is considerably less (the fibers do not contribute)

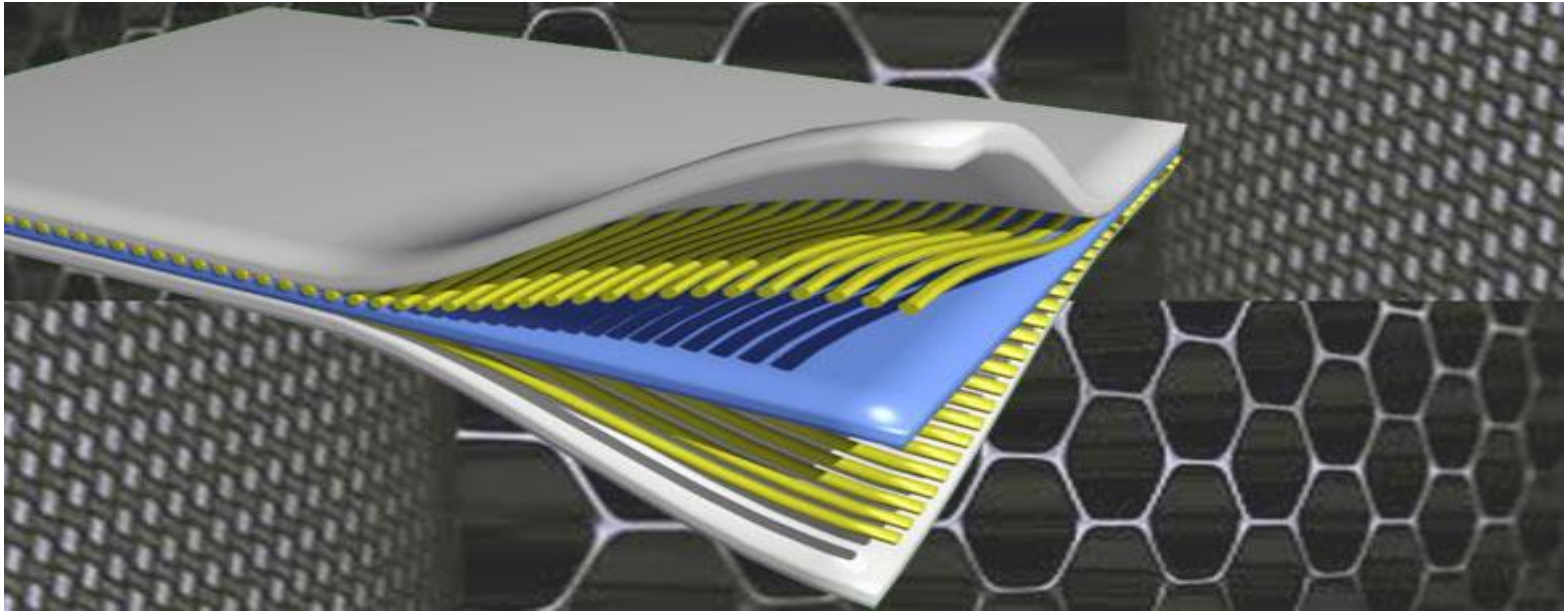
- **When fibers are randomly**
- 1- Properties are isotropic
- 2- not dependent on the direction
- 3- Ultimate tensile strength is less than for aligned fibers

- **Fiber Materials**
- **Glass fibers** consist primarily of silica (silicon dioxide) and metallic-oxide-modifying elements are generally produced by the mechanical drawing of molten glass through a small orifice. E-glass accounts for most of the glass fiber production and is the most widely used reinforcement for composites. The second most popular glass fiber, S-glass, has roughly 30 percent greater tensile strength and 20 percent greater modulus of elasticity than E-glass but is not as widely used because of its higher cost.

- **Graphite or carbon fibers** are the most widely used advanced fiber, and graphite/epoxy or carbon/epoxy composites are now used routinely in aerospace structures. The actual fibers are usually produced by subjecting organic precursor fibers such as polyacrylonitrile (PAN) or rayon to a sequence of heat treatments so that the precursor is converted to carbon by pyrolysis. Graphite fibers are typically subjected to higher heat treatments than carbon fibers. Carbon fibers are typically 90-95% carbon, whereas graphite fibers are at least 99% carbon.

- **Aramid polymer fibers**, produced primarily by E.I. duPont deNemours & Company under the tradename "Kevlar�," were originally developed for use in tires. The density of Kevlar is about half that of glass and its specific strength is among the highest of currently available fibers. Kevlar also has excellent toughness, ductility, and impact resistance; unlike brittle glass or graphite fibers.

Composite Materials



Dr. Abbas Hasan Faris

Lecture 5

MATRIX

As discussed, composites are made of reinforcing fibers and matrix materials. **The matrix** is basically a homogeneous material in which a fiber system of a composite is embedded. **It is completely continuous**. Matrix **surrounds** the fibers and thus protects those fibers against chemical and environmental attack. For fibers to carry the maximum load, **the matrix must have a lower modulus and greater elongation than the reinforcement**.

Matrix selection is performed based on **chemical, thermal, electrical, flammability, environmental, cost, performance, and manufacturing requirements**. The matrix determines the service operating temperature of a composite as well as processing parameters for part manufacturing.

.

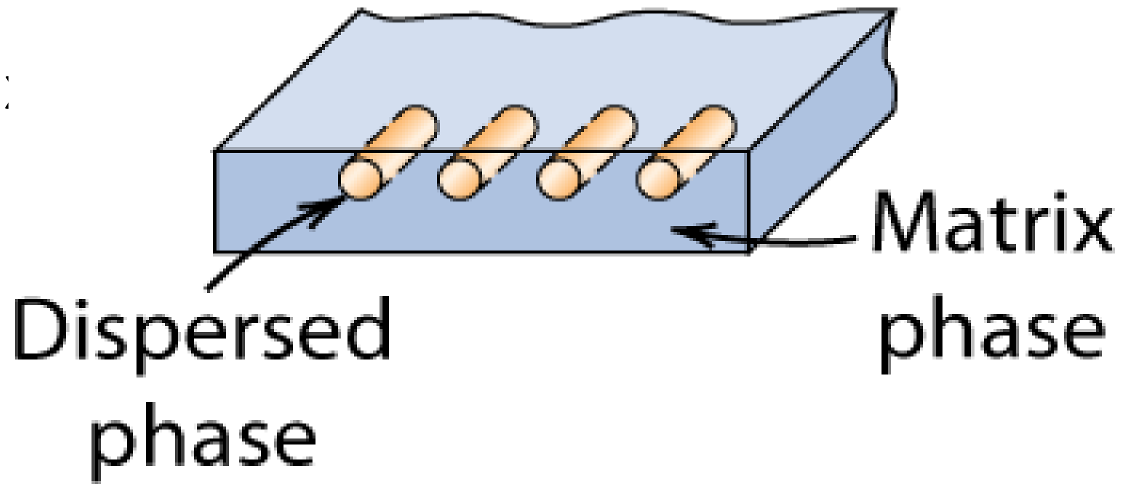
Types of Composite Matrix Materials:-

There are three main types of composite matri

1- Metal matrix composites (MMC)

2- Ceramic matrix composites (CMC)

3- Polymer matrix composite (PMC)



- The functions of a matrix:-
- 1. **binding and holding reinforcements together** into a solid
- 2. **offers protection to the reinforcements from environmental damage**
- 3. Protects the **reinforcements** from abrasion
- **4. Helps to maintain the distribution of reinforcements**
- **5. Distributes the loads evenly between reinforcements**
- 6. Enhances some of the properties of the resulting material and structural component (that fiber alone is not able to impart). These properties are such as:
  - **transverse strength of a lamina**
  - **Impact resistance**
- 7. Provides better finish to final product

- **1- Metal matrix** - Metal matrix composites (MMCs) are composite materials that contain at least two constituent parts – **a metal** and **another material** or a **different metal**. The metal matrix is reinforced with other materials to improve strength and wear. Where three or more constituent parts are present, it is called a **hybrid composite**. In structural applications, the matrix is usually composed of a lighter metal such as magnesium, titanium, or aluminum. In high-temperature applications, cobalt and cobalt-nickel alloy matrices are common. Typical MMC manufacturing is basically divided into three types: solid, liquid, and vapor. Continuous carbon, silicon carbide, or ceramic fibers are some of the materials that can be embedded in a metallic matrix material. MMCs are fire resistant, operate in a wide range of temperatures, do not absorb moisture, and possess better electrical and thermal conductivity. They have also found applications to be resistant to radiation damage, and to not suffer from outgassing. Most metals and alloys make good matrices for composite applications.

- **2- Ceramic matrix** - Ceramic matrix composites consist of ceramic fibers embedded in a ceramic matrix, thus forming a ceramic fiber-reinforced ceramic (CFRC) material. The matrix and fibers can consist of any ceramic material. CMC materials were designed to overcome the major disadvantages such as low fracture toughness, brittleness, and limited thermal shock resistance, faced by traditional technical ceramics.
- **3- Polymer matrix** - Polymer matrix composites (PMCs) can be divided into two main sub-types, namely, thermoset and thermoplastic. A polymer is a large molecule composed of repeating structural units connected by covalent chemical bonds. PMC consists of a polymer matrix combined with a fibrous reinforcing dispersed phase. They are cheaper with easier fabrication methods. PMC is less dense than metals or ceramics, can resist atmospheric and other forms of corrosion, and exhibit superior resistance to the conduction of electrical current.

- In general, metals and polymers are used as matrix materials because some **ductility (flexibility)** is desirable; for ceramic-matrix composites, the reinforcing component is added to **improve fracture toughness**.
- The matrix phase serves several functions
- **First**, it binds the fibers together and acts as the medium by which an **externally applied stress** is transmitted and distributed to the fibers; only a very small proportion of an applied load is sustained by the matrix phase. Furthermore, the matrix material should be **ductile**. In addition, the elastic modulus of the fiber should be much higher than that of the matrix. That's mean
- **For fibers to carry the maximum load, the matrix must have a lower modulus and greater elongation than the reinforcement.**
- **The second** function of the matrix is to protect the individual fibers from surface damage as a result of mechanical abrasion or chemical reactions with the environment. Such interactions may introduce surface flaws capable of forming cracks, which may lead to failure at low tensile stress levels.
- **Finally,** the matrix separates the fibers and, based on its relative softness and malleability, prevents the propagation of brittle cracks from fiber to fiber, which could result in catastrophic failure; in other words, the matrix phase serves as a barrier to crack propagation.

Polymer Matrix Composites (PMCs)

Any material can serve as a matrix material for composite. However, matrix materials are generally ceramics, metals, and polymers. In reality, the majority of matrix materials that exist on the composites market are **polymer .**

A polymer is any of a class of **natural or synthetic substances** composed of very large molecules, called macromolecules, which are multiples of simpler chemical units called monomers. Polymers make up many of the materials in living organisms and are the basis of many minerals and man-made materials.

Thermoplastics

Tough; high melt viscosity; and recyclable

Thermosets

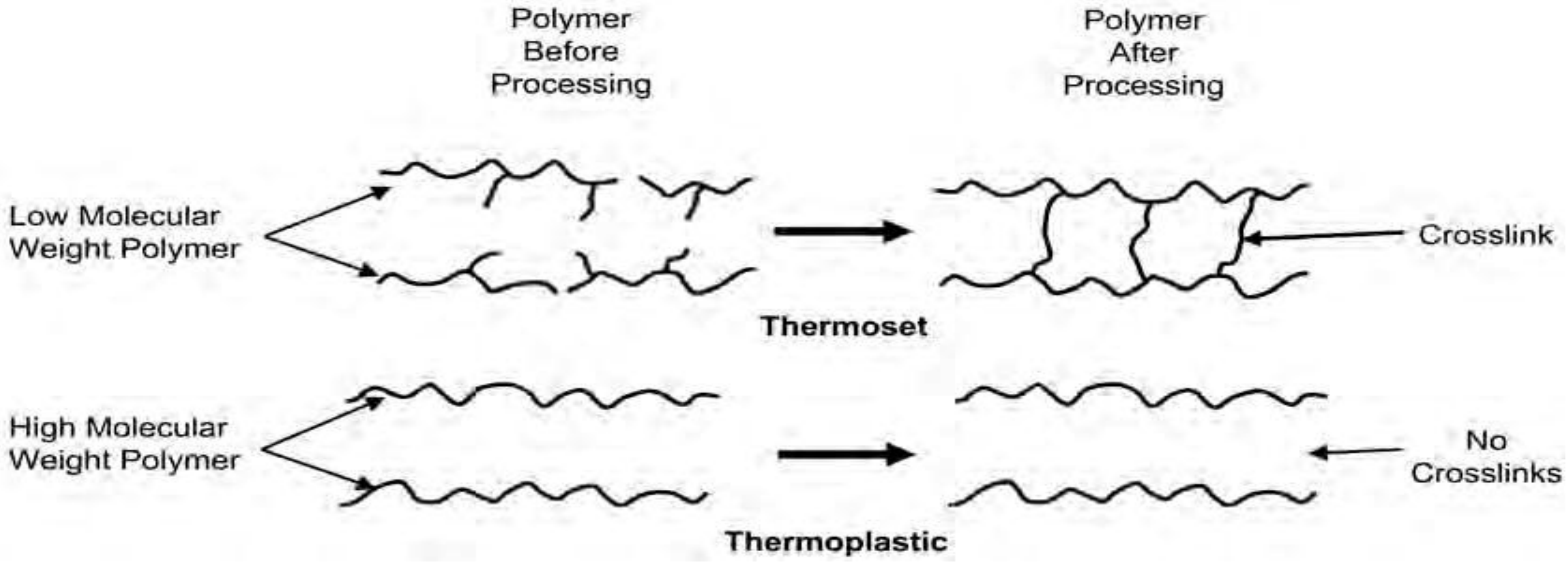
Brittle; low viscosity before cure;
not recyclable

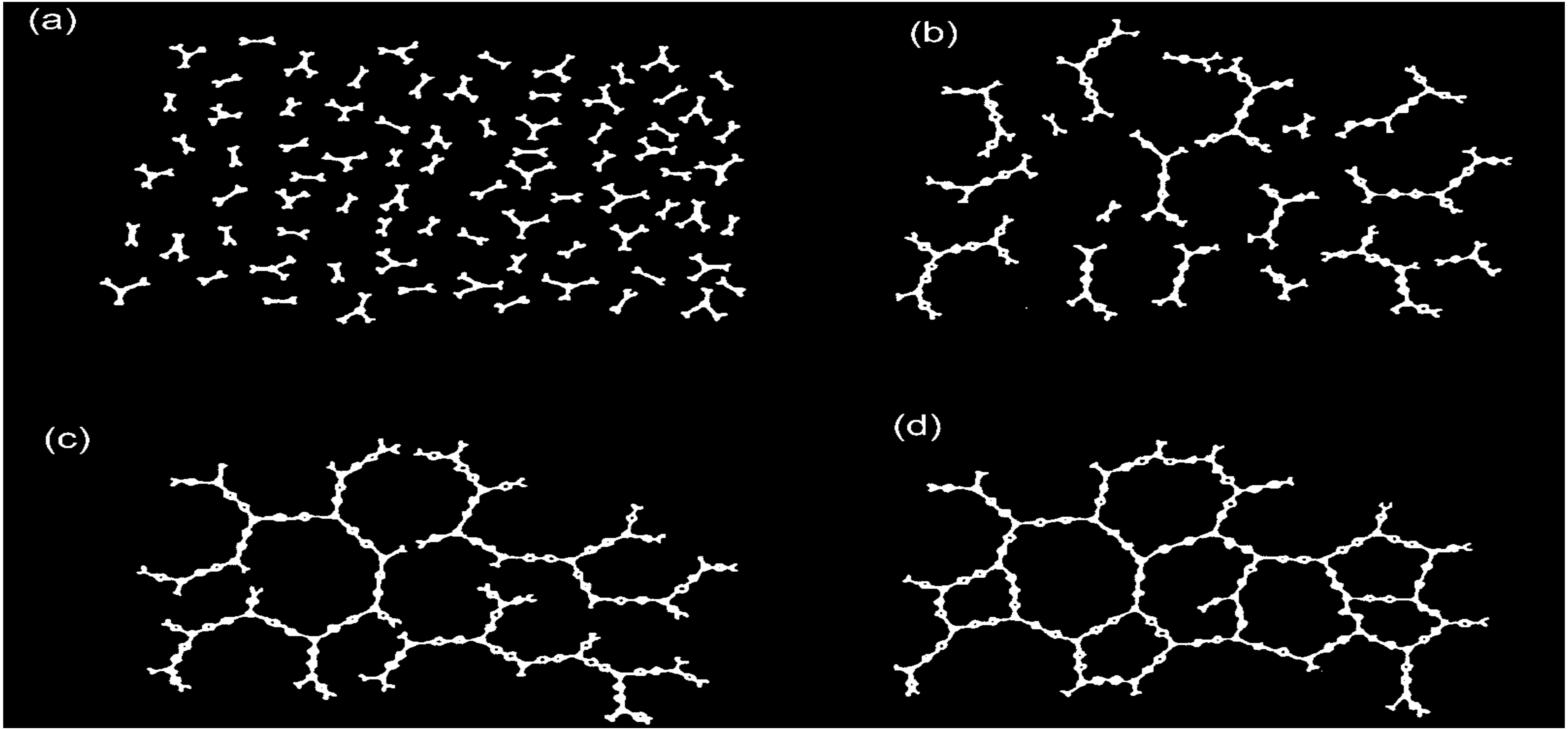
- There are several different polymer matrices that can be utilized in composite materials. Among the polymer matrix composites, **thermoplastic** matrix composites are more dominant than **thermoset** composites. Though thermosets and thermoplastics sound similar, they have very different properties and applications. Understanding the performance differences can help to make better sourcing decisions and the product designs as composites.

- **Thermosets** are materials that undergo a chemical reaction or curing and normally transform from a liquid to a solid. In its uncured form, the material has small, unlinked molecules known as monomers. The addition of a **second material** as a cross-linker, curing agent, catalyst, and/or the presence of heat or some other activating influences will **initiate the chemical reaction or curing reaction**. During this reaction, the molecules cross-link and form significantly longer molecular chains and cross-link networks, causing the material to solidify. The change in the thermoset state is **permanent and irreversible**. Thereafter, exposure to high heat after solidifying will cause the material to degrade, not melt. This is because these materials typically degrade at a temperature below where they would be able to melt.

- **Thermoplastics** are melt-processable plastics. Thermoplastic materials are processed with heat. When enough heat is added to bring the temperature of the plastic above its melting point, the plastic melts liquefies or softens enough to be processed. When the heat source is removed and the temperature of the plastic drops below its melting point, the plastic solidifies back into a glass-like solid. This process can be repeated, with the plastic melting and solidifying as the temperature climbs above and drops below the melting temperature, respectively. However, the material can be increasing subject to deterioration in its molten state, so there is a practical limit to the number of times that this reprocessing can take place before the material properties begin to suffer. Many thermoplastic polymers are addition-type, capable of yielding very long molecular chain lengths or very high molecular weights.

- **Thermoplastic**: Soften upon heating and can be reshaped with heat &
- pressure
- **Thermosetting**: become cross linked during fabrication & do not
- soften upon reheating





Stages of a cure for thermoset resin. (a) Polymer and curing agent prior to reaction. (b) Curing is initiated with the size of molecules increasing. (c) Gelation with full network formed. (d) Full cured and crosslinked.

Polymer Matrix Composites

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.

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.

The Typical Mechanical Properties Of Some Polymer Matrix Composites?

Compare these properties with metals. Table blow gives typical mechanical properties of common polymer matrix composites.

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

- **Thermoplastics:**
- polypropylene,
- polyvinyl chloride (PVC),
- nylon,
- polyurethane,
- poly-ether-ether ketone (PEEK),
- polyphenylene sulfide (PPS),
- Polysulpone

- higher toughness
- high volume
- low-cost processing
- Temperature range ≥ 225ºC

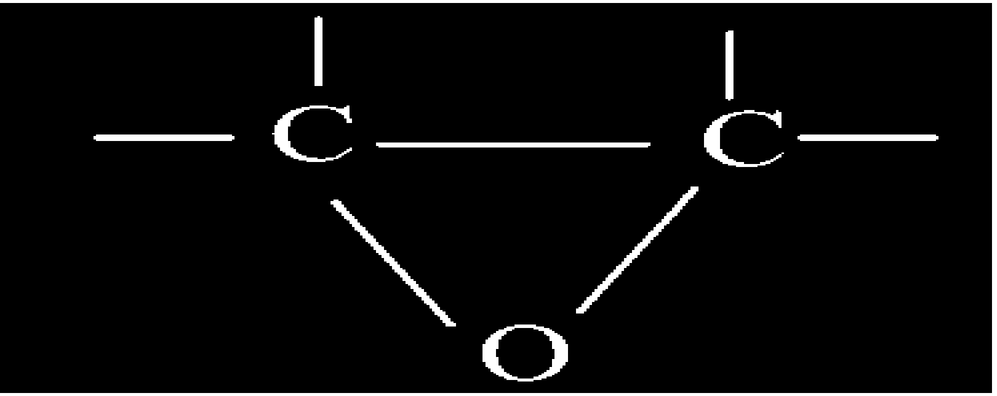
- Thermoplastics:
- Thermoplastics are increasingly used over thermosets becuase of the following reasons:
- • Processing is faster than thermoset composites since no curing reaction is required. Thermoplastic composites require only heating, shaping, and cooling.
- • Better properties:
  - - high toughness (delamination resistance) and damage tolerance,
  - - low moisture absorption
  - - chemical resistance
- • They have low toxicity.
- • Cost is high

