Chapter 16: Composites

ISSUES TO ADDRESS...

- What are the classes and types of composites?
- What are the advantages of using composite materials?
- How do we predict the elastic modulus for composites with simple structures?
- Processing of composites

Composite

- (Purposeful) combination of two or more individual materials

- Design goal: obtain a more desirable **combination of properties**
  - e.g., low density and high strength (carbon fiber composite for auto, aerospace, and sports)
  - e.g., high abrasion capability and good toughness (diamond embedded in metal for cutting ceramics)

Terminology/Classification

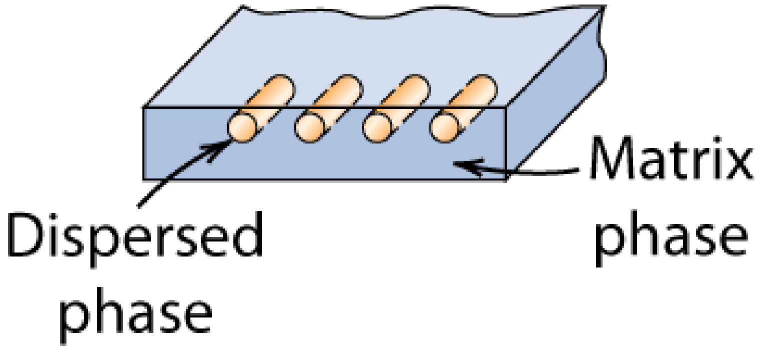
- Composite:

  -- **Multiphase** material that is **artificially** (as opposed to naturally) made for improved (often mechanical) properties.

- Phase types:

  -- **Matrix** - usually continuous

  -- **Dispersed phase** - usually discontinuous and surrounded by matrix



Adapted from Fig. 16.1(a), *Callister & Rethwisch 8e*.

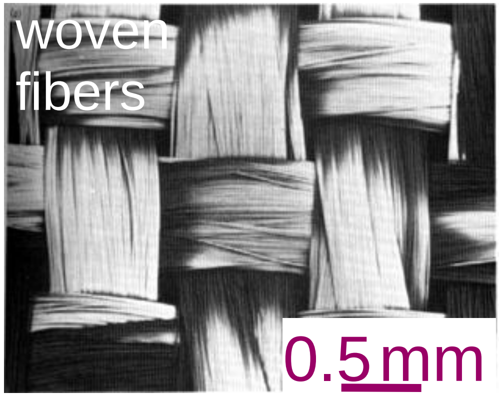
Terminology & Classification by Matrix Type

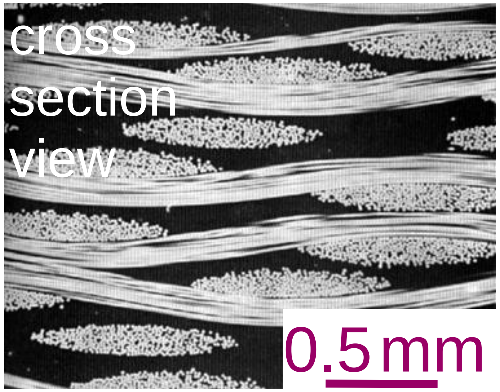
- Matrix phase:
  - -- Purposes are to:
    - - transfer stress to dispersed phase
    - - protect dispersed phase from environment
  - -- Types: MMC, CMC, PMC