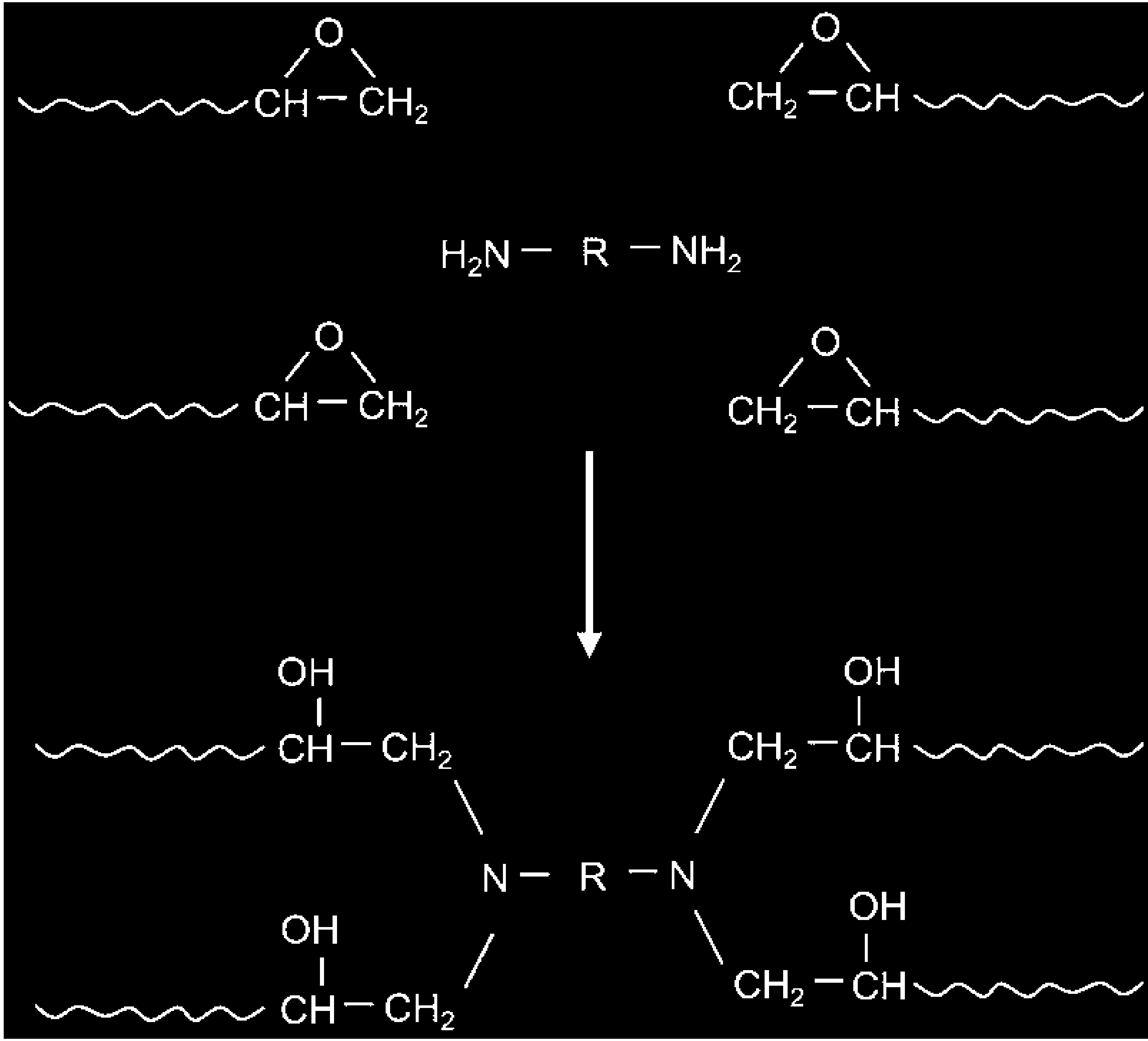
- **Thermosets:**
- **polyesters,**
- **epoxies,**
- **polyimides**
- **Other resins**

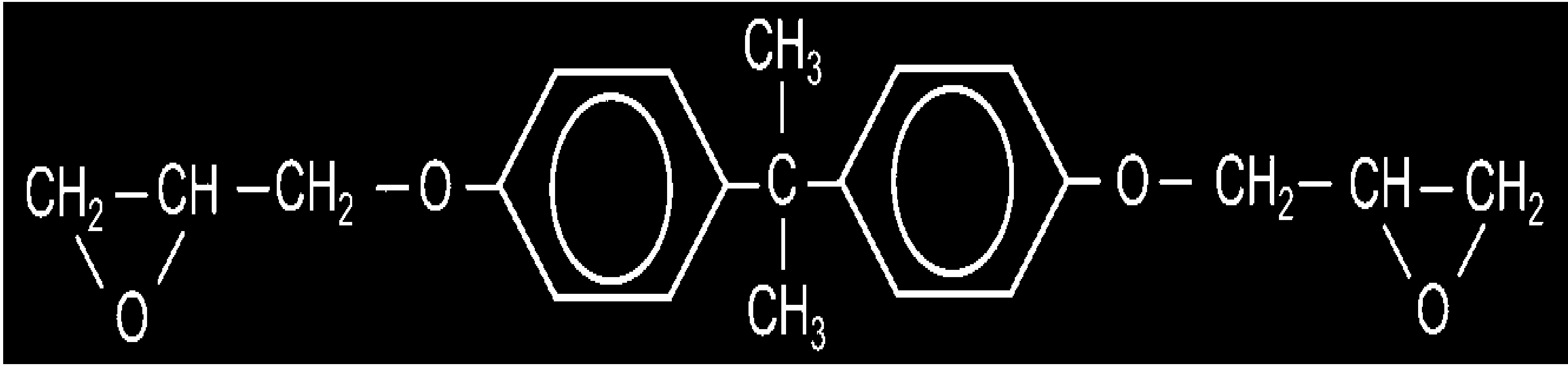
- **Epoxy Resin:**
- • Epoxy resins are widely used for most advanced composites. Epoxies are the most common matrix material for high-performance composites and adhesives. They have an excellent combination of strength, adhesion, low shrinkage, and processing versatility. Commercial epoxy matrices and adhesives can be as simple as one epoxy and one curing agent; however, most contain a major epoxy, one to three minor epoxies, and one or two curing agents.

- The minor **epoxies** are added to provide **viscosity control, impart higher elevated temperature properties, provide lower moisture absorption, or improve toughness.** Two main major epoxies are used in the aerospace industry. The first is diglycidyl ether of Bisphenol A (DGEBA), which is used extensively in filament winding, pultrusion, and some adhesives. The second is tetraglycidyl methylene dianiline (TGMDA), also known as tetraglycidyl-4,4-diaminodiphe-nylmethane (TGGDM), which is the major epoxy used for a large number of the commercial composite matrix systems.

- **The epoxy group, or oxirane ring, is the site of crosslinking:**


C
C
O


O
CH
CH2
H2N
R
NH2
OH
N



(Diglycidyl ether of Bisphenol A (DGEBA

Advantages:

- Low shrinkage during curing
- High strength and flexibility
- Adjustable curing range
- Better adhesion between fiber and matrix
- Better electrical properties
- Resistance to chemicals and solvents

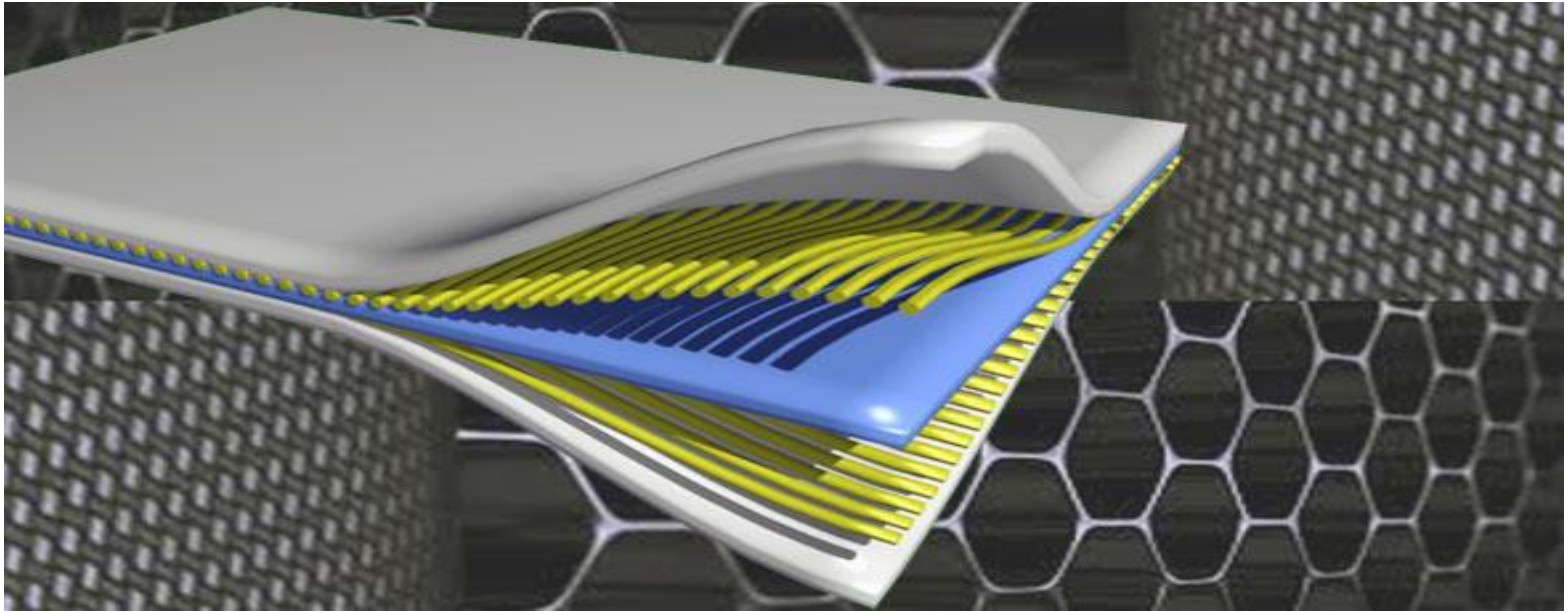
Disadvantages:

- somewhat toxic in nature
- limited temperature application range up to 175°C
- moisture absorption affecting dimensional properties
- high thermal coefficient of expansion
- slow curing

Common PMC Fibers & Matrices

- Fibers
  - Graphite
  - Glass
  - Kevlar
- Matrices
  - Epoxy
  - Phenolic
  - Polyester

Composite Materials



Dr. Abbas Hasan Faris

Lecture 6

Classification: Fiber-Reinforced (v)

Particle-reinforced | **Fiber-reinforced** | Structural

- Critical fiber length for effective stiffening & strengthening:

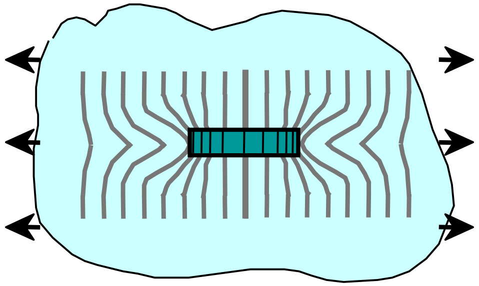
fiber ultimate tensile strength → σ_f; fiber diameter → d; shear strength of fiber-matrix interface → τ_c

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

- Ex: For fiberglass, a common fiber length > 15 mm needed
- For longer fibers, stress transference from the matrix is more efficient

Short, thick fibers:

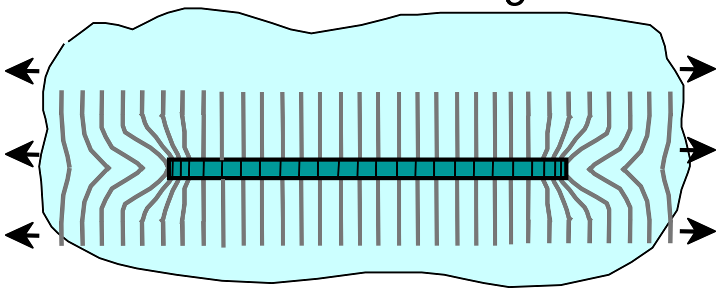
$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$



Low fiber efficiency

Long, thin fibers:

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

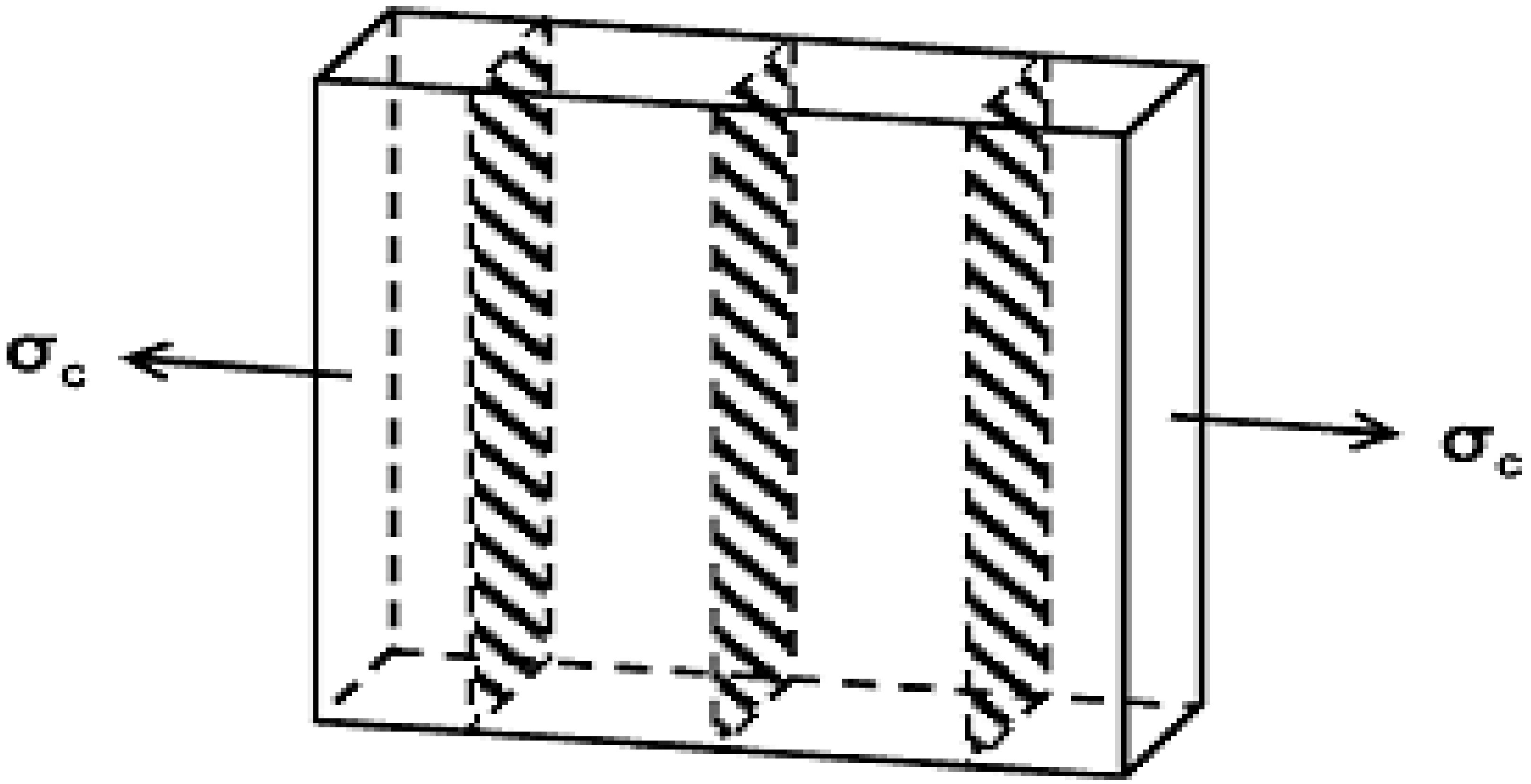


High fiber efficiency

- **Mechanical Properties of Fiber-Reinforced Composites**
- **<u>Tensile Stress-Strain Behavior:</u>**
- **Elastic behavior-Transverse loading (continuous and aligned fiber composite)**

- a continuous and oriented fiber composite may be loaded in the transverse direction. That is, the load is applied at a 90º angle to the direction of fiber alignment.
- **Composite Stiffness: Transverse Loading**
- **For longitudinal loading**, **isostrain** conditions are assumed where the deformation of the fibers and matrix are **identical**. In this assumption, there are **stiff and strong mechanical properties**.
- **For transverse loading**, **isostress** conditions are assumed where the matrix and fibers are under the **same stress** ($\sigma c = \sigma f = \sigma m$). In this assumption, the **mechanical properties are considered soft and weak**.

Transverse loading is a load applied vertically to the plane of the longitudinal axis of a configuration. It causes them to **bend and rebound** from their original position. **(Exposed stresses are same: isostress state)**

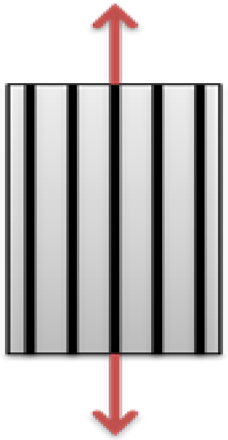


Longitudinal Loading

$$\sigma_c = \sigma_m * V_m + \sigma_f * V_f$$

$$E_c = E_m * V_m + E_f * V_f$$

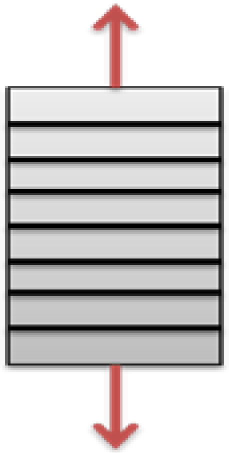
σ = Tensile Strength
E = Elastic Modulus
V = Volume Fraction
M = Matrix
c = composite
f = Fiber

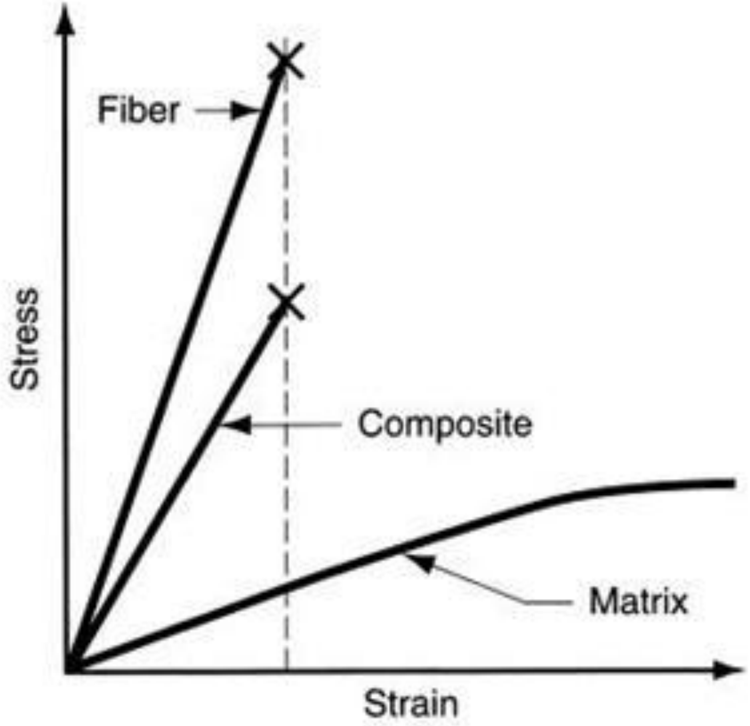


Transverse Loading

$$E_c = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

σ = Tensile Strength
E = Elastic Modulus
V = Volume Fraction
M = Matrix
c = composite
f = Fiber





Composite Stiffness: Transverse Loading

- In transverse loading, the fibers carry less of the load

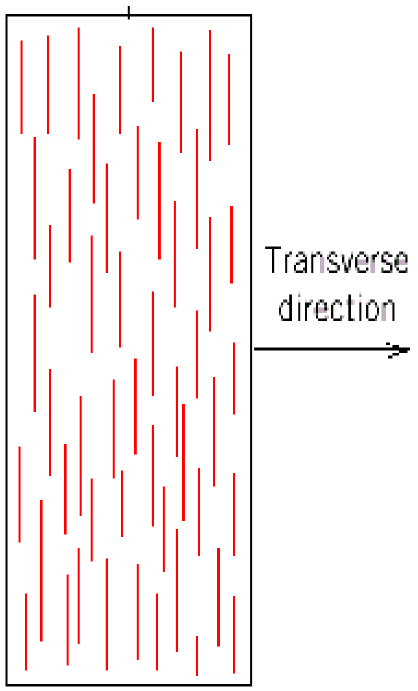
$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$ and $\sigma_c = \sigma_m = \sigma_f = \sigma$

isostress

$$\therefore \quad \boxed{\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}}$$

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

E_{ct} = transverse modulus



(a)

c = composite

f = fiber

m = matrix

- It has been stated previously that an increase in the volume fraction of fibers in composite results in an increase in stiffness. it can be seen how the volume fraction of fibers affects the modulus of the composite in both the **isostrain and isostress conditions**. The modulus in the isostrain condition is **linearly** related to the volume fraction of fibers. In the isostress condition, the relationship is **not linear**. Note how the **isostress** condition **never** produces a **value of modulus** higher than that obtained in the **isostrain** condition.

- For this situation, the stress (σ) of the composite, as well as both phases, are **exposed the same**:
- $\sigma_c = \sigma_m = \sigma_f = \sigma$ ---------------(1) **(σ is the tensile strength (TS))**
- This is termed an **isostress state**. Also, the **strain or deformation** of the entire composite **(ε_c)** is:
- $\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$ ---------------(2)
  - **But, because $\varepsilon = \sigma/E$**
- $\frac{\sigma}{E_c} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f$ -----------(3)
  - **Now, dividing by (σ) yields:**
- $\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$ -----------------(4)
- **Which reduces to:**
- $E_c = \frac{E_m E_f}{V_m E_f + V_f E_m}$ ----------------(5)

- **Example:**
- **Compute the elastic modulus of the composite material described (A continuous and aligned glass fiber-reinforced composite consists of 40 vol % of glass fibers having a modulus of elasticity of 69 GPa and 60 vol % of a polyester resin that, when hardened, displays a modulus of 3.4 GPa).**
- but assume that the stress is applied **perpendicular** to the direction of fiber alignment.

- **Solution**

- **According to equation 5,**

- $E_c = \dfrac{E_m E_f}{V_m E_f + V_f E_m}$

- $E_c = \dfrac{(3.4\ GPa)(69\ GPa)}{(0.6)\ (69\ GPa)+(0.4)\ (3.4\ GPa)}$
- **= 5.5 Gpa**
- From this Example, this value is only one-fifth of the modulus of elasticity along the fiber direction, which indicates the degree of anisotropy of continuous and oriented fiber composite.