metal matrix | ceramic matrix | polymer matrix

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

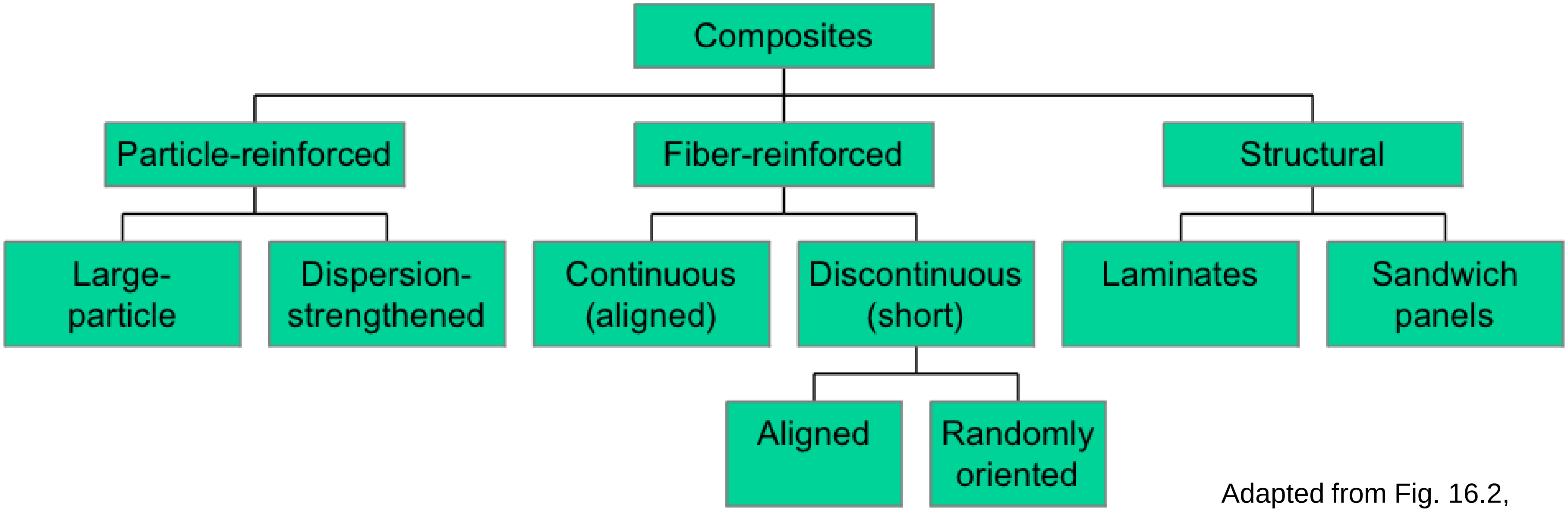
Most common





Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.

Classification of Composites by Reinforcement Type



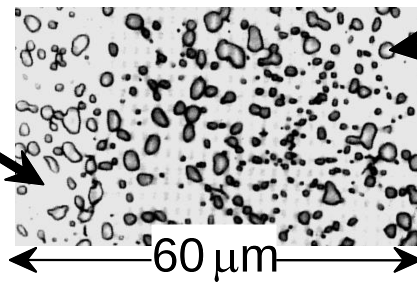
Adapted from Fig. 16.2,
Callister & Rethwisch 8e.

Classification: Particle-Reinforced (i)

Particle-reinforced | Fiber-reinforced | Structural

- Examples:
  - Spheroidite steel

matrix: ferrite (α) (ductile)

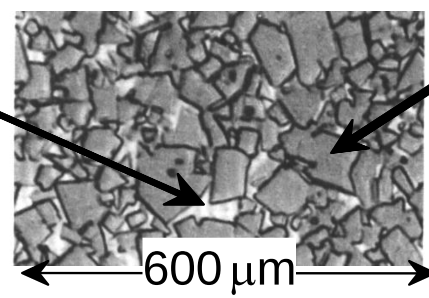


particles: cementite (Fe_3C) (brittle, hard)

Adapted from Fig. 10.19, *Callister & Rethwisch 8e*. (Fig. 10.19 is copyright United States Steel Corporation, 1971.)

  - WC/Co cemented carbide

matrix: cobalt (ductile, tough)

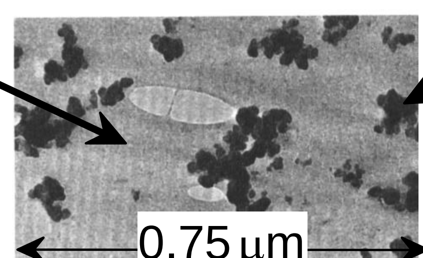


particles: WC (brittle, hard)

Adapted from Fig. 16.4, *Callister & Rethwisch 8e*. (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

  - Automobile tire rubber

matrix: rubber (compliant)



particles: carbon black (stiff)

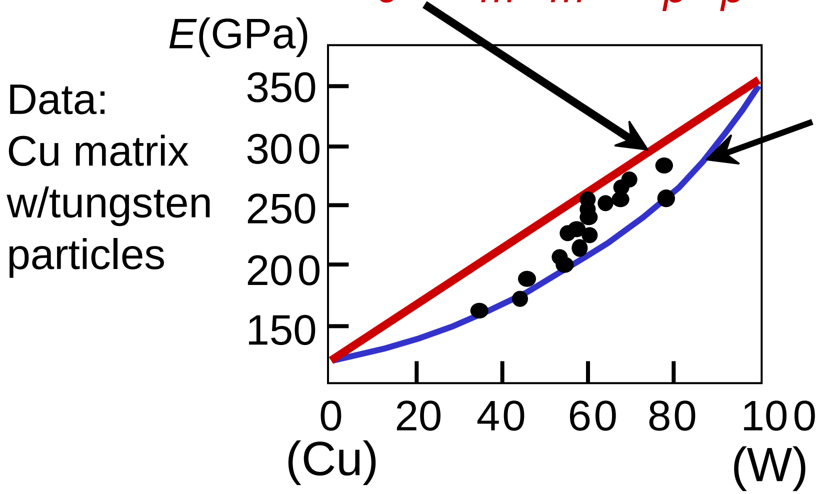
Adapted from Fig. 16.5, *Callister & Rethwisch 8e*. (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

Classification: Particle-Reinforced (ii)

Particle-reinforced | Fiber-reinforced | Structural

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

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



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 for composites:
  - -- Electrical conductivity, σ_e: Replace E's in equations with σ_e's.
  - -- Thermal conductivity, k: Replace E's in equations with k's.