Composite Stiffness: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite modulus of elasticity for continuous fibers

- Longitudinal deformation

$\sigma_c = \sigma_m V_m + \sigma_f V_f$ and $\varepsilon_c = \varepsilon_m = \varepsilon_f$

volume fraction

isostrain

$\therefore \quad \boxed{E_{cl} = E_m V_m + E_f V_f}$ $\quad E_{cl}$ = longitudinal modulus

c = composite

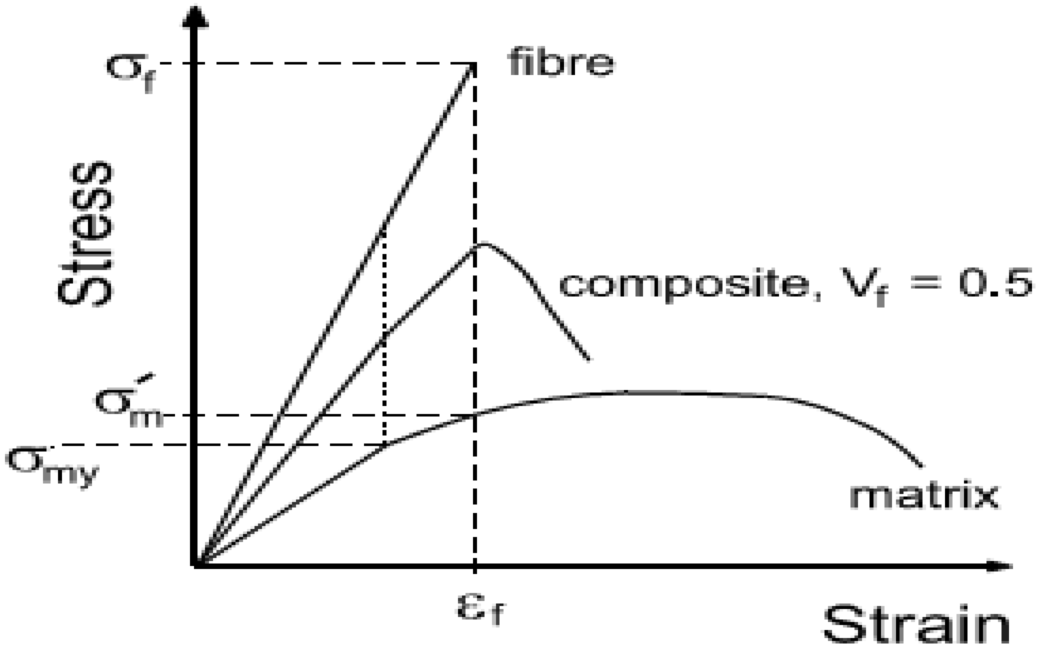
f = fiber

m = matrix

- **Continuous fibers - Estimate fiber-reinforced composite modulus of elasticity for continuous fibers**

- **1- Longitudinal tensile strength for continuous and aligned fibrous composite**

- Under longitudinal load, strength is normally taken as the maximum stress on the stress-strain curve, which corresponds to **fiber fracture** and marks the onset of **composite failure**.
- **Assume $\varepsilon^*_f < \varepsilon^*_m$, the fibers will fail before the matrix. Then:**
- $\sigma^*_c = \sigma^*_m (1 - V_f) + \sigma^*_f V_f$
- σ^*_m **is the stress in the matrix at fiber failure,**
- σ^*_f **is the fiber tensile strength.**



Typical Longitudinal and Transverse Tensile Strengths for Three Unidirectional Fiber–Reinforced Composites. The Fiber Content for Each Is Approximately 50 Vol%

Material	*Longitudinal Tensile Strength (MPa)*	*Transverse Tensile Strength (MPa)*
Glass–polyester	700	20
Carbon (high modulus)–epoxy	1000	35
Kevlar–epoxy	1200	20

• 2- Longitudinal tensile strength for discontinuous and aligned fibrous composite, and l > lc

- For a **discontinuous and aligned**-fiber composite having a uniform distribution of fibers and in which **l > lc** , the longitudinal strength **(σc*)** is given by:

- $\sigma c* = \sigma_f * Vf\left(1 - \frac{lc}{2l}\right) + \sigma^f{}_m\left(1 - Vf\right)$

- **Where σ_f* and σ_m' are the fracture strength of the fiber and the stress in the matrix when the composite fails.**

- **3- Longitudinal tensile strength for discontinuous and aligned fibrous composite, and l < lc**

- If the fiber length is less than critical **(l < lc),** then the longitudinal strength **(σ_c*)** is given by:

- $\sigma_c* = \left(\frac{l\tau_c}{d}\right)V_f + \sigma^f{}_m(1-Vf)$

- Where **d** is the fiber diameter and **τ_c** is the interfacial shear stress.

- **4- Discontinuous and randomly oriented-fiber composite**

- When the fiber orientation is **random**, **short and discontinuous** fibers are used. Under these cases, a (rule of mixtures) expression for the elastic modulus may be used:

$$E_c = KE_fV_f + E_mV_m$$

- Where **K** is a fiber efficiency parameter that depends on **Vf** and the **Ef/Em** ratio.
- Of course, its magnitude will be less than unity, usually in the range of 0.1 to 0.6.
- **Example 3**
- Compute the longitudinal tensile strength of an aligned glass fiber-epoxy matrix composite in which the average fiber diameter and length are 0.010 mm and 2.5 mm, respectively, and the volume fraction of fibers is 0.40. Assume that:
- 1. the fiber-matrix bond strength **(shear strength)** is 75 MPa,
- 2. the fracture strength of the fibers is 3500 MPa,
- 3. the matrix stress at fiber failure is 8.0 MPa.

- **Solution:**
- $lc = \frac{\sigma_f * d}{2\tau_c} = \frac{(3500\ MPa)(0.010\ mm)}{2\ (75\ MPa)} = \frac{7}{30}$ **mm**
- **lc = 0.233 mm**
- Since the critical fiber length of 0.233 mm is much less than the provided length of the fiber (2.5mm) , so we can use the following equation to find the longitudinal tensile strength. **l >lc**

- $\sigma c* = \sigma_f * Vf\left(1 - \frac{lc}{2l}\right) + \sigma'_m (1 - Vf)$
- $\sigma c* = 3500\ MPa * 0.4\left(1 - \frac{7/30}{2*2.5\ mm}\right) + 8\ MPa * 0.6 = 1340\ MPa$

- The longitudinal tensile strength of the aligned glass fiber-epoxy matrix composite is 1339.47 MPa

- **Example 4**
- Consider a uniaxial fiber reinforced composite of aramid fibers in an epoxy matrix. The volume fraction of fibers is (60 %) . The composite is subjected to an axial strain of (0.1 %) . Compute the modulus and strength along the axial direction of the composite, Ef=140 GPa, Em= 5 GPa.
- **Solution**
- $E_c = E_m(1 - V_f) + E_f V_f$
- = 5(1- 0.6) + 140* 0.6
- = 86 GPa
- $\sigma_c = E_c \varepsilon_c$
- = 86 * 0.001* 1000 = 86 MPa

- **Example 5**
- A composite material has a longitudinal modulus of elasticity of (18.2 GPa). Containing unidirectional S – glass fibers in on epoxy matrix.
- **Determine,**
- **a) Volume fraction of glass fiber and the epoxy matrix.**
- **b) The density of the composite.**
- **Note :- Density of epoxy = 1.3 gm/cm^3 , Density of glass = 2.2 gm/cm^3**
- **Modulus of epoxy = 2.75 GPa.**
- **Modulus of glass =380 GPa.**

- **Solution**
- **a)**
- $E_c = E_m(1 - V_f) + E_f V_f$
- $18.2 = 2.75\ (1 - V_f) + 380 * V_f$
- $V_f = 0.041, \quad V_m = 0.959$
- **b)**

$$\rho_c = \rho_m * V_m + \rho_f * V_f$$

$$=1.3*0.959+2.2*0.041$$

$$=1.2467+0.9902=1.3369\ gm/cm^3$$

V = volume fraction
sigma = stress
E = modulus
L = length
A = cross sectional area
delta L = elongation
epsilon = strain
subscripts C, M, P = composite, matrix, particle
Richard Holt, 11/15/2007

LONGITUDINAL LOADING

ISOSTRAIN CONDITION: Deformation of matrix and fibers is the same.

Force parallel to fiber direction

$$S_c = S_m * V_m + S_f * V_f$$

$$E_c = E_m * V_m + E_f * V_f$$

S = Tensile Strength
E = Modulus of Elasticity
V = Volume Fraction
m = Matrix
f = Fiber
c = Composite

Stiff and Strong!!

TRANSVERSE LOADING

ISOSTRESS CONDITION: Matrix and fibers are under the same stress. ($S_c = S_m = S_f$)

Force perpendicular to fiber direction

$$E_c = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

S = Tensile Strength
E = Modulus of Elasticity
V = Volume Fraction
m = Matrix
f = Fiber
c = Composite

Soft and Weak!

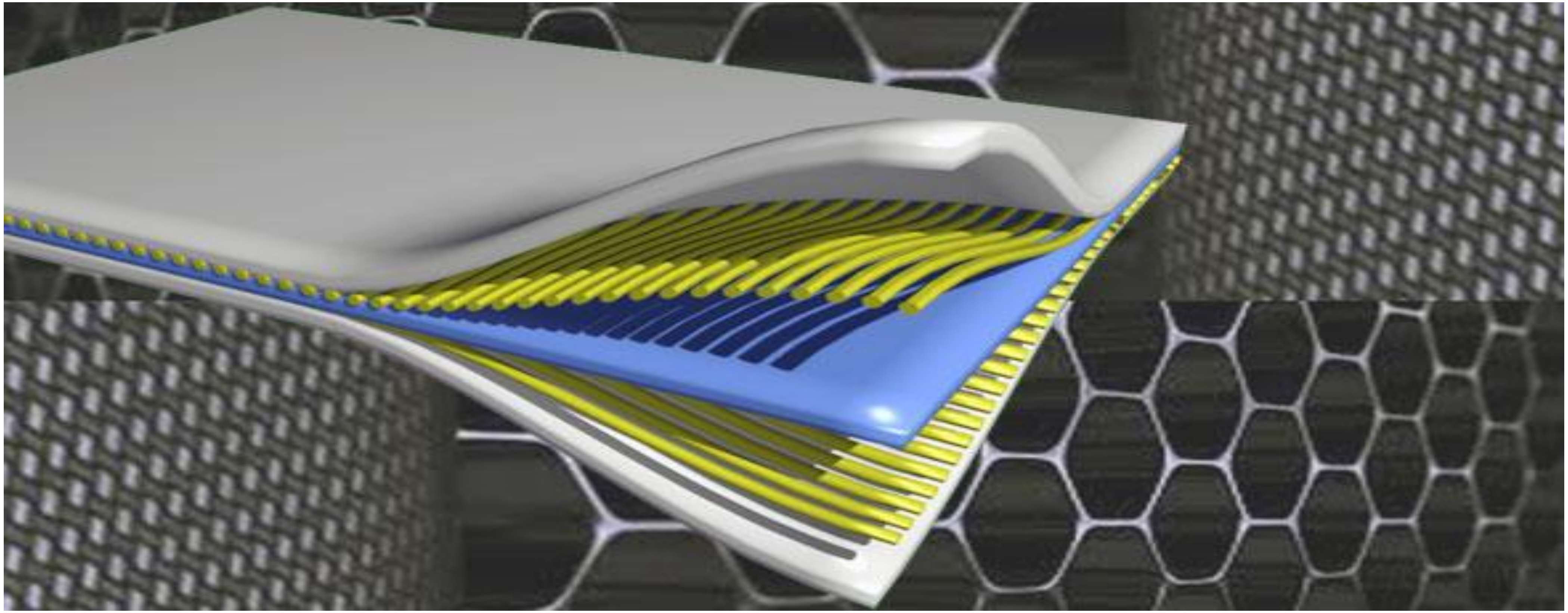
- **Density of Composite**
- **Density of Composite in terms of weight fraction**

$$\rho_c = \rho_f V_f + \rho_m V_m$$

- **Density of Composite in terms of Volume fraction**

$$\frac{w_c}{\rho_c} = \frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}$$

Composite Materials



Dr. Abbas Hasan Faris

Lecture- 7

Rule of Mixtures

The **rule of mixtures (ROM)** is a weighted method used to predict the properties of composite materials such as a fiber-reinforced polymer (FRP) including the tensile performance based upon the following assumptions:

(1) The fiber is homogeneous, linear elastic, and well-arranged regularly in space.

(2) The matrix is also homogeneous, linear elastic, and isotropic.

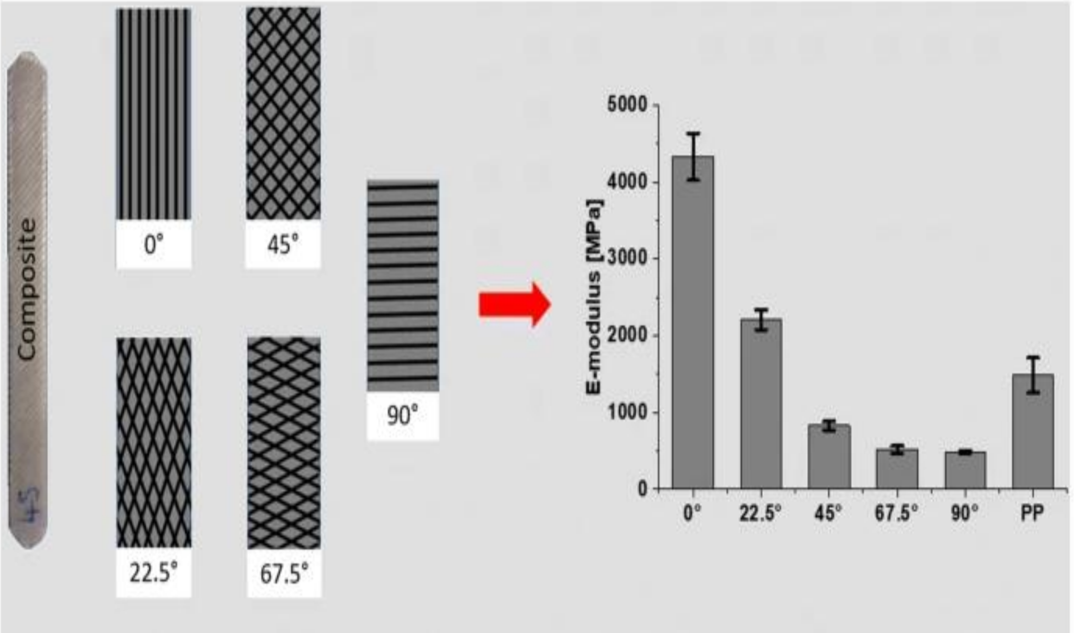
(3) There are no voids, the fiber and the matrix are completely coupled.

Based on these assumptions, the **tensile performance** of FRP composed of fiber and polymer in the matrix can be obtained **by combining** the volume fraction and the tensile properties of the fiber and the matrix linearly.

- Mechanical properties of composites depend on the **volume fraction of reinforcement and matrix.**
- The basic properties can be calculated using the rule-of-mixture principle with some assumptions
- The type of reinforcement (fiber, particle or whiskers) and their orientation play a major role in determining the strength of composites
- In composites, if fibers are oriented at an angle **of 0**, their strength along the fiber direction will be more than in the other directions
- In particle-reinforced composites, the **distribution** of particles throughout the component is key to providing **uniform** material property

- According to the Rule of Mixtures properties of composite materials are estimated as follows:

- [Density]
- [Coefficient of Thermal Expansion]
- [Modulus of Elasticity]
- [Shear modulus]
- [Poisson's ratio]
- [Tensile strength]



Effect of fibre orientation on the mechanical properties of polypropylene-lyocell composites

The density, electrical and thermal conductivity, and modulus of elasticity parallel to the laminae

$$\text{Density} = \rho_{c,\parallel} = \sum \rho_i * V_i$$

$$\text{Electrical Conductivity} = \sigma_{c,\parallel} = \sum \sigma_i * V_i$$

$$\text{Thermal Conductivity} = k_{c,\parallel} = \sum k_i * V_i$$

$$\text{Modulus of elasticity} = E_{c,\parallel} = \sum E_i * V_i$$

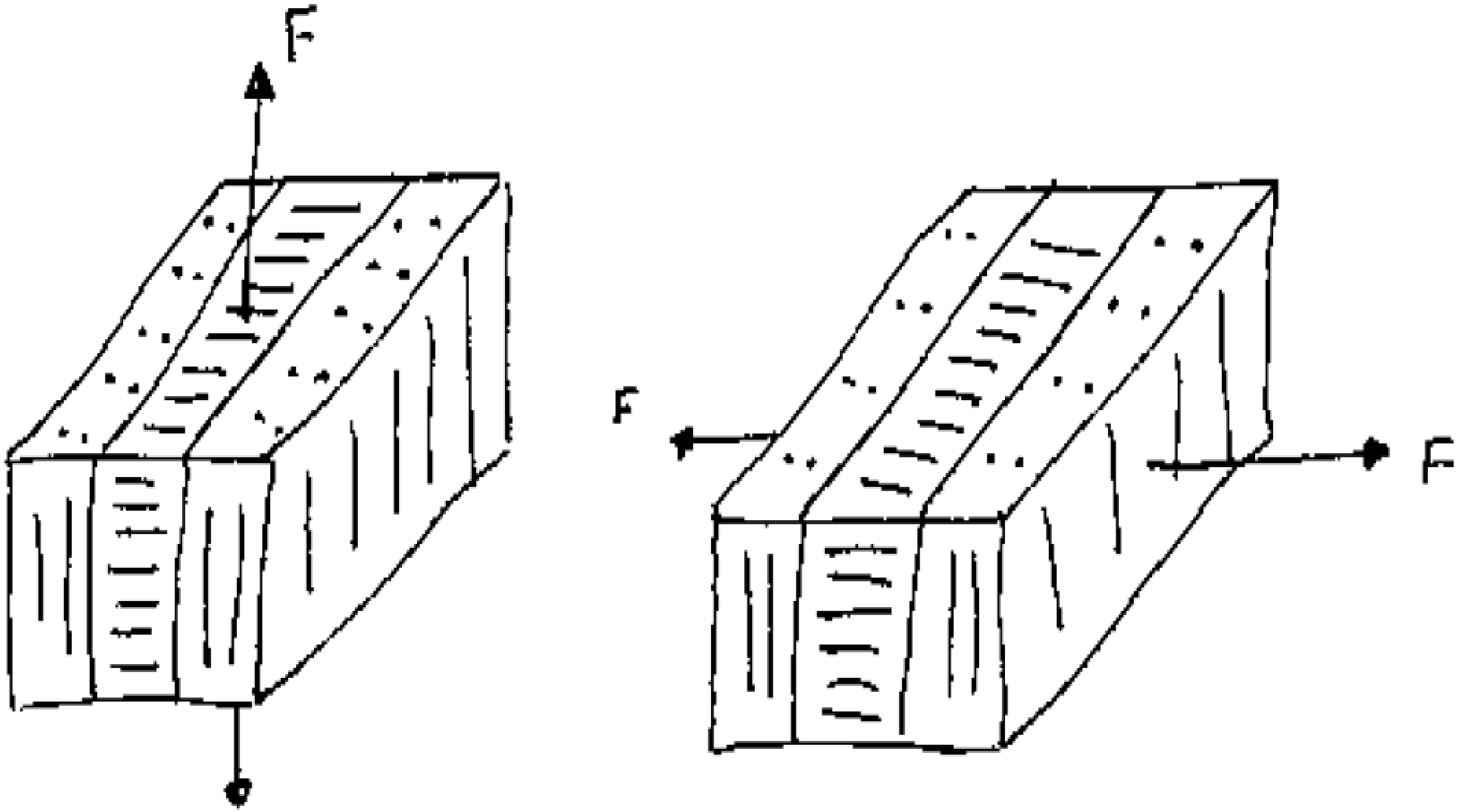
While the properties perpendicular to the laminar composite

$$\text{Electrical Conductivity} = \frac{1}{\sigma_{c,\perp}} = \sum \frac{v_i}{\sigma_i}$$

$$\text{Thermal Conductivity} = \frac{1}{k_{c,\perp}} = \sum \frac{v_i}{k_i}$$

$$\text{Modulus of elasticity} = \frac{1}{E_{c,\perp}} = \sum \frac{v_i}{E_i}$$

Example:- A sheet of plywood Consist of three equally thickness sheets, the left and right sheets having their fiber in the same direction and the middle sheet with its fiber at right angles. The wood has a tensile modulus for forces in the direction parallel to the fiber of 10 GPa. and in the transverse diraction 0.4 GPa. Determine the tensile modulus of the laminate when loaded in a direction parallel to the fiber direction of the outer sheet and the tensile modulus of the laminate when loaded in a directional perpendicular to the fiber direction of the


F
F
F

solution:

$$E_{c,\parallel} = E_1 V_1 + E_2 \cdot V_2 + E_3 \cdot V_3$$

$$= 10 * \frac{1}{3} + 0.4 * \frac{1}{3} + 10 * \frac{1}{3} = 6.8\ GPa.$$

$$\frac{1}{E_{c,\perp}} = \frac{V_1}{E_1} + \frac{V_2}{E_2} + \frac{V_3}{E_3} = \frac{\frac{1}{3}}{10} + \frac{\frac{1}{3}}{0.4} + \frac{\frac{1}{3}}{10}$$

$$E_{c,\perp} = 1.11\ GPa.$$

Also the properties of a unidirectional lamina are found by using the following equations;

$$E_1 = E_f \cdot V_f + E_m \cdot V_m$$

$$E_2 = \frac{E_f \cdot E_m}{(E_f \cdot V_m + E_m \cdot V_f)}$$

- Notations used in rule-of-mixture are as follows:
- **c, f, and m** represent composite, **fiber, and matrix** respectively, **V is Volume** fraction, **P is load withstand**, **A is the cross-sectional area**, E is Elastic modulus, **σ is stress**, **ε is Strain**, **μ is a Poisson ratio and ρ is Density**.

- **Volume fraction of fiber,** **vf = volume of fiber/ volume of composite**
- **Volume of composite,** $V_c = V_f + V_m$
- **For unit volume of composite,** $1 = V_f + V_m$
- **Volume fraction of matrix,** $V_m = 1 - V_f$
- The Rule of Mixtures is actually composed of two models: Voigt, W. (1889) and Reuss, A. (1929).
- The first model is normally applied to calculate elastic modulus in the **fiber direction (longitudinal direction)**, while the second one is used for estimations in the **transverse direction**.

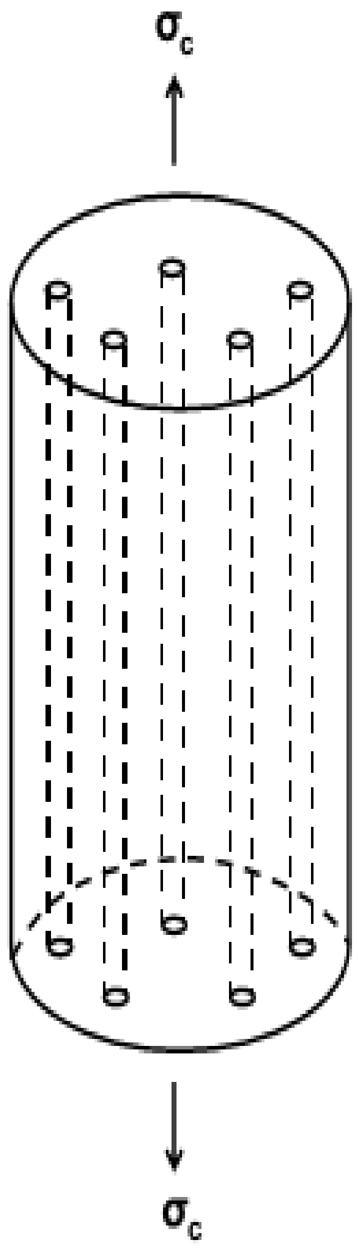
- In general terms "Rule of Mixtures" may be expressed as follows:

  - $X_c = V_f X_f + V_m X_m$

- X_c is the composite property
- X_f is the fiber property
- X_m is the matrix property
- V_f is the volume fraction of fiber
- V_m is the volume fraction of matrix and = 1- V_f

- **Elastic behavior-**
- **Longitudinal loading (continuous and aligned fiber composite)**
- Let the load applied to the composite be **Fc**. This load is **shared by the fiber and the matrix** according to the fraction of the cross-sectional area (area perpendicular to the stress direction) occupied by these components.

- **Hence**
- $F_c = F_m + F_f$ --------- (1)
- **With**
- $F_c = \sigma_c A_c$ ------------ (2)
- $F_m = \sigma_m A_m$ -------- (3)
- $F_f = \sigma_f A_f$ ------------- (4)
- Where **A_c, A_m and A_f are the cross-sectional areas of the**
- composite, matrix and fiber (all the fibers together), respectively,
- such that:
- $A_c = A_m + A_f$ ------ (5)
- σ_c , σ_m , σ_f are the **stresses** of the **composite**, **matrix** and **fiber**,
- respectively.