Classification: Fiber-Reinforced (i)

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

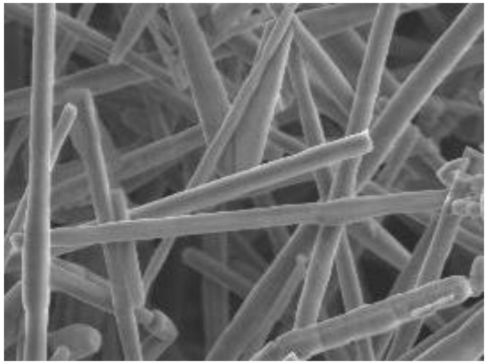
- Fibers very strong in tension
  - Provide significant strength improvement to the composite
  - Ex: fiber-glass - continuous glass filaments in a polymer matrix
    - Glass fibers
      - strength and stiffness
    - Polymer matrix
      - holds fibers in place
      - protects fiber surfaces
      - transfers load to fibers

Classification: Fiber-Reinforced (ii)

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

Glass fibers

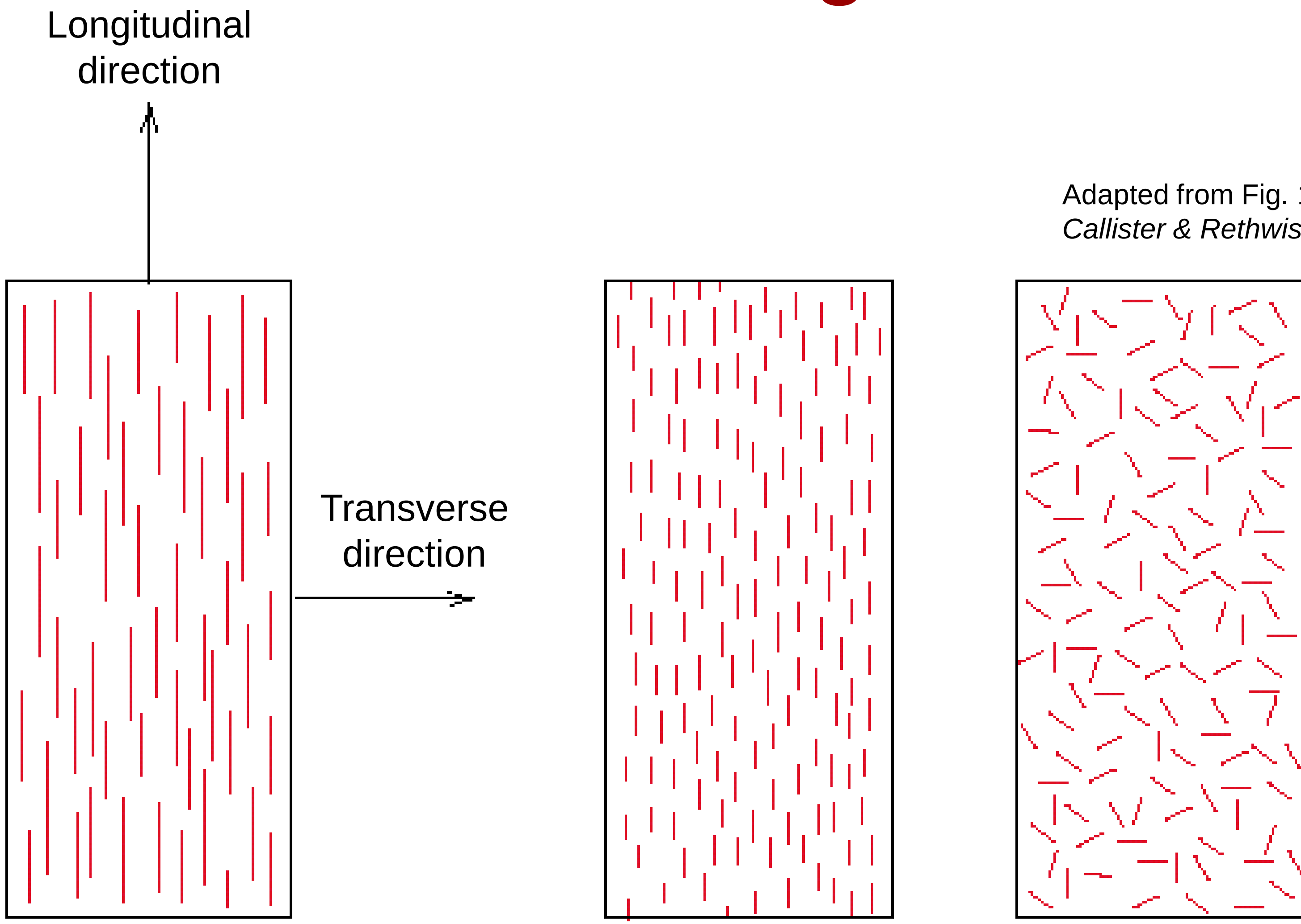
SiC whiskers



http://www.acm-usa.com/Pages/Materials/detail/Materials/0/7

- Fiber Types by shape
  - Fibers (meters long)
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: E-glass, alumina, boron
  - Whiskers – thin, single crystals with large length to diameter ratios (μm-mm long)
    - graphite, silicon nitride, silicon carbide
    - high crystal perfection – extremely strong, strongest known
    - expensive and difficult to disperse
  - Wires
    - metals – steel, molybdenum, tungsten

Modes of Fiber Alignment



Adapted from Fig. 16.8, *Callister & Rethwisch 8e*.