- Iso-Strain Elastic Modulus of Lamellar Composite
- • Isostrain condition:
- Equal strain
- $\varepsilon_c = \varepsilon_f = \varepsilon_m = \varepsilon$
- Total applied load
- $F_c = F_f + F_m$
- Stress
- $\sigma = F/A$
- $\sigma_c A_c = \sigma_f A_f + \sigma_m A_m$

- **From equation 1:**
- $\boldsymbol{\sigma_c A_c = \sigma_m A_m + \sigma_f A_f}$ ------- **(6)**
- **However,**
- $\boldsymbol{\sigma_c = E_c \varepsilon_c}$ ----------------------**(7)**
- $\boldsymbol{\sigma_m = E_m \varepsilon_m}$ --------------- **(8)**
- $\boldsymbol{\sigma_f = E_f \varepsilon_f}$ ------------------ **(9)**
- **Thus, Eq. 6 becomes**
- $\boldsymbol{E_c \varepsilon_c A_c = E_m \varepsilon_m A_m + E_f \varepsilon_f A_f}$ ---------- **(10)**
- When a fiber-oriented composite is loaded in the **longitudinal direction** of fiber the alignment then the **strain** in the **fiber**, **matrix**, and **composite** are **equal (iso-strain).**
- ***E*= elasticity of matrix**
- Due to the isostrain situation **(**$\boldsymbol{\varepsilon_c = \varepsilon_m = \varepsilon_f}$**),** the three strains are equal and can be **canceled**. Hence,

- $E_cA_c = E_mA_m + E_fA_f$ ----------- (11)
- **Dividing by Ac gives**
- $E_C = E_m\left(\frac{A_m}{A_c}\right) + E_f\left(\frac{A_f}{A_c}\right)$ ---------**(12)**
- Where $\frac{A_m}{A_c}$ **and** $\frac{A_f}{A_c}$ are the area fractions of the **matrix** and **fiber** phases, respectively. **If the composite, matrix, and fiber phase lengths are all equal,** $\frac{A_m}{A_c}$ is equivalent to the volume fraction of the matrix, (Vm) , and likewise for the fibers, **Vf =** $\frac{A_f}{A_c}$ thus **equation 12 becomes**
- $E_c = E_mV_m + E_fV_f$ ----------------- **(13) (Rule of mixture of binary composites)**
- Or, $E_c = E_m(1 - V_f) + E_fV_f$ ---- **(14)**
- Because the composite consists of only matrix and fiber phases;
- that is, $V_m + V_f = 1.$
- It can also be shown, for longitudinal, that the ratio of the load carried by the fibers to that carried by the matrix is
- $\frac{E_f}{E_m} = \frac{E_fV_f}{E_mVm}$ ------------------------ **(15)**

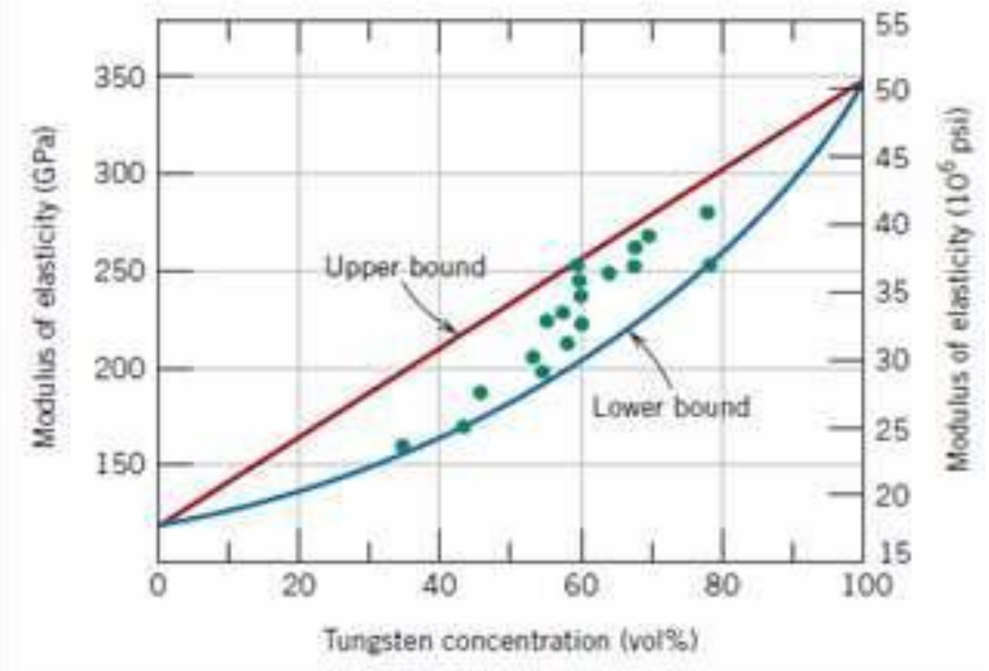
- In particle reinforced composite the elastic modulus shall fall between **upper and lower values** as **per volume fraction**.

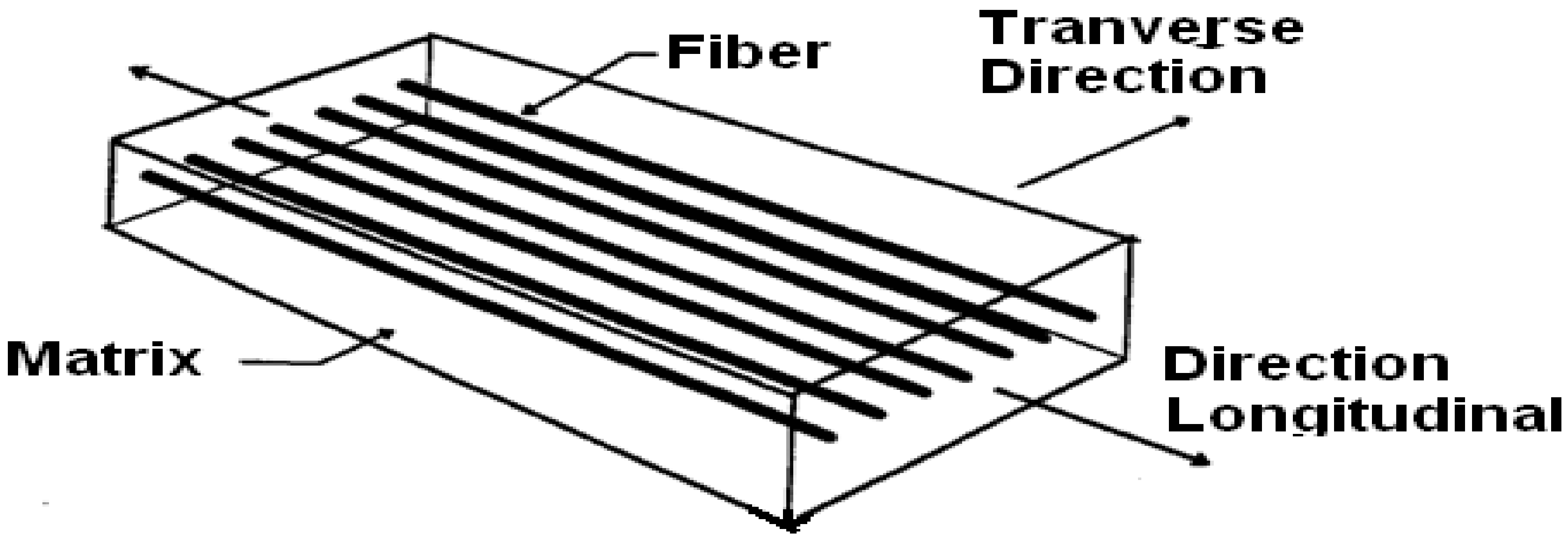
- Rule of mixture: equation predict that the **elastic modulus** should fall between an **upper and lower bound** as shown:
- • Example: Fig. plots upper and lower bound $\mathbf{E_c}$ – versus $\mathbf{V_p}$ curves for a copper–tungsten composite; in which tungsten is the particulate phase.
- **Upper Elastic Modulus of composite,**

$$E_c(u) = E_m V_m + E_p V_p$$

- **Lower Elastic Modulus of composite,**

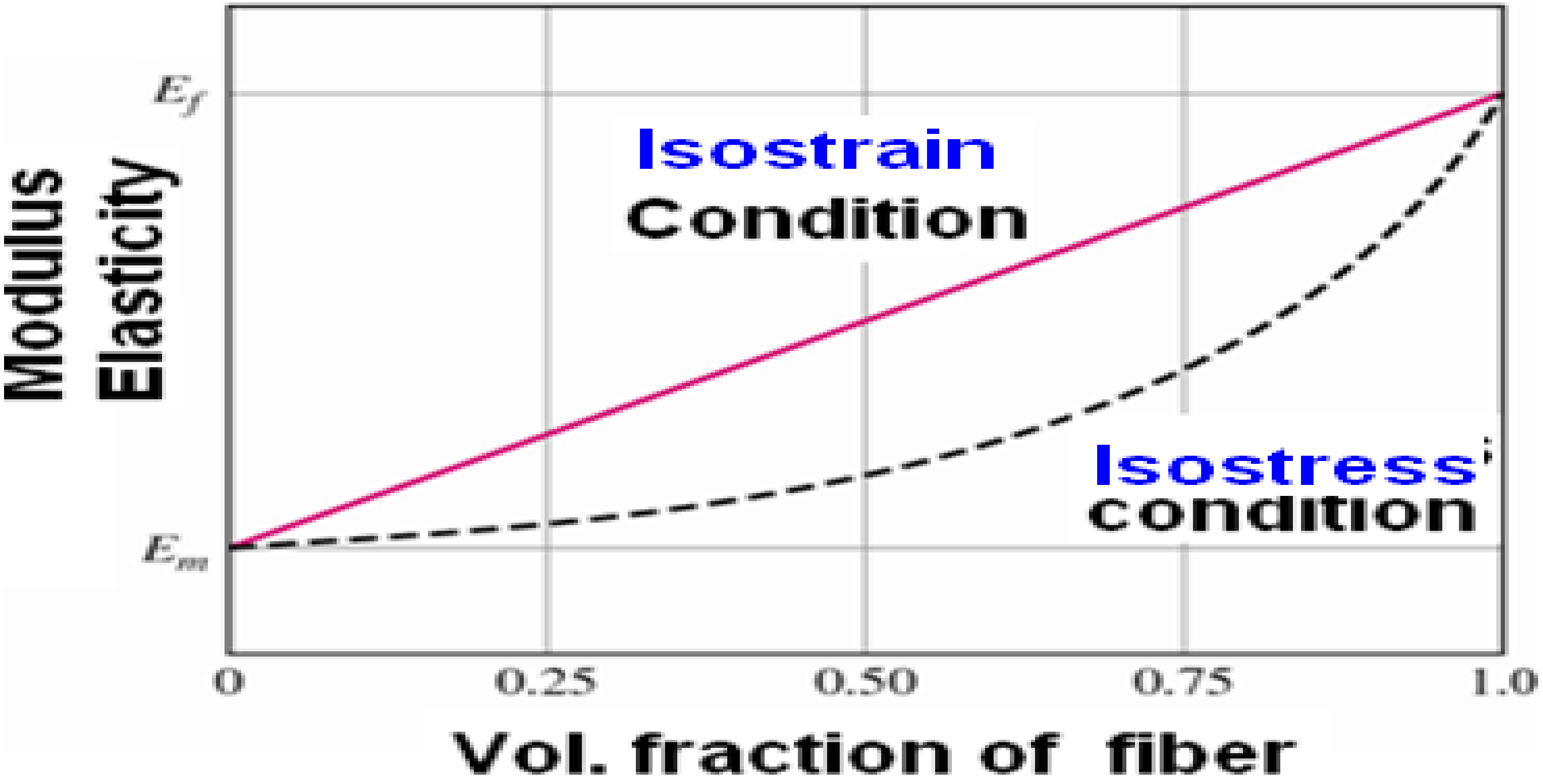
$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$





The longitudinal tensile strength of composite materials is determined mostly by the strength and volume content of the fiber reinforcement. The breaking strength of the **fibers** is much **greater than the strength** of the polymer **matrix**, and therefore the **fibers determine** the **ultimate strength** of the composite. The fiber strengths are typically **50 to 100 times** higher than the matrix and, consequently, the strength of the matrix has little influence on the in-plane tensile strength of composite materials.

- Higher modulus values are obtained with isostrain loading for equal volume of fibers



- **Example**
- A continuous and aligned glass fiber-reinforced composite consists of 40 vol% of glass fibers having a modulus of elasticity of 69 GPa and 60 vol% of a polyester resin that, when hardened, displays a modulus of 3.4 GPa.
- **(a) Compute the modulus of elasticity of this composite in the longitudinal direction.**
- **(b) If the cross-sectional area is 250 mm^2 and a stress of 50 MPa is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.**
- **(c) Determine the strain that is sustained by each phase when the stress in part (b) is applied.**

- **Solution**
- (a) The modulus of elasticity of the composite is calculated using
- equation (13): $E_c = E_m V_m + E_f V_f$
- E_c = (3.4 GPa)(0.6) + (69 GPa)(0.4)
- = 30 GPa
- (b) To solve this portion of the problem, first find the ratio of fiber load to matrix load, using equation (15); thus,
- $\frac{F_f}{F_m} = \frac{(69 Gpa)(0.4)}{(3.4\ Gpa)(0.6)}$
- **Or F_f = 13.5 F_m**
- In addition, the total force sustained by the composite Fc may be computed from the applied stress σ and total composite cross-sectional arae A_c according to:
- **$F_c = A_c\ \sigma$ = (250 mm2)(50 MPa) = 12,500 N**
- However, this total load is just the sum of the loads carried by fiber and matrix phases; that is,
- **$F_c = F_f + F_m$ = 12,500 N**
- **Substitution for Ff from the preceding equation yields**
- **13.5 Fm + Fm = 12,500 N Or Fm = 860 N**
- **Whereas $F_f = F_c - F_m$ = 12,500 N – 860 N = 11,640 N**
- **Thus, the fiber phase supports the vast majority of the applied load.**

- (c) The stress for both fiber and matrix phases must first be calculated. Then, by using the elastic modulus for each [from part (a)], the strain values may be determined.
- For stress calculation, phase cross-sectional areas are necessary:
- Am = Vm Ac = (0.6)(250 mm^2) = 150 mm^2
- and Af = Vf Ac = (0.4)(250 mm^2) = 100 mm^2

- thus, $\boldsymbol{\sigma_m} = \frac{F_m}{A_m} = \frac{860\ N}{150\ mm^2} = \mathbf{5.73\ MPa}$

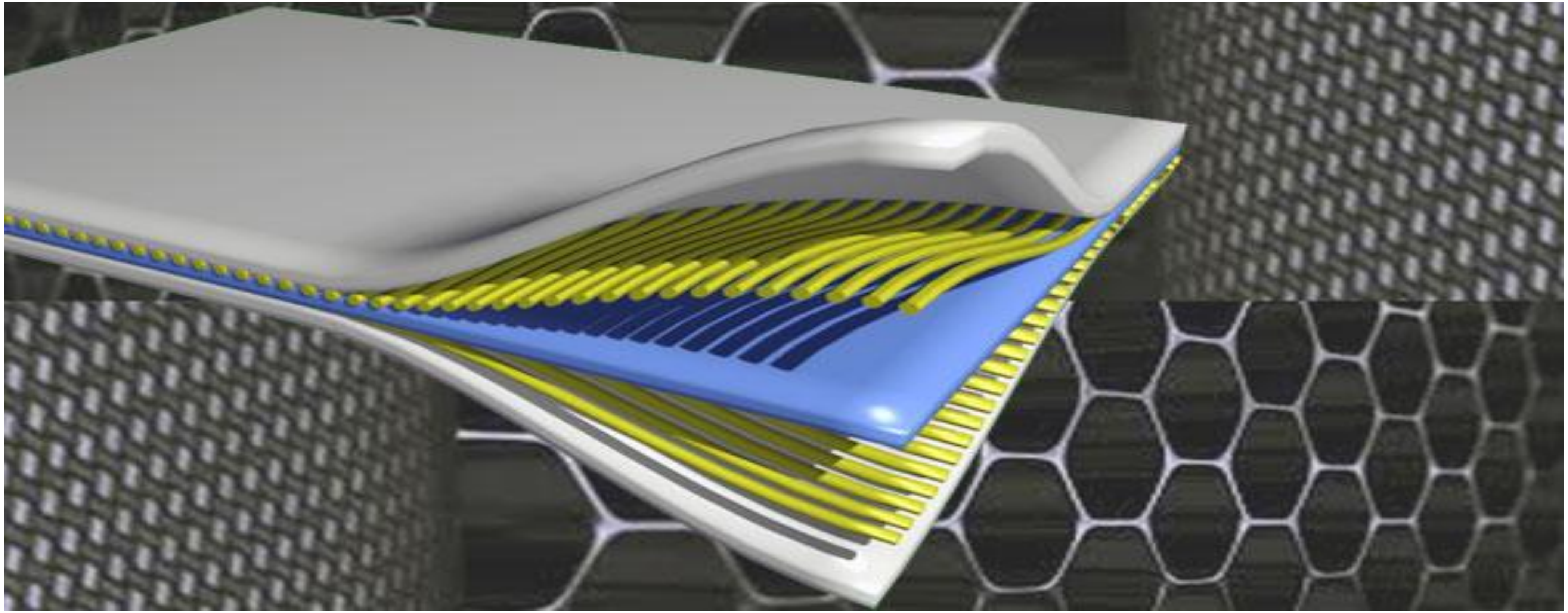
- $\boldsymbol{\sigma_f} = = \frac{F_f}{A_f} = \frac{11640\ N}{100\ mm^2} = \mathbf{116.4\ MPa}$
- **Finally, strains are computed as:**

- $\varepsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73\ MPa}{3.4x103\ MPa} = 1.69 * 10^{-3}$

- $\varepsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4\ MPa}{69x103\ MPa} = 1.69 * 10^{-3}$

- Therefore, strains for both matrix and fiber phases are identical according to isostrain assumption.

Composite Materials



Dr. Abbas Hasan Faris

- **Manufacturing Techniques**
- Composite production techniques utilize various types of composite raw materials, including fibers, resins, mats, fabrics, prepregs, and molding compounds, for the fabrication of composite parts. Each manufacturing technique requires different types of material systems, different processing conditions, and different tools for part fabrication. Part production success relies on the correct selection of a manufacturing technique as well as the careful selection of processing parameters.
- **Manufacturing Process Selection Criteria**
- It is a monumental challenge for design and manufacturing engineers to select the right manufacturing process for the production of a part, the reason being that design and manufacturing engineers have so many choices in terms of raw materials and processing techniques to fabricate the part.

- **1. Production Rate/Speed**
- Depending on the application and market needs, the rate of production is different. For example, the **automobile market** requires a high rate of production, for example, **10,000 units per year (40 per day) to 5,000,000 per year (20,000 per day).** In the **aerospace market**, production requirements are usually in the range of **10 to 100 per year.** Similarly, there are **composites manufacturing techniques** that are suitable for **low-volume and high-volume production** environments. For example, hand lay-up and wet lay-up processes cannot be used for high-volume production, whereas compression molding (SMC) and injection molding are used to meet high-volume production needs.

- **2. Cost**
- Factors influencing cost are **tooling**, **labor**, **raw materials**, **process cycle time**, and **assembly time**. There are some composite processing techniques that are good at producing low-cost parts, while others are cost prohibitive. The cost of a product is significantly affected by production volume needs as well. For example, compression molding (SMC) is selected over stamping of steel for the fabrication of automotive body panels when the production volume is less than 150,000 per year. For higher volume rates, steel stamping is preferred.

- **3. Performance**
- Each composite process utilizes different starting materials and therefore the final properties of the part are different. The **strength of the composite part strongly depends** on **fiber type**, **fiber length, fiber orientation, and fiber content** (60 to 70% is the strongest, as a rule). Depending on the application need, suitable raw materials and thus a suitable composite manufacturing technique are selected.

- **4. Size**
- The **size of the structure** is also a deciding factor in screening manufacturing processes. The automobile market typically requires smaller-sized components compared to the aerospace and marine industries. For **small- to medium-sized** components, **closed moldings are preferred**; whereas for **large structures** such as a boat hull, an **open molding process** is used.

- **5. Shape**
- The shape of a product also plays a deciding role in the selection of a production technique. For example, **filament winding** is most suitable for the manufacture of **pressure vessels and cylindrical shapes**. **Pultrusion** is very economical in producing **long parts with uniform cross-sections**, such as circular and rectangular.

Product Fabrication Needs

- To make a part, the four major items needed are:
- **1. Raw material**
- **2. Tooling/mold**
- **3. Heat**
- **4. Pressure**

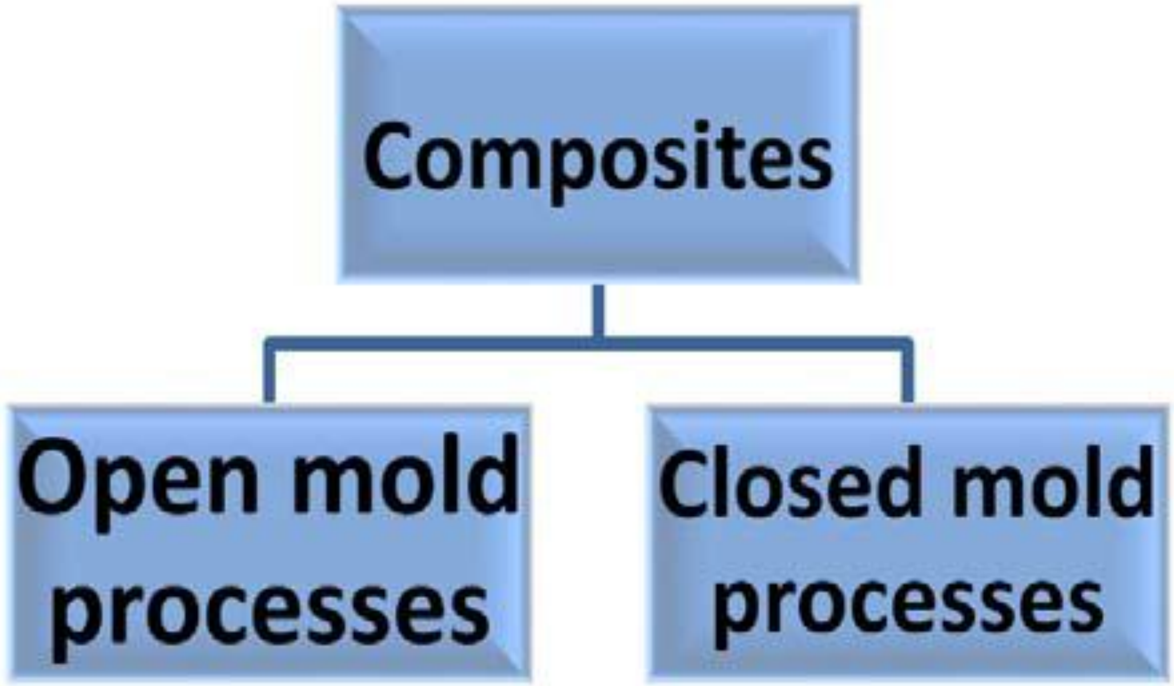
- Depending on the manufacturing process selected, a suitable raw material is chosen and **spread on the tool/mold**. Then, **heat and pressure** transform the raw material into the **final shape**. Heat and pressure requirements are different for different material systems. Solid materials such as metals or thermoplastics require a large amount of heat to melt the material for processing, whereas thermosets require less heat. Generally, the **higher the melting temperature** of a material, the **higher the temperature and pressure** required for processing.

- There are a lot of techniques to cast a composite structure whether it is straightforward or mind-boggling, single or numerous. Every method has its own particular benefits and confinements. The combination of fibers and matrix material is depending upon the **final use and required applications** in the various field. Other important parameters include temperature, pressure, curing of the matrix, and end-use of the product to form a cost-effective method.

- The control of these various parameters is a challenge to forming adequate manufacturing techniques for composites. For an adequate chemical reaction, **high temperature and pressure** are required for **highly viscose resins** to get **adhere and flow inside the fibers** so, that **good bonding between fiber and matrix** material be formed. The chemical reaction of resin forming cross-linking is called **curing**. The time required to complete the curing is called the **cure cycle**.

- Depending on the manufacturing process selected, a suitable raw material is chosen and laid on the tool/mold. Then, heat and pressure are applied to transform the raw material into the final shape. Heat and pressure requirements are different for different material systems.
- For example, **steel**, which **melts at 1200°C**, requires higher temperatures and pressures to process the part. **Aluminum**, which **melts at around 500°C**, requires less heat and pressure for transforming the shape as compared to steel processing. **Thermoplastics** have **melting temperatures** in the range of **100 to 350°C** and therefore require lesser amounts of heat and pressure as compared to **steel and aluminum**. **Thermosets** are in a liquid state at room temperature and therefore are easy to form and process.

- There are two main processes for composites manufacturing



The difference between open molding and closed molding is in **how the resin is cured**. When the resin is **exposed** to the **atmosphere during the cure**, it is referred to as **open molding**. When the resin is **not exposed** to the **atmosphere during cure**, it is referred to as **closed molding**.

Open molding – resin is impregnated into the fibers and they are placed in an open mold, where they cure or harden.

- Relatively low cost due to little to no tooling (the mold)
- can accommodate very large parts with the ability to change mold sizes, (Wide part size potential).
- Secondary finishing processes are needed as only one side of the finished part will have a good surface finish (the side that was against the mold)
- Best for low volume production (<1,500 parts per year) as well as large and complex part geometries

- **Closed molding -** composite materials are placed in a two-sided mold, closed to the atmosphere
  - Allows for more complex part geometries
  - Produces better parts faster and more consistently than open molding processes
  - Less waste produced
  - More expensive due to tooling (mold) requirements

- 1. **Open molding process:** In this process the laminates are exposed to the atmosphere during the process.
- There are three main methods for **impregnating** **matrix/resins** into reinforcement/fibers

Types of open mold process

- **Wet lay-up process**
- **Spray-up process**
- **Filament Winding**

2. Close Mold Processes: In this process, the composite is processed in a two-sided mold set, or within a vacuum bag. Fibers and resin cure inside a two-sided mold. Usually require automation and special equipment, for high-volume manufacturing.

Types of open mold process

- **Resin Transfer Molding (RTM)**
- **Vacuum assisted resin transfer Molding**
- **Compression molding**
- **Pultrusion**
- **Injection molding**

Basic Steps in a Composites Manufacturing Process

- **There are four basic steps involved in composites part fabrication:**
- All composites manufacturing processes involve the same four steps, although they are accomplished in different ways.
- **1- Impregnation**
- In this step, fibers and resins are mixed together to form a lamina. For example, in a **filament winding process**, fibers are passed through the resin bath for impregnation. The purpose of this step is to make sure that the resin flows entirely around all fibers. **Viscosity, surface tension, and capillary action** are the main parameters affecting the impregnation process. Thermosets, which have viscosities in the **range of 10 e1 to 10 e4 cp** are easier to wet-out. Viscosities of thermoplastics fall in the range of **10 e4 to 10 e8 cp** and require a greater amount of pressure for good impregnation.

2- Lay-up

In this step, **composite laminates** are formed by placing fiber resin mixtures or prepregs at **desired angles** and at places where they are needed. The desired composite thickness is built up by placing various layers of the fiber and resin mixture. The purpose of this step is to achieve the desired **fiber architecture** as dictated by the design. The performance of a composite structure relies heavily on **fiber orientation and lay-up sequence**.

3- Consolidation

This step involves creating **tight contact** between each layer of prepreg or lamina. This step ensures that all the **entrapped air** is removed between layers during processing. **Consolidation is a very important step in obtaining a good quality part**. Poorly consolidated parts will have **voids and dry spots**. Consolidation of continuous fiber composites involves **two important processes**: (1) **resin flows through porous media (2) and elastic fiber deformation**. During the consolidation process, an applied pressure is shared by both resin and fiber structure. Initially, however, the applied pressure is carried solely by the resin (zero fiber elastic deformation). **Fibers go through elastic deformation** when the compressive **pressure increases** and resins **flow out toward the boundary**.

4- Solidification

- The final step is solidification, which may take less than **a minute for thermoplastics or may take up to 120 min for thermosets**. Vacuum or pressure is maintained during this period. The lower the solidification time, the higher the production rate achievable by the process. In thermoset resins, usually the higher the cure temperature, the faster the cross-linking process. In thermoplastics, there is no chemical change during solidification and therefore solidification requires the least amount of time.

- **The above four steps are common in thermoset as well as thermoplastic composites processing.**

Advantages of Thermoset Composites Processing

The common thermoset resins are **epoxy, polyester, and vinylester**. These materials could be **one-part or two-part systems** and are generally in the **liquid state at room temperature**. These resin systems are then cured at **elevated temperatures or sometimes at room temperature** to get the final shape.

1. Processing of thermoset composites is much easier because the initial resin system is in the liquid state.

2. Fibers are easy to wet with thermosets, thus voids and porosities are less.

3. Heat and pressure requirements are less in the processing of thermoset composites than thermoplastic composites, thus providing energy savings.

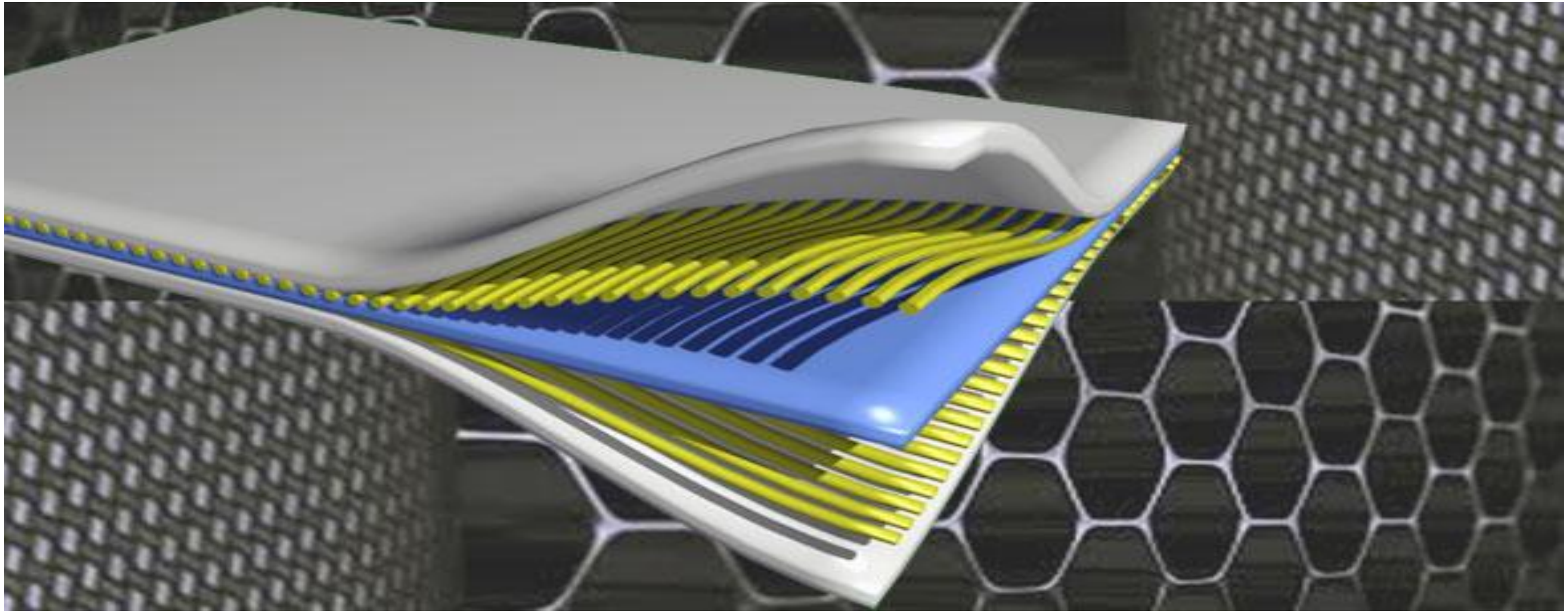
4. A simple low-cost tooling system can be used to process thermoset composites.

- **Disadvantages of Thermoset Composites Processing**
- 1. Thermoset composite processing requires a lengthy cure time and thus results in lower production rates than thermoplastics.
- 2. Once cured and solidified, thermoset composite parts cannot be reformed to obtain other shapes.
- 3. Recycling of thermoset composites is an issue.

- **Advantages of Thermoplastic Composites Processing**
- The initial raw material in thermoplastic composites **(e.g., polyimide (PI), polyetheretherketone (PEEK)** is in a solid state and needs to be melted to obtain the final product.
- 1. The process cycle time is usually very short because there is no chemical reaction during processing, and therefore can be used for high-volume production methods. For example, the process cycle time for injection molding is less than 1 min and therefore very suitable for automotive-type markets where production rate requirements are usually high.
- 2. Thermoplastic composites can be reshaped and reformed with the application of heat and pressure.
- 3. Thermoplastic composites are easy to recycle.

- **Disadvantages of Thermoplastic Composites Processing**
- 1. Thermoplastic composites require heavy and strong tooling for processing. Moreover, **the cost of tooling is very high in thermoplastic** composites manufacturing processes. For example, the tooling cost in the injection molding process is typically more than $50,000, whereas a mandrel for the filament winding process costs less than $500.
- 2. Thermoplastic composites are **not easy to process** and sometimes require sophisticated equipment to apply heat and pressure.

Composite Materials



Dr. Abbas Hasan Faris

- **Composites Manufacturing Processes**
- Composites manufacturing processes can be broadly subdivided into two main manufacturing categories: manufacturing processes for thermoset composites and manufacturing processes for thermoplastic composites. In terms of commercial applications, thermoset composite parts dominate the composite market. About 75% of all composite products are made from thermoset resins. Thermoset composite processes are much more mature than their thermoplastic counterparts mainly because of the widespread use of thermoset composites as well as their advantages over thermoplastic composite processing techniques. The first use of thermoset composites (glass fiber with unsaturated polyester) occurred in the early 1940s, whereas the use of thermoplastic composites came much later.

- **Manufacturing Processes for Thermoset Composites**
- **Hand lay-up process**

The hand lay-up process is mainly divided into two major methods: wet lay-up and prepreg lay-up.

Hand lay-up, or contact molding, is the oldest and simplest way of making fiberglass–resin composites. Applications are standard wind turbine blades, boats, etc.)

1. prepreg lay-up process

is very common in the aerospace industry, It is also called the autoclave processing or vacuum bagging process. Complicated shapes with very high fiber volume fractions can be manufactured using this process. It is an open molding process with low-volume capability.

In this process, prepregs are cut, laid down in the desired fiber orientation on a tool, and then vacuum bagged. After vacuum bagging, the composite with the mold is put inside an oven or autoclave and then heat and pressure are applied for curing and consolidation of the part.

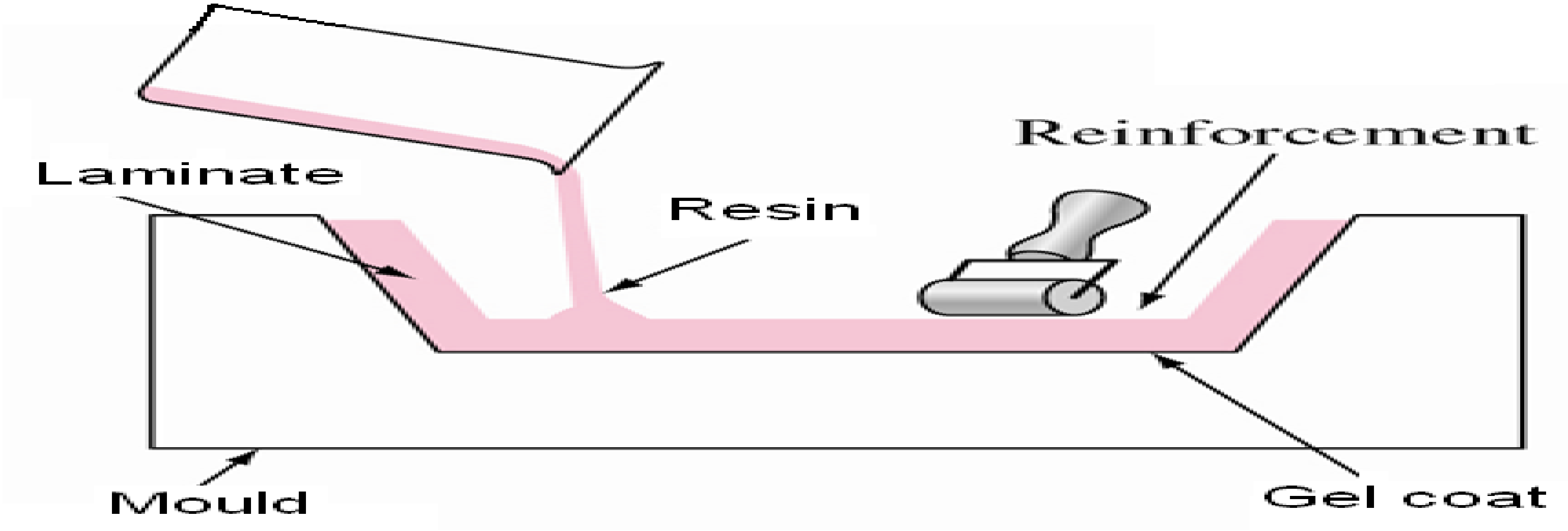
The prepreg lay-up or autoclave process is very labor intensive. Labor costs are 50 to 100 times greater than filament winding, pultrusion, and other high-volume processes; however, for building prototype parts and small quantity runs, the prepreg lay-up process provides advantages over other processes.

- **Hand lay-up process:**

  * Gel coat is applied to open mold. (An even layer of resin, up to (0.5 mm) thickness is applied to the mould surface. This resin layer, known as the " gel coat " contains additives to give colour to the surface.)

  * Fiberglass reinforcement is placed in the mold.

  * Base resin mixed with catalysts is applied by pouring brushing or spraying..



- **The functions of the gel coat is to :-**

  (i) Protect the fibers from external effects, mainly moisture penetration.

  (ii) Provide a smooth finish surface.

- when the gel coat is sufficiently cured , the first layer of fibers is placed on resin and used brush and roller to ensure the impregnation between the fibers and the matrix .

- **It is used for boats and medium to large building**

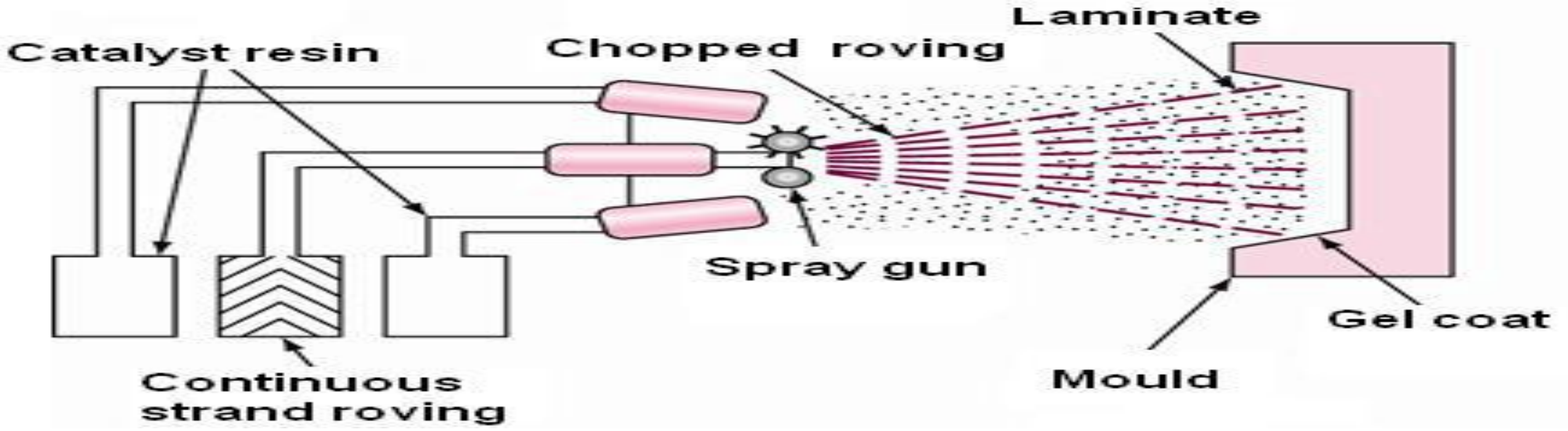
• Spray-up process:

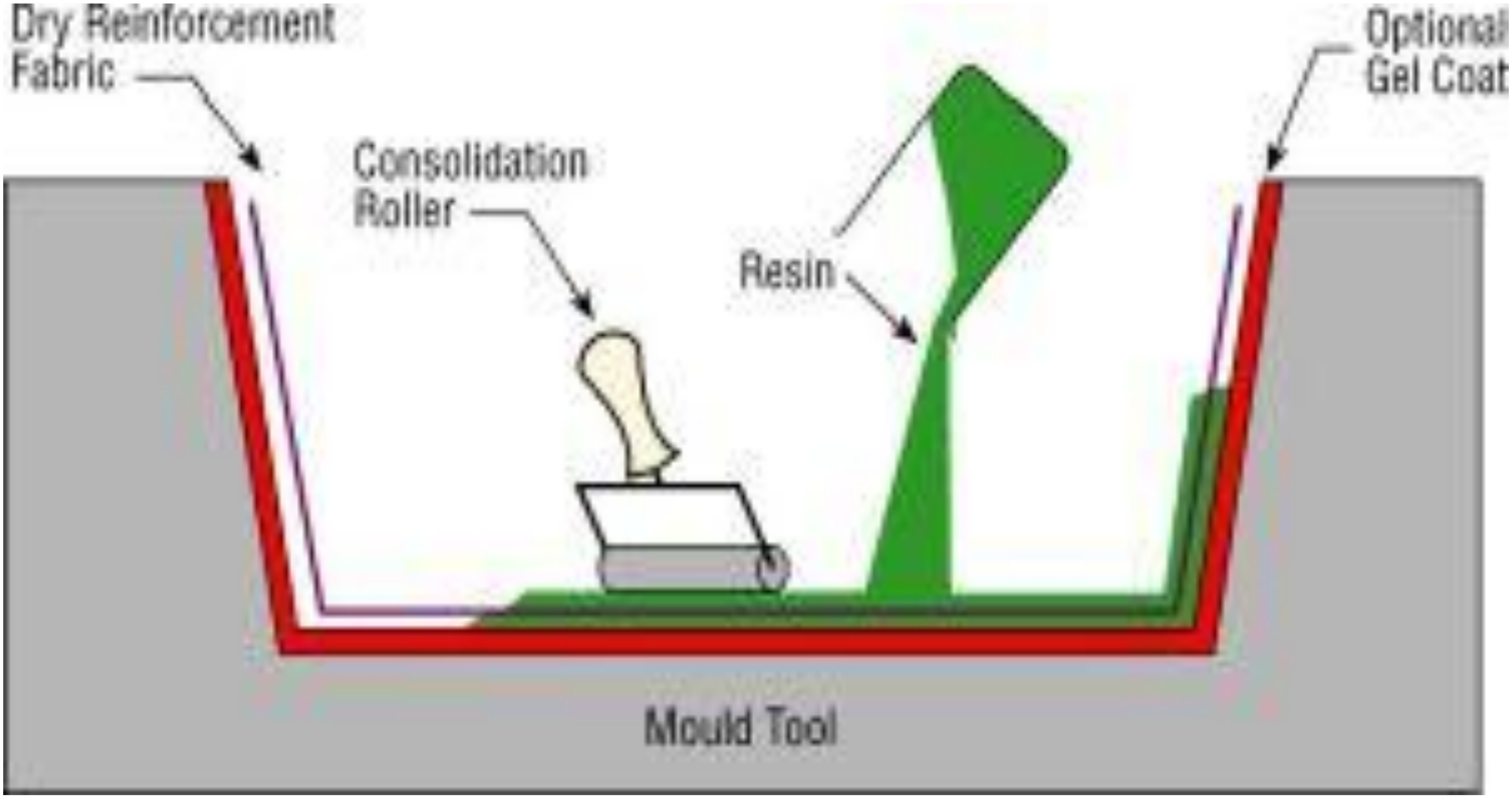
- This method is essentially similar to the hand lay-up method, but the reinforcement is usually chopped strands.
- The gel coat is applied to the mold, and then cured in a heated oven at 120ºC. Continuous strand of fiber roving are fed into chopper gun and then the fibers along with catalyzed resin are fed through a chopper gun over the mould. Fibers are cut into lengths, varying from 20 to 60 mm.