Aligned	aligned	random
Continuous (long fiber)	Discontinuous (short fiber)

Classification: Fiber-Reinforced (iii)

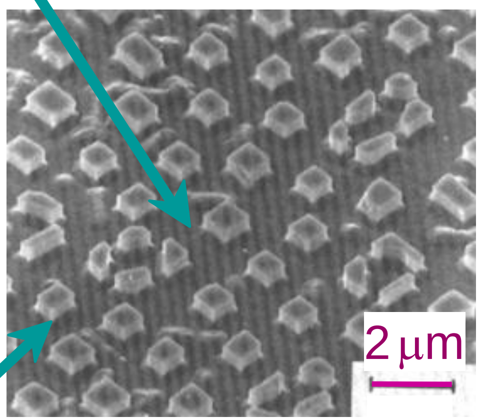
Particle-reinforced | **Fiber-reinforced** | Structural

Aligned Continuous fibers

- Examples:

-- MMC: γ'(Ni_3Al)-α(Mo) by eutectic solidification.

matrix: α (Mo) (ductile)



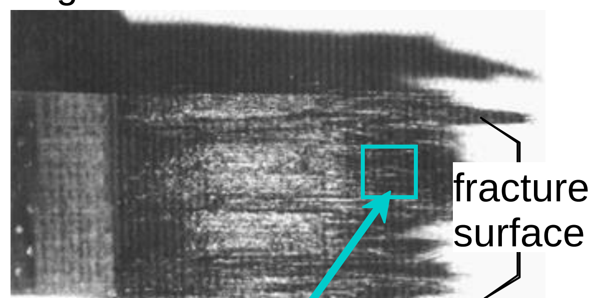
fibers: γ' (Ni_3Al) (brittle)

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.

-- CMC: 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 (iv)

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

Discontinuous fibers, random in 2D

- Example: Carbon-Carbon composite
  -- fabrication process:
  - carbon fibers embedded in polymer resin matrix,
  - polymer resin pyrolyzed at up to 2500ºC.

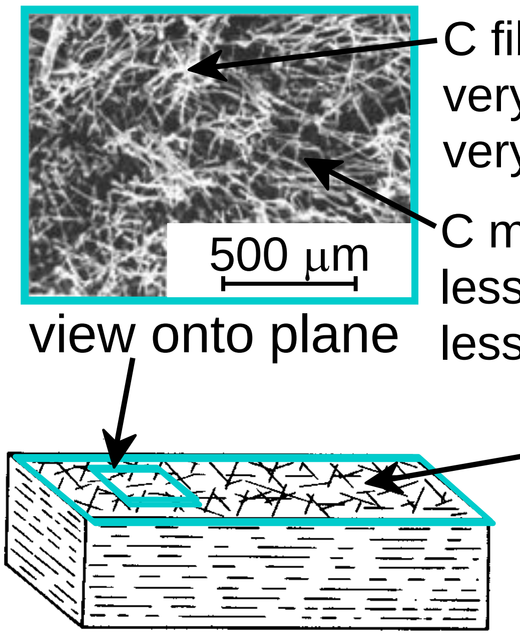
  -- uses: disk brakes, gas turbine exhaust flaps, missile nose cones.

Other possibilities:

-- Discontinuous, random 3D

-- Discontinuous, aligned

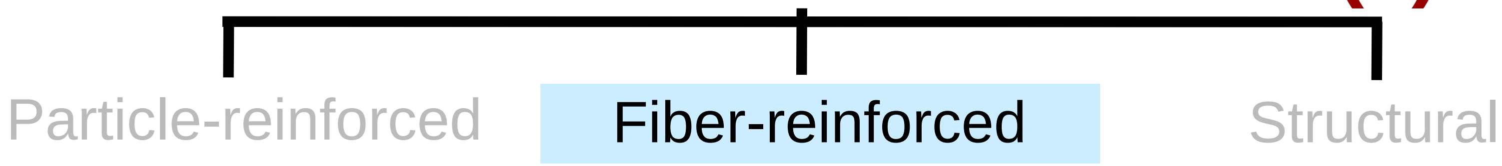
(b)



(a)

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.