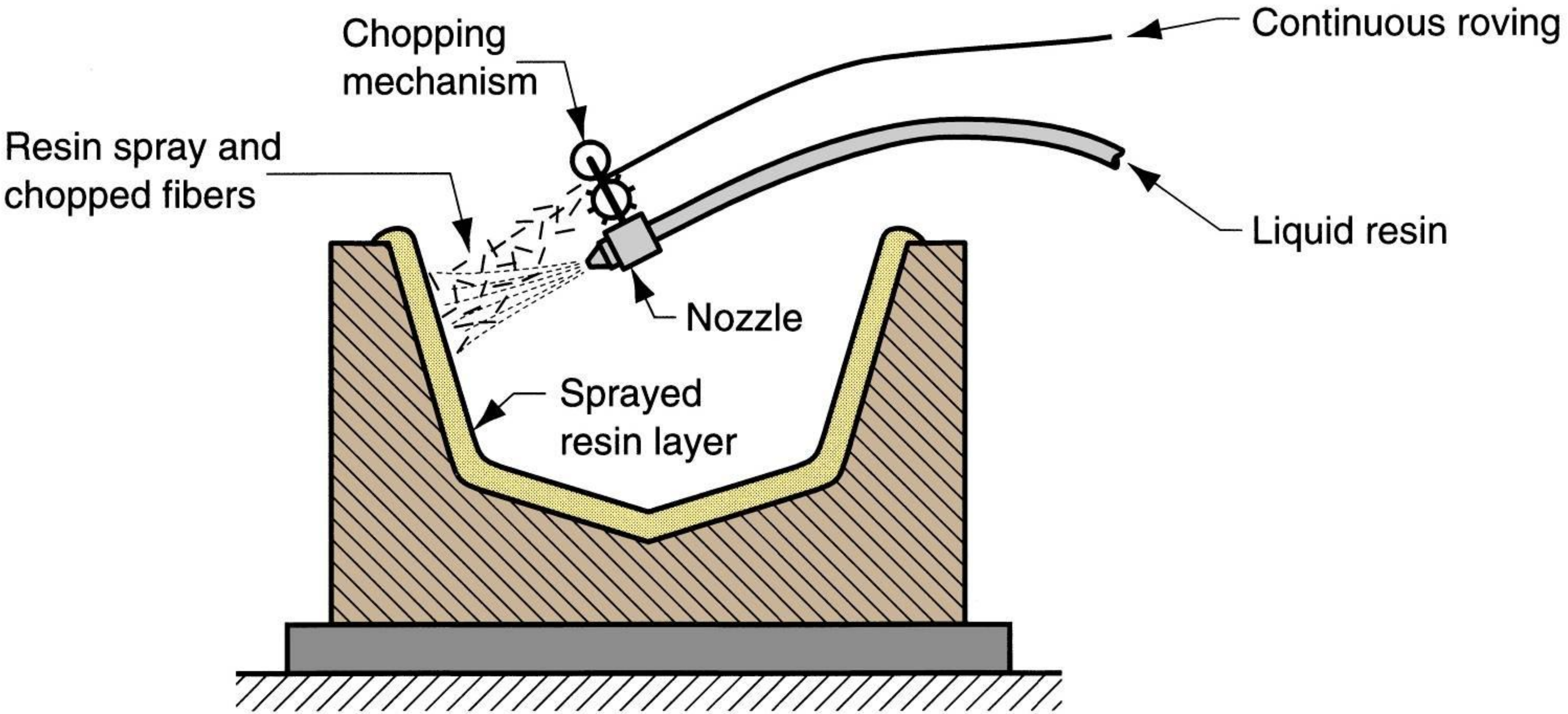
➢ Fiber roving is fed continuously through a chopping unit. At the same time with resin by means of a spray gun.

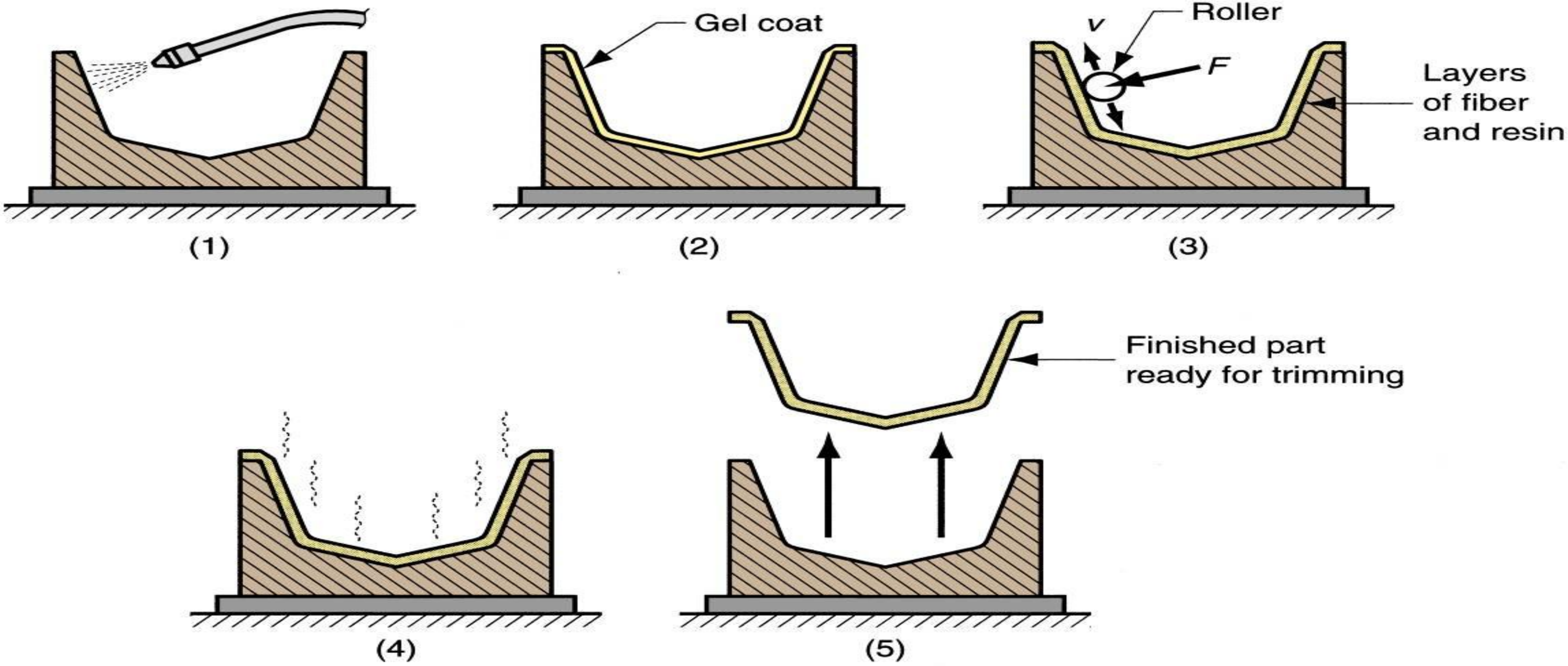
➢ The mixture is then rolled to consolidate and remove any air that may be present in the composite

➢ **It is used for:- 1. containers 2. automobile body parts**




Dry Reinforcement
Fabric
Consolidation
Roller
Resin
Mould Tool


Continuous roving
Chopping
mechanism
Resin spray and
chopped fibers
Liquid resin
Nozzle
Sprayed
resin layer



Hand lay-up : (fo ecafrus edistuo eht ot ،deilppa si (niser) taoc leg niht (٢) ؛tnega esaeler dlom htiw detaert si dlom (١ ؛htolc ro tam fo mrof eht ni si rebfi eht ،deilppa era rebfi dna niser fo sreyal ،tes yllatirap sah taoc leg nehw (٣) ؛gnidlom devomer si trap denedrah ylluf (٥) ؛deruc si trap (٤) ؛ria evomer dna niser htiw rebfi eht etangerpmi ot dellor si reyal hcae .dlom morf

- **1.1 Major Applications**
- The prepreg lay-up process is widely used in the aerospace industry as well as for making prototype parts. Wing structures, radomes, yacht parts, and sporting goods are made using this process.

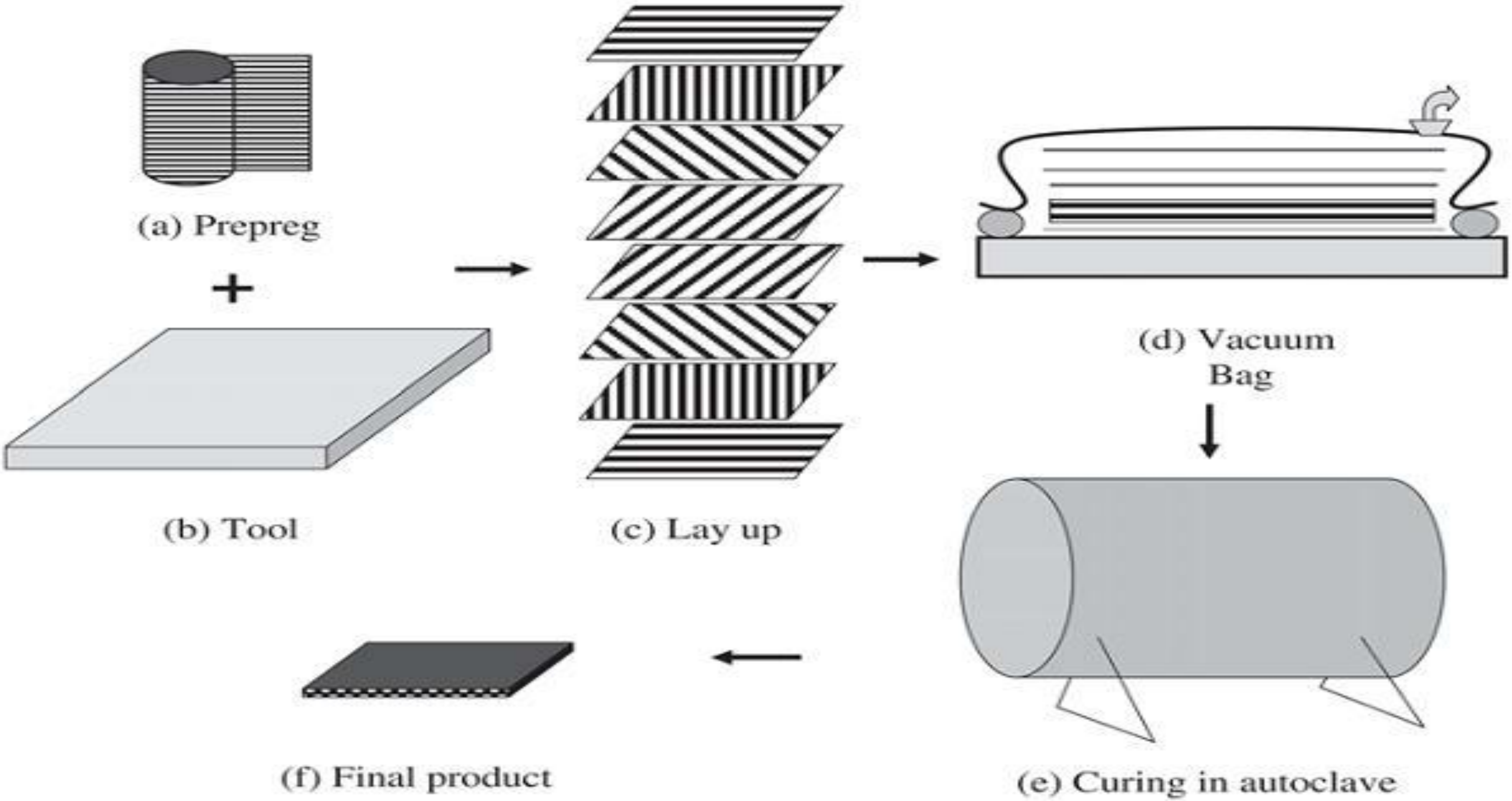
Large glass/epoxy/honeycomb sandwich fairings for the Airbus 330/340 flap tracks. (Courtesy of Marion Composites.)

- **1.2 Basic Raw Materials**
- 1.2.**1. Thermoset Prepregs**
- The most common resin used in thermoset prepreg materials is epoxy. Graphite/epoxy prepregs are the most commonly used materials for the prepreg lay-up process. Glass/epoxy and Kevlar/epoxy are also used but their use is much less than carbon/epoxy prepregs. The main reason is that carbon/epoxy is much lighter and stronger than other prepreg materials and provides greater mass savings in the component.
- Because this process is widely used in the aerospace industry, where weight is a critical design factor, carbon fiber prepreg is the material of choice. Moreover, in terms of cost, there is no significant price difference between carbon/epoxy prepregs and other prepregs.
- Other than epoxy, high-temperature resins such as polyimides, polycyanate, and bismaleimide (BMI) are also used in prepreg systems.

- These prepregs are generally stored in a low-temperature environment and have a limited shelf life. Room-temperature prepregs are also becoming available. Usually, the resin is partially cured to a tack-free state called B-staging. Several additives (e.g., flame retardants, catalysts, and inhibitors) are added to meet various end-use properties and processing and handling needs. Thermoset prepregs require a longer process cycle time, typically in the range of 1 to 8 hr due to their slower kinetic reactions. Due to higher production needs, rapid-curing thermoset prepregs are being developed. Thermoset prepregs are more common and more widely used than thermoplastic prepregs. They are generally made by solvent impregnation and hot melt technology.

- **1.2.2 Thermoplastic Prepregs**
- Thermoplastic prepregs have an unlimited shelf life at room temperature and are generally processed at the melting temperature of the resin. The most common resins are nylon, polyetheretherketone (PEEK), polyphe-nylene sulfide, polyimide, etc. The process cycle time for thermoplastic com-posites is much faster than thermoset composites, in the range of a few minutes. It is a relatively new technology and provides several processing and design advantages over thermoset prepregs. The benefits of thermoplas-tic prepregs are:
- Recyclability
- Good solvent and chemical resistance
- Reduced process cycle time
- Higher toughness and impact resistance
- Indefinite shelf life with no refrigeration
- Reshaping and reforming flexibility
- Greater flexibility for joining and assembly by fusion bonding and in situ consolidation
- Better repairability potential

- The disadvantages of thermoplastic prepregs are that they require higher temperatures and pressures for processing. They provide some processing difficulties because of their poor drape capabilities.
- Thermoplastic prepregs are manufactured by solvent impregnation and hot melt coating techniques similar to thermoset prepreg manufacturing. Solvent impregnation becomes difficult because thermoplastics offer more chemical resistance.


(a) Prepreg
+
(b) Tool
(c) Lay up
(d) Vacuum
Bag
(e) Curing in autoclave
(f) Final product

Tooling Requirements

- The tooling for the prepreg lay-up process is an open mold on which prepregs are laid in the desired fiber orientation and sequence. For prototype building purposes, tools are made by machining metals, woods, and plastics.
- For the manufacture of aerospace components, the tooling material is mostly the composite tooling material such as carbon/epoxy prepregs.

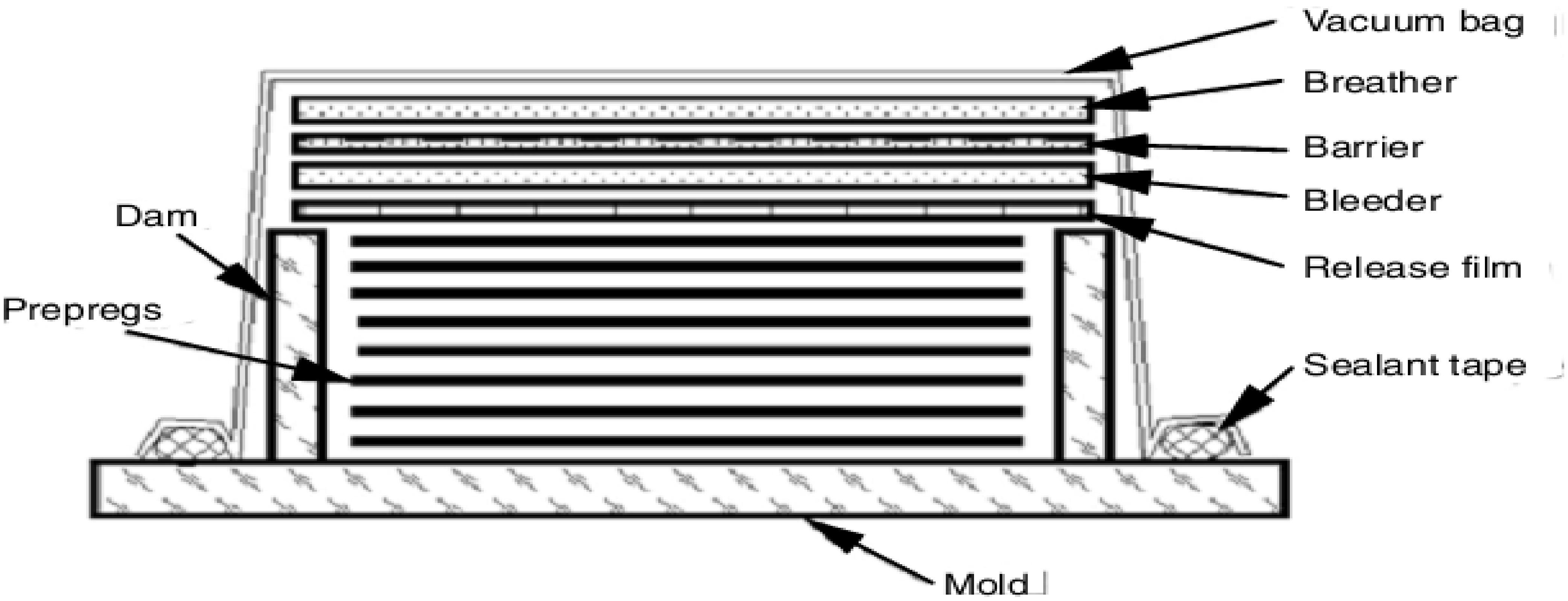
Making of the Part

1. The raw material for this process is prepreg material, which is kept refrigerated. To make the composite part, prepreg is removed from the refrigerator and brought slowly to room temperature.

2. Once the prepreg is brought to room temperature, it is cut to the desired length and shape. Predominantly unidirectional fiber prepregs are used for part fabrication.

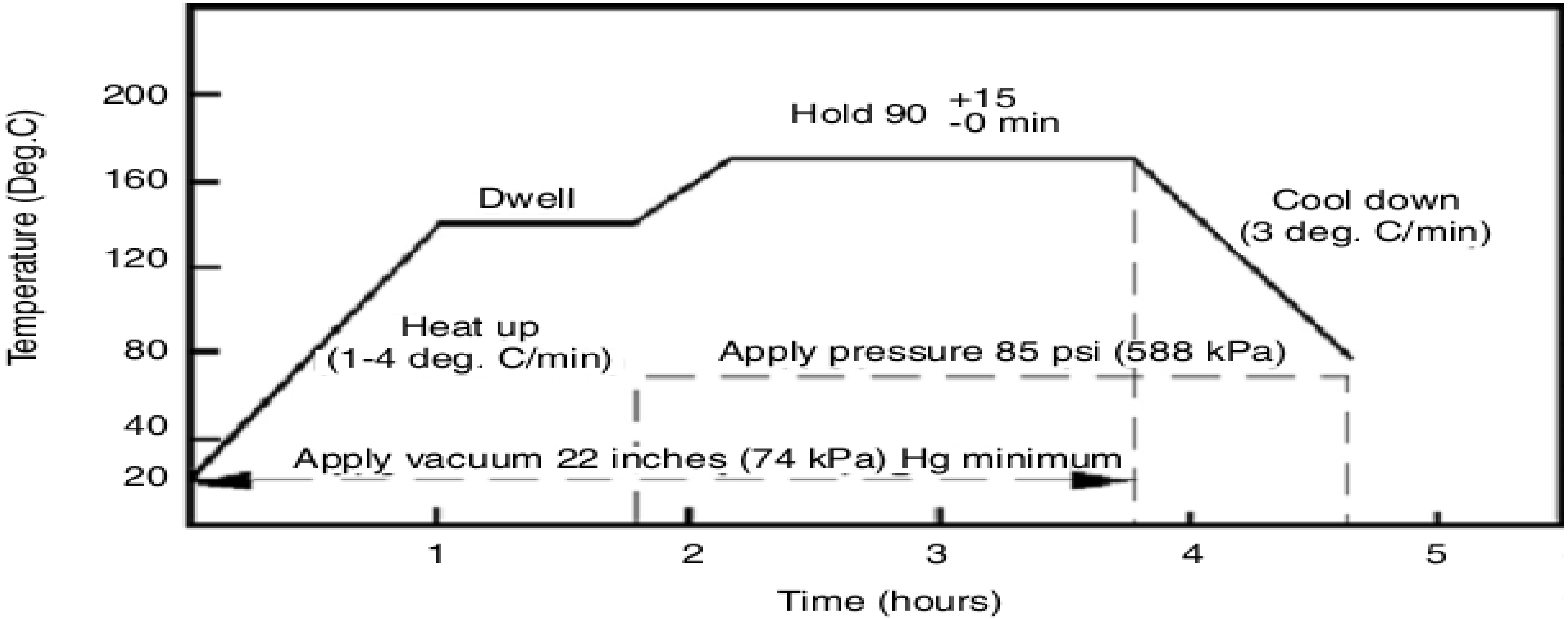
3. Part fabrication is done by laying the prepregs on top of an open mold. Release agent is applied to the mold for easy removal of the part.

- 4. Vacuum bagging preparations are made as shown in Figure for curing and consolidation of the part. The steps required for vacuum bagging are: Apply release film, bleeder, barrier film, breather layer which allow entrapped air, excess resins, and volatiles to escape. Finaly, apply the vacuum bag, which is connected to a vacuum hose for creating vacuum inside the bag.
- Once the part is cured, the vacuum bag is removed and the part is taken out.



- ## Methods of Applying Heat and Pressure

- After lamination and bagging, the mold is placed inside an autoclave for curing and consolidation. An autoclave, similar to a pressure vessel, can maintain the desired pressure and temperature inside the chamber for processing of the composite. A typical cure cycle is shown in Figure below.



1. The pressure is created in two ways: using the vacuum bag as well as the external pressure inside the autoclave.

2. To create vacuum inside the bag, the nozzle in the bagging system is connected to the vacuum pump using a hose. The vacuum pump generates the desired vacuum. External pressure inside the autoclave is created by injecting pressurized air or nitrogen.

3. the external pressure outside the bag and the vacuum inside the bag creates sufficient pressure to compact the laminate against the mold and create intimate contact between each laye.

4. The heat for curing comes from heated air or nitrogen. The pressurized gas supplied to the chamber comes heated to increase the temperature inside the autoclave.

5. As shown in Figure , vacuum is applied in the bagging system first and then the temperature is raised to a level to increase the resin flow. The heating rate is usually 2°C/min to 4°C/min. After dwelling for some time at the dwell temperature, the temperature is further raised to another level for curing of the composites. During this stage, pressure is applied to the outside of the bagging system and maintained for about 2 hr, depending on the requirements.

- Therefore, one can calculate the heat transfer to the autoclave as:
- $Q = \dot{Q}\Delta t$
- $Q = MCp\Delta T$
- Where $\dot{}$ is the heat power, Δt is the time to increase the temperature of the autoclave by ΔT = 1ºC, Cp is the specific heat of autoclve material, and M is the mass of the autoclave.