Classification: Fiber-Reinforced (v)



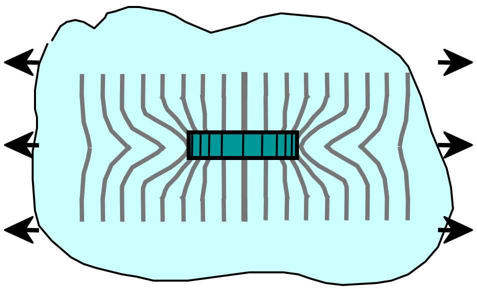
- Critical fiber length for effective stiffening & strengthening:

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

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

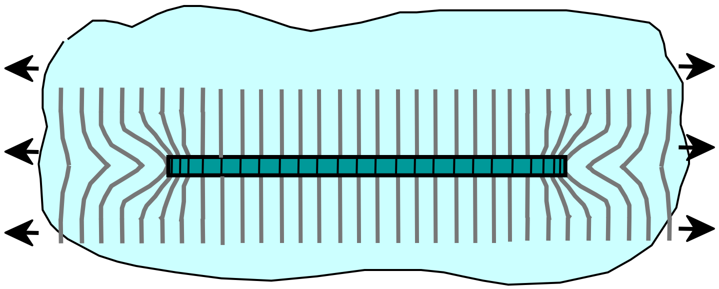
- Ex: For fiberglass, common fiber length > 15 mm needed
- For longer fibers, stress transference from matrix is more efficient and strengthening is more significant

Short fibers:



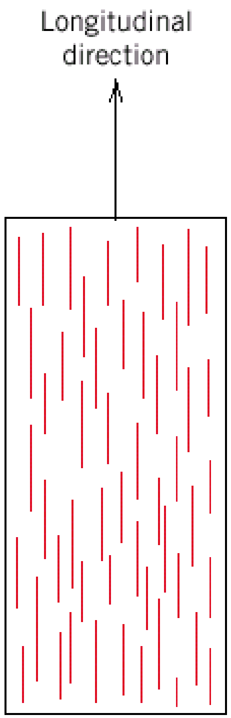
Low fiber efficiency

Long fibers:



High fiber efficiency

Composite Modulus: Longitudinal Loading



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

Longitudinal deformation

$F_c = F_m + F_f \rightarrow \sigma_c A_c = \sigma_m A_m + \sigma_f A_f$; Also $\frac{A_m}{A_c} = V_m \quad \frac{A_f}{A_c} = V_f$

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

volume fraction

isostrain

$\therefore E_{cl}$ = longitudinal modulus

$$E_{cl} = E_m V_m + E_f V_f$$

c = *composite*
f = fiber phase
m = matrix phase

Class Exercise

A continuous and aligned fiber-reinforced composite consists of 40 vol.% of glass fiber having modulus of elasticity of 69 GPa and 60 vol% of polyester that, when hardened, display a modulus of 3.4 Gpa

(a)Calculate the modulus of elasticity of the composite in the longitude direction

(b)If an external tensile force of 12500 N is applied along the longitude direction, calculate the load carried by each of the fiber and matrix phase assuming isostrain condition is satisfied along that direction and the load carried by each phase (fiber and matrix) satisfy

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

Class Exercise

(a) Modulus of elasticity for composite with continuous aligned fiber along longitude direction is:

$$E_{cl} = E_m V_m + E_f V_f$$

Therefore,

E_{cl} **= 3.4 x 60% + 69 x 40% = 29.6 GPa**

(b) Under the testing condition, isostrain

$\varepsilon_c = \varepsilon_m = \varepsilon_f$

Load born by fiber Ff and load born by matrix Fm satisfy

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m} = \frac{69 \times 0.4}{3.4 \times 0.6} = 13.5$$

Total load Fcl = Fm + Ff

Therefore, Fcl=(13.5+1)Fm

Fm= Fcl/14.5=12500/14.5=862N

Ff=13.5*Fm=11638N

Composite Modulus: Transverse Loading

In **<u>transverse</u>** loading for aligned fiber reinforced composition, the fibers carry MUCH LESS of the load and <u>very little strengthening</u> effect

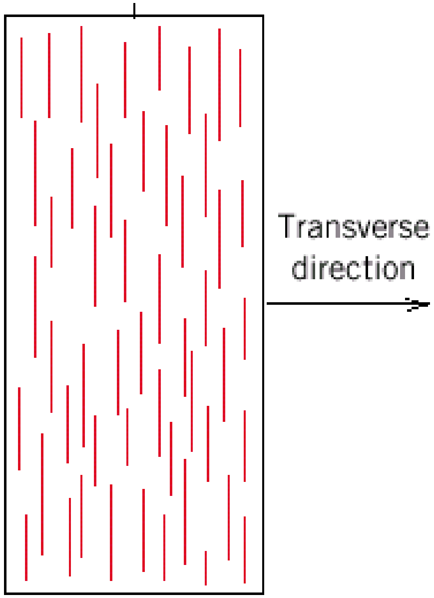
$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$ and $\sigma_c = \sigma_m = \sigma_f = \sigma$

<u>isostress</u>

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

E_{ct} = transverse modulus

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

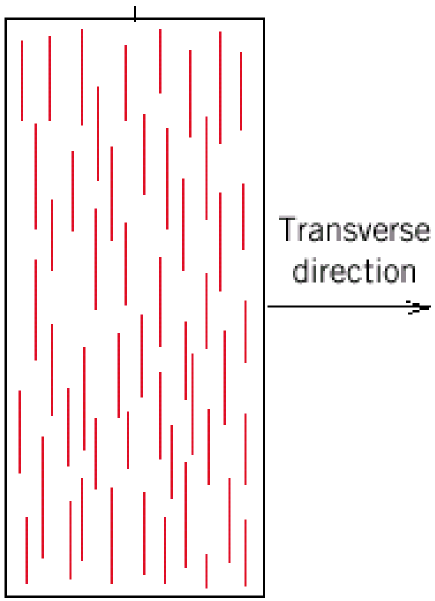


c = *composite*
f = fiber
m = matrix

Exercise

A continuous and aligned fiber-reinforced composite consists of 40 vol.% of glass fiber having modulus of elasticity of 69 GPa and 60 vol% of polyester that, when hardened, display a modulus of 3.4 Gpa

(a)Calculate the modulus of elasticity of the composite in the <u>transverse</u> (i.e., perpendicular to the fiber alignment) direction



Composite Modulus

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

- E_{cd} for ***discontinuous*** fibers:

  -- When fiber length is short, i.e., $< 15 \frac{\sigma_f d}{\tau_c}$

  -- Elastic modulus:

$$E_{cd} = E_m V_m + K E_f V_f$$

efficiency factor:

-- aligned: $K = 1$ (aligned parallel)
-- aligned: $K = 0$ (aligned perpendicular)
-- random 2D: $K = 3/8$ (2D isotropy)
-- random 3D: $K = 1/5$ (3D isotropy)

Values from Table 16.3, *Callister & Rethwisch 8e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

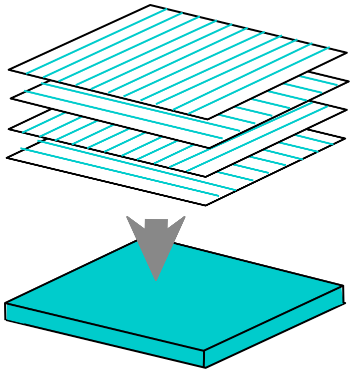
Classification: Structural

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

- Laminates -

  -- stacked and bonded fiber-reinforced sheets

  - stacking sequence: e.g., 0º/90º
  - benefit: balanced in-plane stiffness

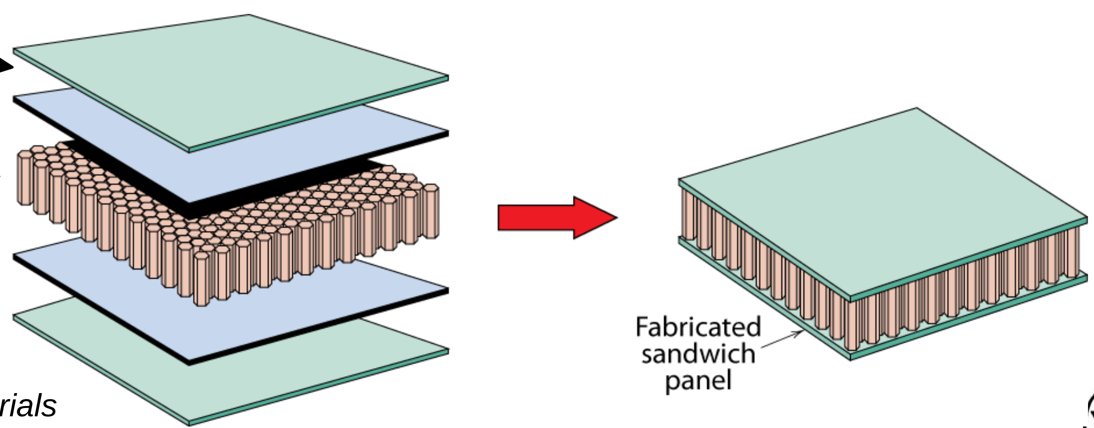


Adapted from Fig. 16.16, *Callister & Rethwisch 8e*.

- Sandwich panels

  -- honeycomb core between two facing sheets

  - benefits: low density, large bending stiffness



Adapted from Fig. 16.18, *Callister & Rethwisch 8e*.
(Fig. 16.18 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

Composite Production Methods (i)

Pultrusion

- Continuous fibers pulled through resin tank to impregnate fibers with thermosetting resin
- Impregnated fibers pass through steel die that preforms to the desired shape
- Preformed stock passes through a curing die that is
  - precision machined to impart final shape
  - heated to initiate curing of the resin matrix