• Example

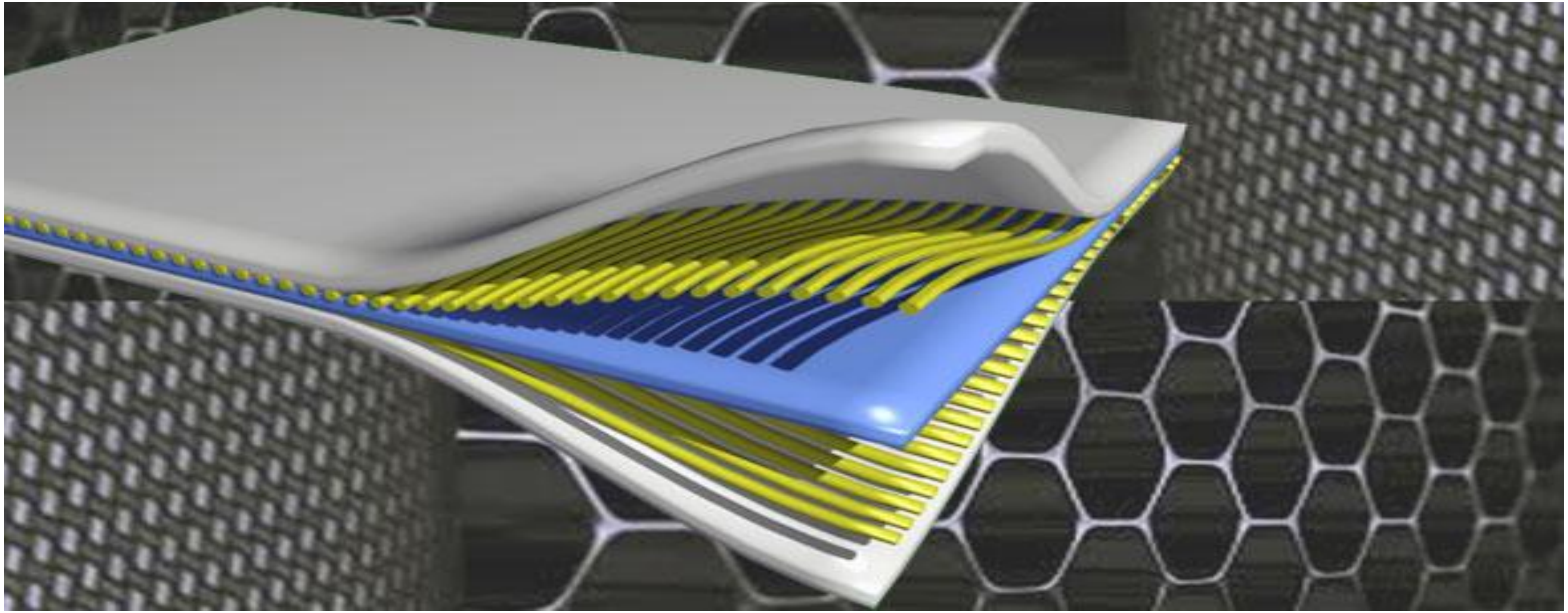
- Calculate the time required to heat an autoclave made of welded steel by 1 ºC. The autoclave is cylindrical tube with volume 0.94 m3. The heater power supplied to the autoclve was 50 kW. Given that ρ of steel is 7800 kg/m3 and Cp is 460 J/kg ºC.

- **Solution**
- M = ρ * V
- M = 7800 * 0.94
- = 7,351 kg
- $\dot{Q}\Delta t = MCp\Delta T$
- $\Delta t = MCp\ \Delta T /\ Q$
- $\Delta t = 7351 * 460 * 1/50 * 1000 = 67.6\ seconds$

- **Typical Manufacturing Challenges**
- 1. Maintaining accurate fiber orientations in the part is difficult because prepregs are laid down by hand.
- 2. Obtaining void-free parts is a challenge during this process. Voids are caused by entrapped air between layers.
- 3. Achieving warpage- or distortion-free parts during the prepreg lay-up process is challenging. Warpage is caused by built-in residual stresses during processing.

- **Advantages of the Prepreg Lay-Up Process**
- 1. It allows production of high fiber volume fraction (more than 60%) composite parts because of the use of prepregs. Prepregs usually have more than 60% fiber volume fraction.
- 2. Simple to complex parts can be easily manufactured using this process. 3. This process is very suitable for making prototype parts. It has the advantage of low tooling cost but the process requires high capital investment for the autoclave.
- 4. Very strong and stiff parts can be fabricated using this process.
- **Limitations of the Prepreg Lay-Up Process**
- 1. It is very labor intensive and is not suitable for high-volume pro duction applications.
- 2. The parts produced by the prepreg lay-up process are expensive.

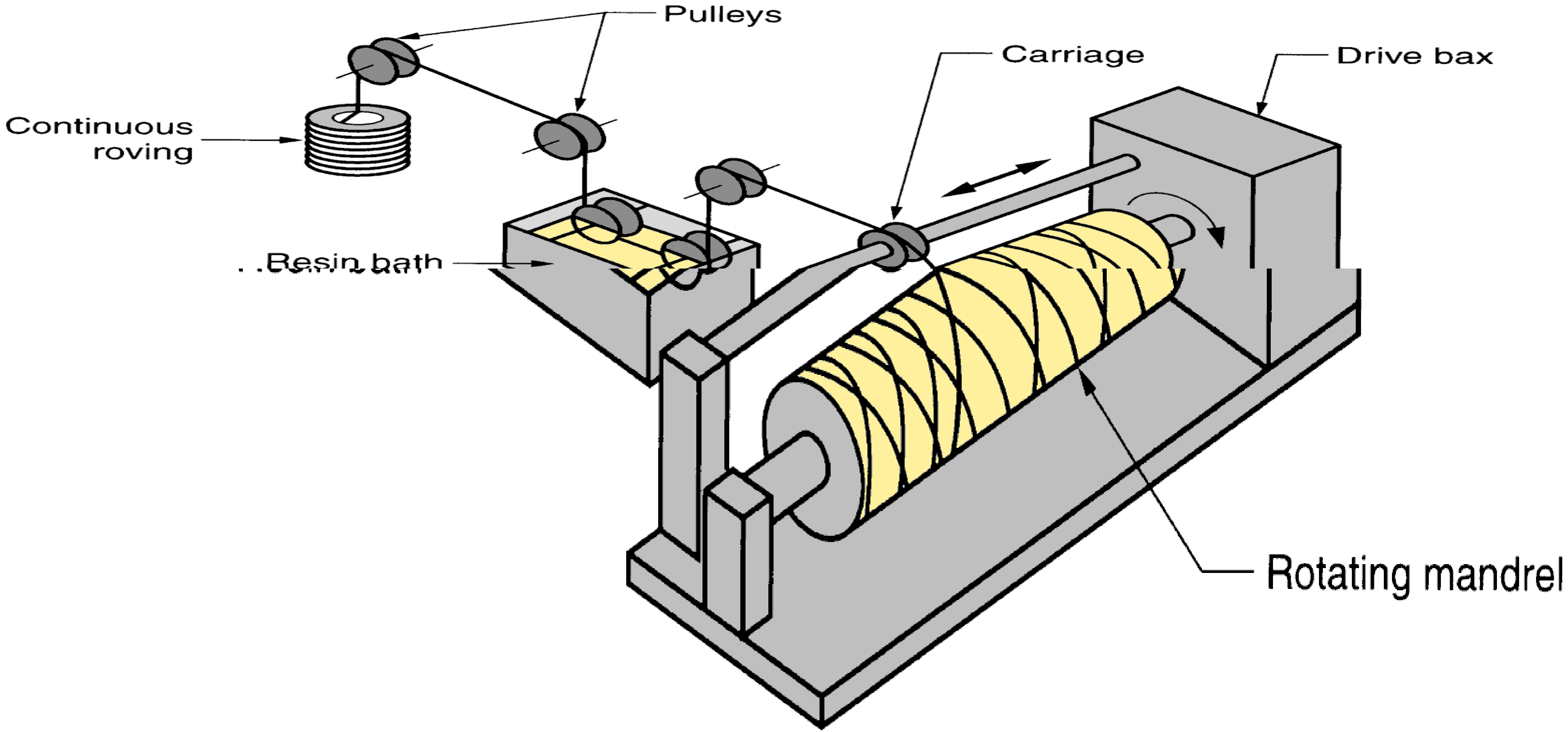
Composite Materials



Dr. Abbas Hasan Faris

Lecture-10

- **Filament Winding Process**
- Filament winding is a process in which resin-impregnated fibers are wound over a rotating mandrel at the desired angle. A typical filament winding process is shown in Figure.
- Filament winding is an automated open molding process that uses a rotating mandrel as the mold. This process is used for the manufacturing of hollow, (generally cylindrical) products.
- The operation is repeated to form additional layers, each having a criss-cross pattern with the previous until the desired part thickness has been obtained


Pulleys
Carriage
Drive bax
Continuous
roving
Resin bath
Rotating mandrel

- in which, a carriage unit moves back and forth and the mandrel rotates at a specified speed. By controlling the motion of the carriage unit and the mandrel, the desired fiber angle is generated.
- This is a predominant composites manufacturing process for axisymmetric composites – such as compressed gas storage tanks or pipeline sections. The process also offers speed and cost advantages for structural axisymmetric parts such as struts, axles, and drive shafts.

- The advantages of this process are that it is a very fast method, resin content is controlled, makes high-weight to strength laminates, can obtain high fiber weight percentages, and can achieve controlled fiber orientation that gives directional strength characteristics. Disadvantages are that the shape is limited to circular and oval products, the mandrel may be expensive, and poor external surface finish may affect aerodynamics in some applications (thus needs a finishing process, machining/sanding of the exterior surface).

-
- **1- Major Application**
- The most common products produced by the filament winding process are tubular structures, pressure vessels, pipes, chemical storage tanks.
- Used to produce round-form products that have a high degree of structural integrity (tanks, pipes, pressure vessels, etc.). A rotating mandrel is used as the mold and is automated.
- Examples: sail boat masts, cement mixers, aircraft fuselages, tanks, chemical storage tanks, gas and pressure cylinders.
- Filament wound glass reinforced plastic (GRP) is used for water supply piping systems. It provides clean and lead-free piping system. Filament wound pipe reduces the pumping energy required to move water by 10 to 35%, due to its smooth interior surfaces compared to concrete or ductile iron pipe.

- **2- Basic Raw Materials**
- In general, starting materials for filament winding are continuous fibers (yarns) and liquid thermoset resins. Yarns are kept in spool form at the back rack and passed through a resin bath located in the carriage unit. Fibers get wet as they pass through the resin bath.
- Glass, carbon, and Kevlar fibers are used for the filament winding process but glass fibers are more common because of its low cost. Epoxy, polyester, and vinylester are used as resin materials. Glass fibers with polyester resins are widely used for low-cost applications.

- **3- Tooling**
- The most common tooling material for the filament winding process is a steel mandrel. Steel mandrels are chrome plated in certain applications to get a high-gloss finish on the inside surface of the composite structure as well as to aid in easy removal of the mandrel.

- For some applications, such as pressure vessels, the mandrel is not removed and becomes an integral part of the composite structure. The non-removal mandrel provides an impermeable layer/barrier surface on the composite inner surface and thus avoids leakage of compressed gas or liquid inside the pressure vessel.

- **4- Making of the Part**

- To make filament wound structures, a mandrel is place on the filament winding machine as shown in Figure. The mandrel rotates and the carriage unit moves relative to the mandrel to lay down the resin-impregnated fibers at a specific angle.
- The carriage unit can move along the x, y, and z axes as well as rotate about these axes. In two-axes filament winding machines, the mandrel rotates and the carriage unit moves back and forth only in one direction.

- Before winding begins, the mandrel is coated with release agent. Once the mandrel is prepared, it is placed between the head and tail stocks of the machine. During wet winding, fiber yarns, which are placed in spool form at the creels, are passed through the resin bath located in the carriage unit and then to the mandrel through the payout eye.
- Laminate is formed after a series of relative motions between the mandrel and the carriage unit. To get the desired winding, the machine operator inputs various parameters such as pipe diameters, mandrel speed, pressure rating, band width, fiber angle, etc., depending on the software requirements.
- After creating the desired fiber angle distribution, the mandrel with the composite laminate is removed to a curing area where the laminate is cured at room temperature or at elevated temperature.
- Once the part is cured, the mandrel is extracted using an extracting device. Sometimes, a small taper angle is provided in the mandrel for easy removal of the composite part.

- **5- Methods of Applying Heat and Pressure**
- The pressure during filament winding is applied by creating fiber tension. In general, 1 lbf to 6 lbf fiber tension is created using some tensioning device or by passing the fibers through the carriage unit in such a way that it creates tension.
- Composites thus fabricated are cured at room temperature, or in an oven at a higher temperature. For large-volume production, the process of part fabrication is automated. In an automated line, the filament wound part with the mandrel is moved to a heated chamber using a robot. The part slowly moves in the heated chamber and comes out after partial or full cure of the composite part. The part is then sent to the mandrel extracting station where the mandrel is extracted and sent back to the filament winding machine for winding purposes. All of this can be done automatically.

- The stress in each fiber is σf, acting on the cross-sectional area A of the fiber band. The force on the fiber is $A\sigma f$. The component of this force along the x direction (along the length of the cylinder) is $A\sigma f \cos\alpha$. This force is acting over an area $Ax=A/\cos\alpha$. Dividing the force along the x direction over the area normal to the x direction yields the stress σx
- as:
- $\sigma x = \sigma_f \cos^2\alpha$ (1)
- Similarly, for the stress along the y direction (or hoop direction):
- $\sigma y = \sigma_f \sin^2\alpha$ (2)
- where α is the winding angle. It can easily be seen that
- $\sigma y/\sigma x = \tan^2\alpha$ (3)
- Also from equilibrium conditions, it can be shown that for a thin-walled pressure vessel under internal pressure, the longitudinal and hoop stresses are given by:

- $\sigma x = \frac{pr}{2t}$ (4)
- $\sigma y = \frac{pr}{t}$ (5)
- wehere
- p= internal pressure
- t= thickness
- r= radius of the cylinder (for thin cylinder either inside or out-side radius can be used)
- from previous equations:
- $\frac{\sigma y}{\sigma x} = 2$

- **winding at layers at two different angles:**
- When winding consists of two layers at different angles, the following equations can be derived.
- Using equilibrium along the longitudinal direction:
- $\sigma x(t_1 + t_2) = \sigma_{f1} t_1 \cos^2\alpha_1 + \sigma_{f2} t_2 \cos^2\alpha_2$ (6)

- Using equilibrium along the hoop direction:
-
- $\sigma y(t_1 + t_2) = \sigma_{f1} t_1 \sin^2\alpha_1 + \sigma_{f2} t_2 \sin^2\alpha_2$ (7)

- **Example**
- A pressure vessel with internal diameter of 40 cm is subjected to an
- internal pressure of 7 MPa. It is to be wound using fibers at 90°and at
- +/−45°. Fiberglass with a strength of 1 GPa is used. If the thickness of the
- hoop (90°) layer is 2 mm, what would be the required thickness of the
- +/−45°layer?
- **Solution**
- From Equations (6) and (7) we have:
- $\sigma x(t_1 + t_2) = \sigma_{f1} t_1 \cos^2\alpha_1 + \sigma_{f2} t_2 \cos^2\alpha_2$
- $\sigma y(t_1 + t_2) = \sigma_{f1} t_1 \sin^2\alpha_1 + \sigma_{f2} t_2 \sin^2\alpha_2$
- Let layer 1 be the 90°layer and layer 2 be the +/−45°layer.
- $\sigma x(0.002 + t_2) = (10^9 \text{Pa}) t_2 (0.5)$

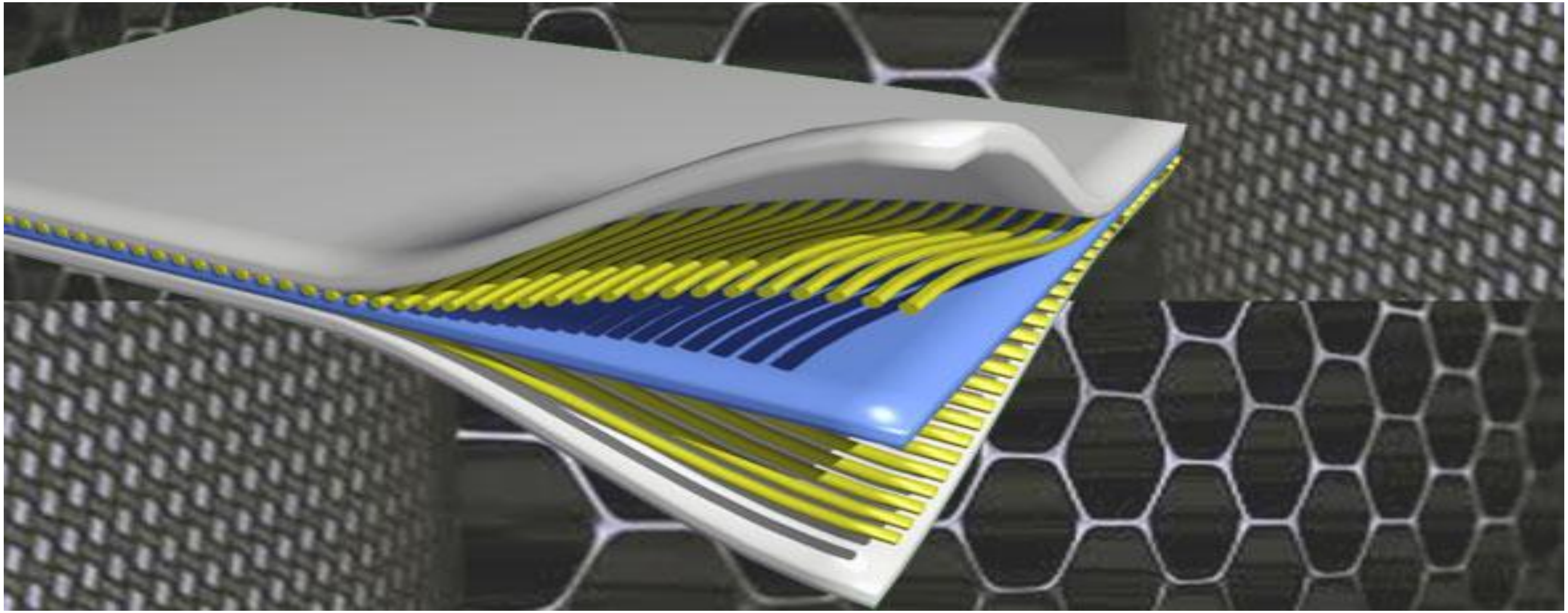
- $\sigma y(0.002 + t_2) = (10^9 Pa)(0.002\ m) + (10^9 Pa)t_2\ (0.5)$
- But, $\sigma y/\sigma x = 2$

- $(10^9 Pa)(0.002\ m) + (10^9 Pa)(0.5\ t_2) = (10^9 Pa)\ t2$

- **6- Advantages of the Filament Winding Process**
- 1. For certain applications such as pressure vessels and fuel tanks, filament winding is the only method that can be used to make cost-effective and high-performance composite parts.
- 2. Filament winding utilizes low-cost raw material systems and low-cost tooling to make cost-effective composite parts.
- 3. Filament winding can be automated for the production of high-volume composite parts.

- **7- Limitations of the Filament Winding Process**
- Filament winding is highly suitable for making simple hollow shapes. However, the process has the following limitations.
- 1. It is limited to producing closed and convex structures. It is not suitable for making open structures such as bathtubs. In some applications, filament winding is used to make open structures such as leaf springs, where the filament wound laminate is cut into two halves and then compression molded.
- 2. Not all fiber angles are easily produced during the filament winding process. In general, a geodesic path is preferred for fiber stability. Low fiber angles (0 to 15°) are not easily produced.
- 3. The maximum fiber volume fraction attainable during this process is only 60%.
- 4. During the filament winding process, it is difficult to obtain uniform fiber distribution and resin content throughout the thickness of the laminate.

Composite Materials



Dr. Abbas Hasan Faris

Lecture-11

Pultrusion Process

- **The pultrusion** process is a **low-cost, high-volume manufacturing process** in which resin-impregnated fibers are pulled through a die to make the part.
- Pultrusion creates parts of **constant cross-section** and **continuous length**.

1- Major Applications

- Pultrusion is used to fabricate a wide range of solid and hollow structures with constant cross-sections. The most common applications are in making beams, channels, tubes, flooring and equipment support, walkways and bridges, ladders, light poles, electrical enclosures,etc.

2- Basic Raw Materials

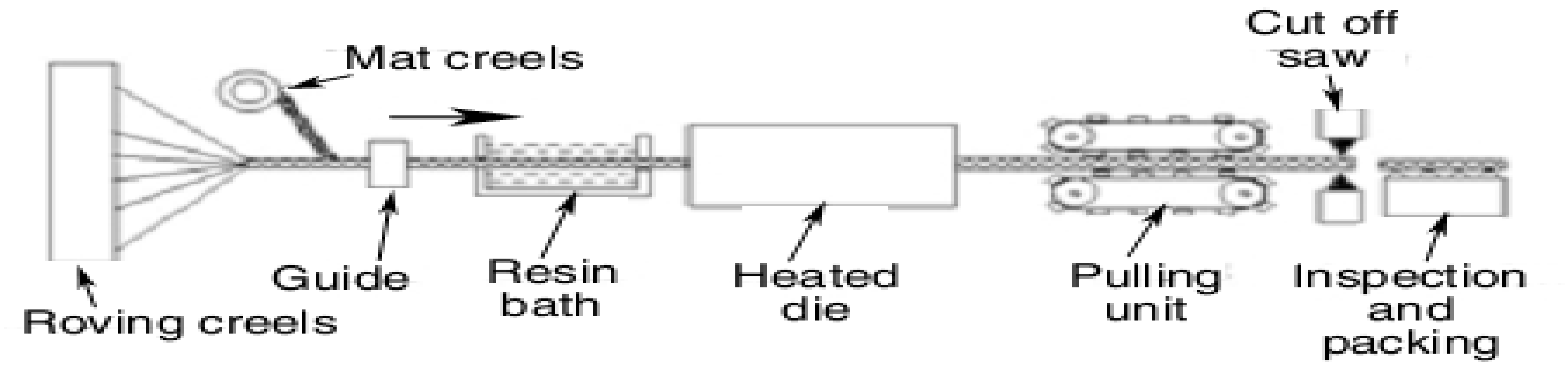
- Pultrusion is typically used for making parts with unidirectional fibers. E- glass, S-glass, carbon, and aramid fibers are used as reinforcements, the most common type being E-glass rovings. Fabrics and mats are also used to add bidirectional and multidirectional strength properties.
- Unsaturated polyester is the most common resin material for the pultrusion process. Pultrusion offers an attractive performance-to-price ratio as well as easy processing.
- Various types of fillers are added to the polyester resin to improve the insulation characteristics, chemical resistance, and fire resistance, and to lower the overall cost. Calcium cabonates are added to lower the cost of the pultruded part.

3- Tooling

- For the pultrusion process, steel dies are used to transform resin-impregnated fibers to the desired shape. Dies have a constant cross-section along their length, except for some tapering at the raw material entrance. The dies are heated to a specific temperature for partial or complete cure of the resin.
- Tooling costs depend upon the complexity of the part as well as the volume requirement. The cost of the die ranges from $4000 to $25,000, depending on the size and cross-section of the part.

4- Making of the Part

- To make composite parts using the pultrusion process, spools of rovings are placed on the creel similar to the filament winding process and then reinforcements are passed through a resin bath where fibers are impregnated with the resin.



There are two major impregnation options. In the first option, rovings are passed through an open resin bath. The reinforcement can pass horizontally inside the bath or up and down through a guiding mechanism.

In the second option, reinforcement passes through a cavity where resin is injected under pressure. The advantages of this method are no or minimum styrene emission and low resin loss.

- Reinforcements thus impregnated are passed through a heated die. The die has a slight taper at the entrance and a constant cross-section along its length. The resin cures and solidifies as it passes through the heated die. The length of the die depends on resin reactivity, part thickness, and production rate requirements. The higher the resin reactivity, the shorter the die length requirement.

- The solidified material is pulled by caterpillar belt pullers or hydraulic clamp pullers. These pullers are mounted with rubber-coated pads that grip the composite material. The puller is distanced from the die in such a way that the composite material cools off enough to be gripped by the rubber pads.

5- Methods of Applying Heat and Pressure

- During pultrusion, there is no external source to apply presure for consolidation. Therefore, this process is known as a low-pressure process. The resin-impregnated rovings or mat, when passed through a restricted passage of the die, gets compacted and consolidated. The die is heated to a temperature and applies heat to incoming material for desired cure. The heat in the die cures the resin. The part coming out of the die is hot and is allowed to cool before it is gripped by the puller.