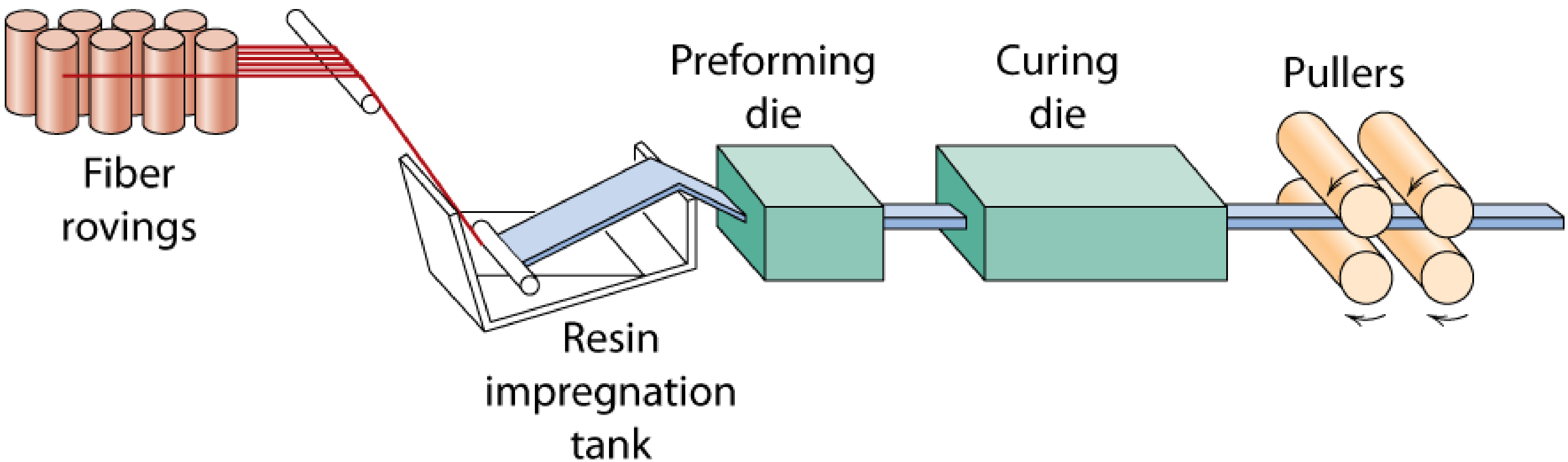
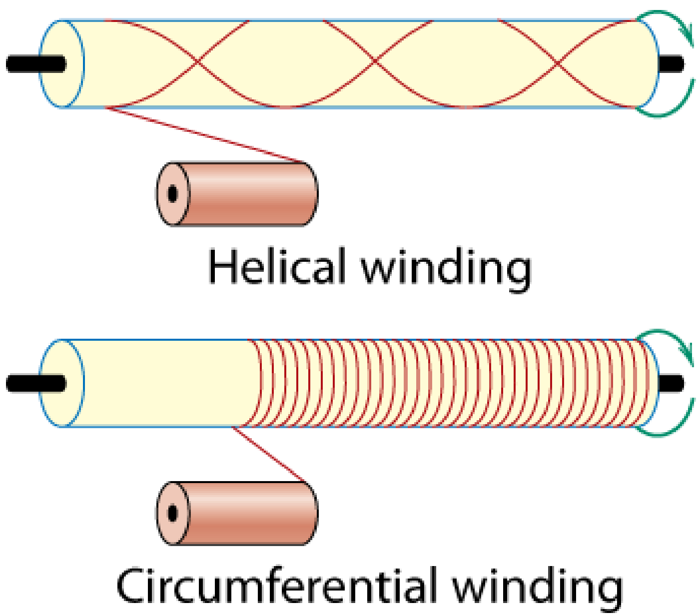


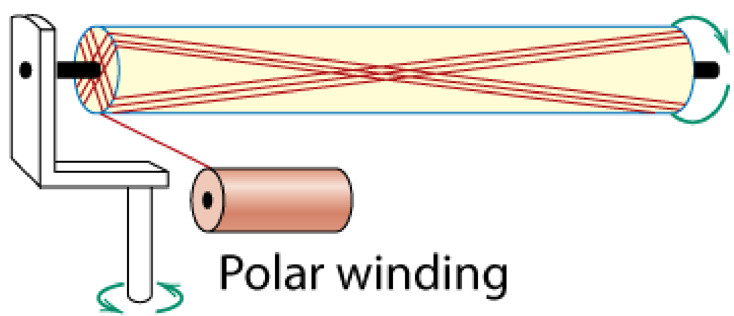
Fig. 16.13, *Callister & Rethwisch 8e*.

Composite Production Methods (ii)

- Filament Winding
  - Continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape
  - Fibers are fed through a resin bath to impregnate with thermosetting resin
  - Impregnated fibers are continuously wound (typically automatically) onto a mandrel
  - After appropriate number of layers added, curing is carried out either in an oven or at room temperature
  - The mandrel is removed to give the final product

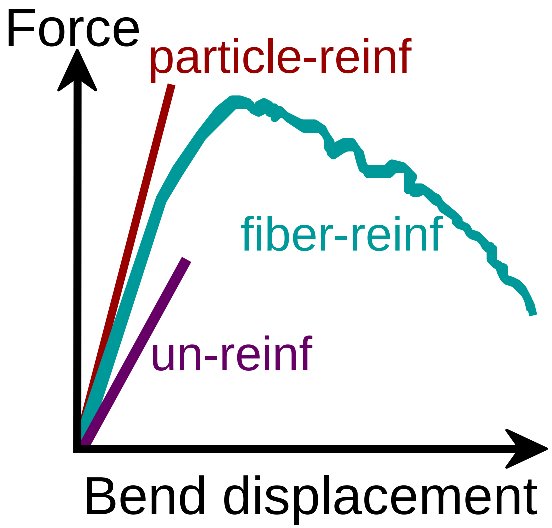


Adapted from Fig. 16.15, *Callister & Rethwisch 8e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.]

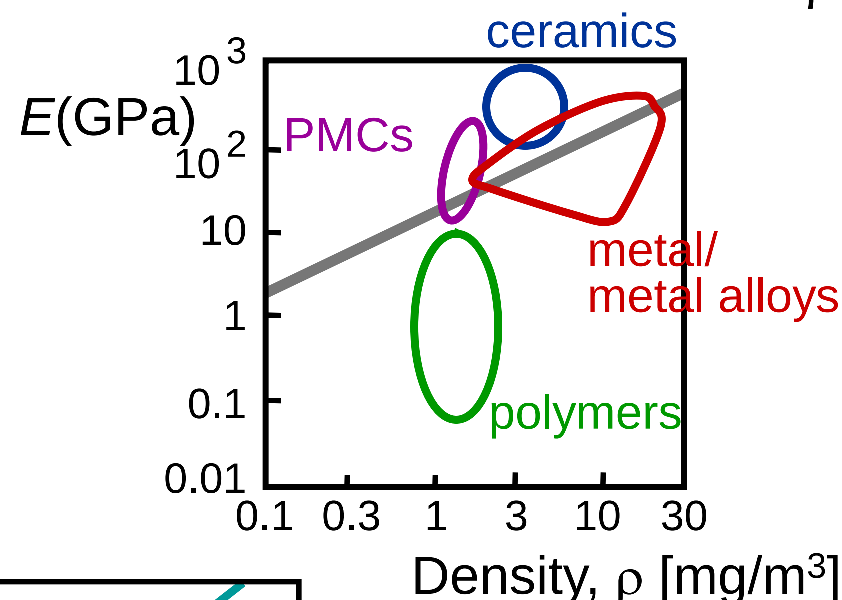


Other Examples of Composite Benefits

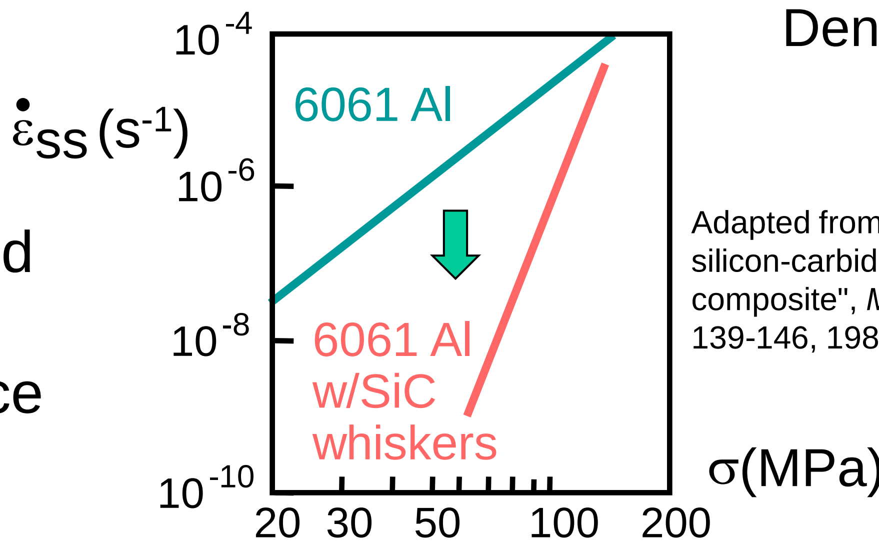
- CMCs: Increased toughness



- PMCs: Increased E/ρ



- MMCs:
  Increased creep resistance



Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

Limitations with Current Composites

- Higher cost, especially for MMC and mostly for CMC
- Limitations with regard to matrix materials
  – PMC: degrades rapidly at elevated temperature (e.g., >~200 ^{o}C)
  – MMC: Oxidation for light metals (e.g., Al)
  – CMC: Very difficult to form and shape

Summary

- Composites types are designated by:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement (particles, fibers, structural)
- Composite property benefits:
  -- MMC: enhanced E, σ^*, creep performance
  -- CMC: enhanced K_{Ic}
  -- PMC: enhanced E/ρ, σ_y, TS/ρ
- Particulate-reinforced:
  -- Types: large-particle and dispersion-strengthened
  -- Properties are isotropic
- Fiber-reinforced:
  -- Types: continuous (aligned)
  discontinuous (aligned or random)
  -- Properties can be isotropic or anisotropic
- Structural:
  -- Laminates and sandwich panels

Expectations on Chapter 16

- **Understand the concepts of composites. Be able to classify composites by matrix materials and by the form of dispersion phase (reinforcement phase) and give simple real world examples**
- **Be able to describe the major advantages for different composites over their respective matrix phase used**
- **Understand the influence of addition of secondary phase on the mechanical property (modulus and strength) for composites under simplified conditions and be able to use the formula to solve simple problems**
- **Understand the distribution of the dispersion (reinforcement) phase on mechanical property of the composites**