6- Advantages of the Pultrusion Process

- 1. It is a continuous process and can be compeletely automated to get the finished part. It is suitable for making high-volume composite parts. Typical production speeds are 2 to 10 ft/min.
- 2. It utilizes low-cost fiber and resin systems and thus provides production of low-cost commercial products.

7- Limitations of the Pultrusion Process

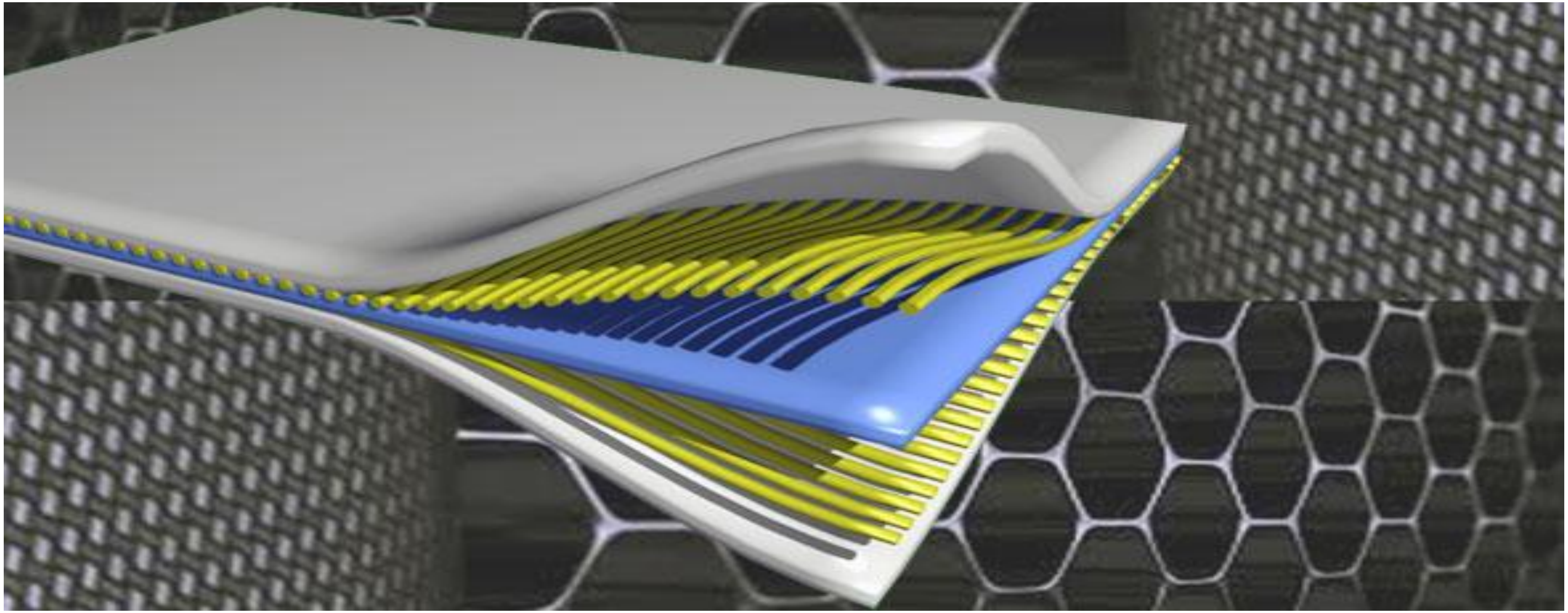
- 1. It is suitable for parts that have constant cross-sections along their length. Tapered and complex shapes cannot be produced.
- 2. Thin wall parts cannot be produced.
- 3. Fiber angles on pultruded parts are limited to 0°. Fabrics are used to get bidirectional properties.
- 4. Structures requiring complex loading cannot be produced using this process because the properties are mostly limited to the axial direction.

- **Thermoset versus Thermoplastic Pultrusion**
- Physically, thermoset pultrusion involves an additional station of a resin bath between fiberrovings and the preheater .Despite this additional step, the thermoset and thermoplastic pultrusion processes are physically quite similar.
- They both pull fibers and resin through a converging die to form continuous composite sections. However, from an analysis viewpoint, the flow in thermoplastic pultrusion is modeled differently than in thermoset pultrusion.
- In thermosets, one uses Darcy’s law to model resin impregnation and the heat transfer involves cure kinetics, whereas in thermo-plastic pultrusion due to the high viscosity of the material, Darcy’s law is not the correct model to calculate the relationship between flow rate and pressure drop. Also, due to the shear thinning nature of thermoplastics, one would expect the viscosity to vary inside the die.

- The heat transfer models do not usually involve cure but sometimes will consider the crystallization of the thermoplastics as it passes through the cooling die.

- In this section, the focus will be on development of a model that can describe the flow dynamics for a thermoplastic matrix as the material passes through the tapering die. The goal will be to calculate the pressure drop as a function of the pulling speed and material parameters such as viscosity and fiber volume fraction.

Composite Materials



Dr. Abbas Hasan Faris

Lecture-12

Characterization of Composite Materials

- The composites have major applications in advanced fields such as structure, thermal engines, blades, automobiles, aerospace, rocket, and missiles. The characterization of a composite is one of the essential tasks for developing the desired composite products for particular applications.

- Composite material characterization is a vital part of the product development and production process. Physical and chemical characterization helps developers to further their understanding of products and materials, thus ensuring quality control.

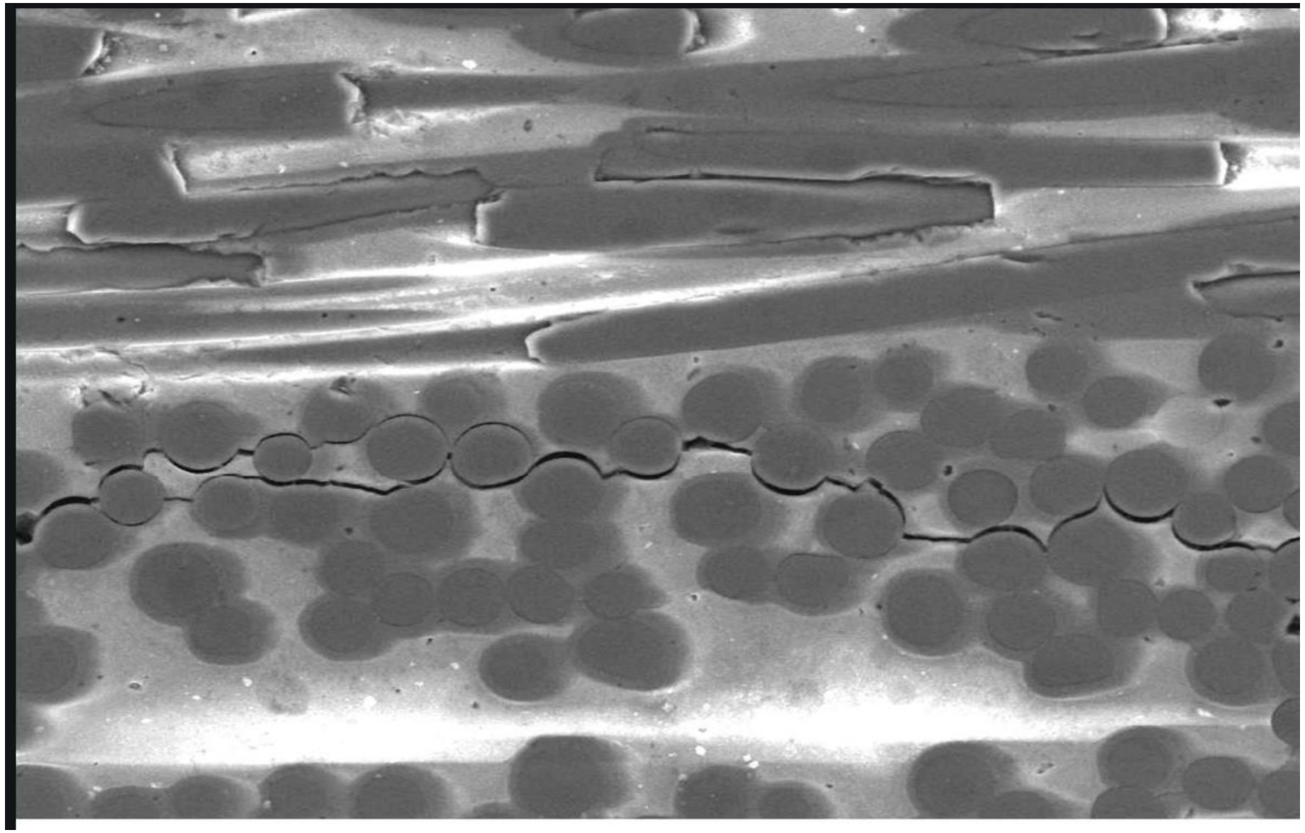
- The major characterization studies used for composites for the evaluation of performance in the targeted areas are mechanical, thermal, electrical, magnetic, piezoelectric, tribological, rheological, and biological.

1. Volume Fraction

In a composite material, the parameter "volume fraction" plays a major role in characterizing its various properties such as mechanical, thermal, electrical, etc. The fiber volume fraction determines the strength of the composites.

Delamination is the major damage noticed for specimens with higher fiber volume percent,

- while the matrix cracking and interface debonding occur for materials with low fiber volume percent.

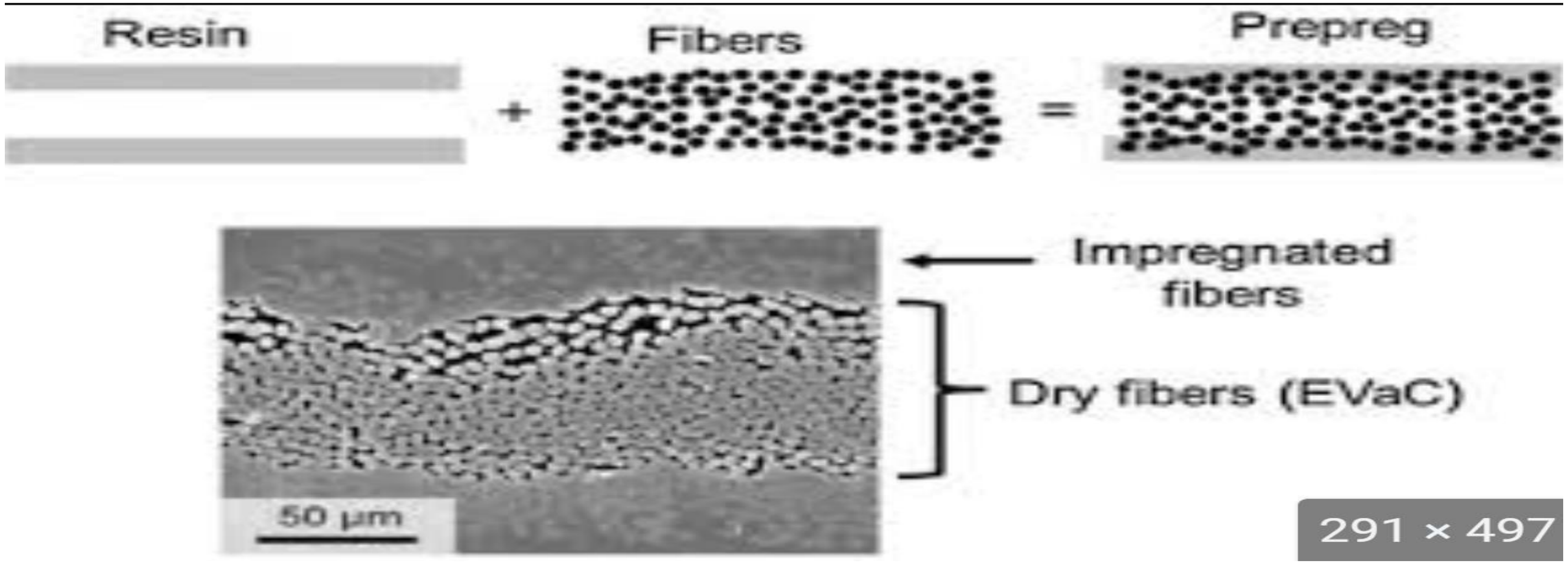


The fiber volume fraction (Vf) can be written in terms of fiber weight fraction(Wf) as :

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

- Where ρm, ρf, Wf, and Wm are the density of the matrix, the density of the fiber, the weight fraction of the fiber, and the weight fraction of the matrix, respectively.
- The fiber volume percent of a composite are determined by chemical matrix digestion method, the burn test, or by photomicrographic techniques.

- **2. Voids**
- Voids form at the interface of composite structures.



- These are generally formed as gas bubbles trapped inside the cured composite materials. The primary sources of voids include the material constituents and the synthesis processes.
- Void is undesirable and has an adverse effect on the mechanical properties of composites. Void area greater than 0.03 mm2 results in the deterioration of mechanical properties.The equation for determining the volume fraction of the void is given as:

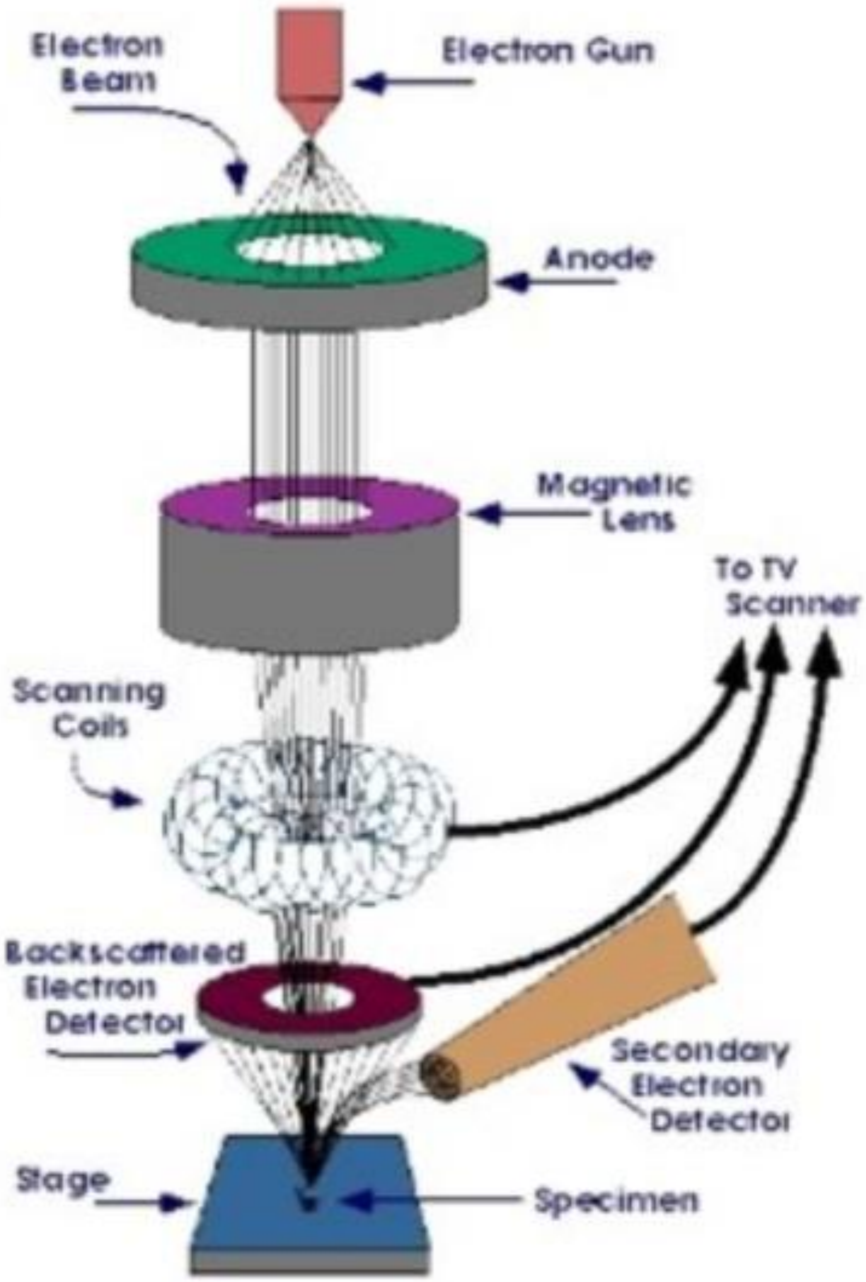
$$V_{void} = 1 - \rho_{com}^{exp} \left(\frac{W_m}{\rho_m} + \frac{W_f}{\rho_f} \right)$$

- Where is the experimentally determined composite density.

- **3. Surface Roughness**
- Surface roughness is an important parameter for ascertaining surface quality and aesthetic value. The average surface roughness (Ra value) is one of the most frequently used parameters for surface roughness, which describes the height of irregularities and gives an indirect indication of the sharpness and depth of surface notches. Researchers have used this Ra value for studying the impacts of various process parameters on the surface quality of FRP(fiber-reinforced polymer composites) composites.

- **4. Surface Topography**
- Scanning electronmicroscope (SEM)
- is also used for studying the topography of solids. In the field of FRPs, it is used to reveal the actual distribution of fibers and matrix in the composite. It is also used for the analysis of fractured surfaces and helps to examine the crack propagation in fibrous composite materials in order to gain an insight into composite strength, the adhesion between the phases, and the mode of failure.

Scanning Electron Microscope (SEM)



- **5. Mechanical properties**

- The mechanical properties of composites include (i) strain and yield strength in tension, compression, shear, and torsion, (ii) ILSS (Interlaminar Shear Strength) between the matrix and fiber, (iii) flexural fatigue strength, (iv) impact strength, (v) stress relaxation, and (vi) creep.

- **6. Thermal properties**

- Thermal characterization is very important to achieve precise measurements before the application. The thermal behavior of composite materials is evaluated based on the coefficient of thermal expansions (CTEs). The CTEs are given by Eq:

$$\alpha_l = \frac{V_f \alpha_{fl} E_{fl} + V_m \alpha_m E_m}{V_f E_{fl} + V_m E_m}$$

- Where α_l, α_{fl}, E_{fl}, α_m, E_m, are the coefficient of thermal expansion in the longitudinal direction, the coefficient of thermal expansion of fibers in the longitudinal direction, the modulus of fibers in the longitudinal direction, the coefficient of thermal expansion of the matrix, the mod++++ulus of the matrix.

- Similarly, the longitudinal thermal conductivity of the composite can be written as:

$$K_l = V_f K_{fl} + V_m K_m$$

- where K_l, K_{fl}, and K_m are the thermal conductivity of the composite in the longitudinal direction, the thermal conductivity of fibers in the longitudinal direction, the thermal conductivity of the matrix, respectively.

- **Glass Transition Temperature:**
- Glass transition temperature (denoted by“Tg”) is the temperature at which a material experiences a significant change in properties from hard and brittle to soft and pliable.
- At glass transition temperature, the polymeric structure turns “rubbery” upon heating and“glassy” upon cooling. It is to be noted that in the case of low Tg materials, in order to achieve the benefit of the orientation enhancement effect, the Tg should be in the vicinity of or lower than the measuring temperature.

- **7. Electrical properties**

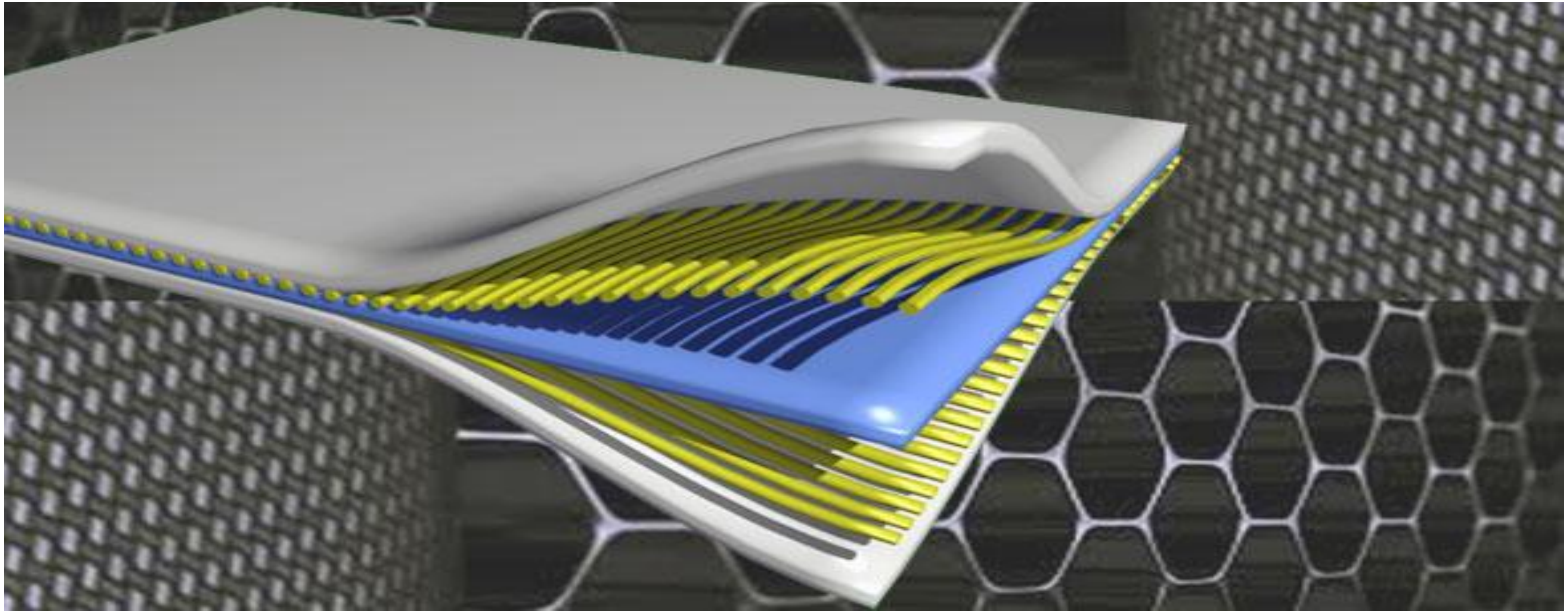
- It has been shown that the composite structure using an insulating a polymer as the host matrix improves the physical and chemical properties of electrically conductive polymers (ECPs).
- In the high-temperature region, the electrical conductivity (σ) of the films is found to follow the equation given below :

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{kT}\right)$$

- where E_a, T, and k are the activation energy, absolute temperature, and Boltzmann constant, respectively. It has been reported that the mechanical properties of the conductive composites can be improved with a decrement in electrical conductivity.

- **8. Biological properties**
- Biological characterizations of composite materials include toxicity and degradation testing procedures, which are most important in biological applications. The interphases of such composites are particularly important in the case of bio-related applications; hence, their properties in terms of biocompatibility, biodegradability, and bioactivity have to be well understood before practical applications.

Composite Materials



Dr. Abbas Hasan Faris

Lecture-13

REFERENCES

- **1- Composite Materials, Science and Engineering. Third Edition. By Krishan K. Chawla**

2- COMPOSITES MANUFACTURING, Materials, Product, and process Engineering. By Dr. Sanjay K. Mazumdar

- 2-