Chapter 16: Composite Materials

ISSUES TO ADDRESS...

- What are the classes and types of composites?
- Why are composites used instead of metals, ceramics, or polymers?
- How do we estimate composite stiffness & strength?
- What are some typical applications?

Composites

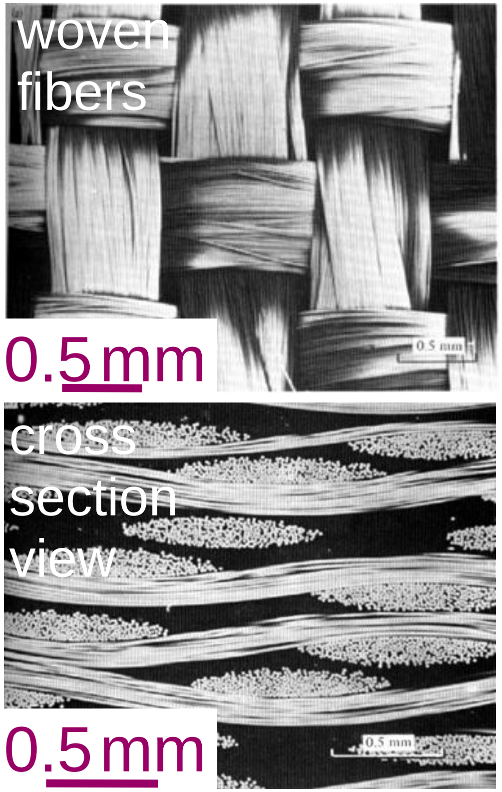
- Combine materials with the objective of getting a more desirable combination of properties
  - Ex: get flexibility & weight of a polymer plus the strength of a ceramic
- Principle of combined action
  - Mixture gives “averaged” properties

Terminology/Classification

- Composites:
  - -- Multiphase material w/significant proportions of each phase.
- Matrix:
  - -- The continuous phase
  - -- Purpose is to:
    - - transfer stress to other phases
    - - protect phases from environment
  - -- Classification: MMC, CMC, PMC

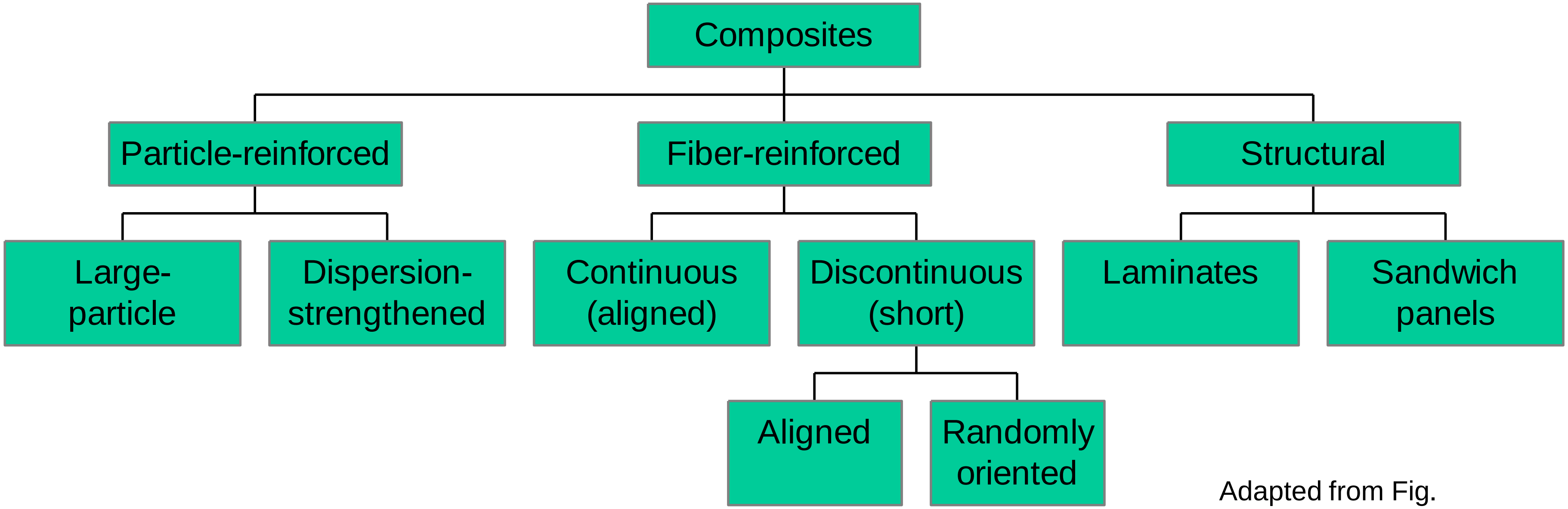
metal ceramic polymer

- Dispersed phase:
  - -- Purpose: enhance matrix properties.
    - MMC: increase σ_y, TS, creep resist.
    - CMC: increase K_c
    - PMC: increase E, σ_y, TS, creep resist.
  - -- Classification: Particle, fiber, structural



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.

Composite Survey



Composites

- Particle-reinforced
  - Large-particle
  - Dispersion-strengthened
- Fiber-reinforced
  - Continuous (aligned)
  - Discontinuous (short)
    - Aligned
    - Randomly oriented
- Structural
  - Laminates
  - Sandwich panels

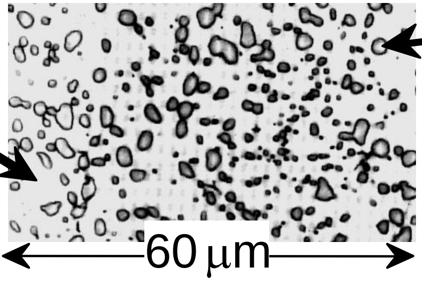
Adapted from Fig. 16.2, *Callister 7e*.

Composite Survey: Particle-I

Particle-reinforced Fiber-reinforced Structural

- Examples:
  - Spheroidite steel

matrix: ferrite (α) (ductile)



particles: cementite (Fe_3C) (brittle)

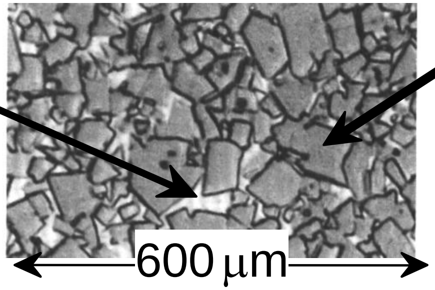
Adapted from Fig. 10.19, *Callister 7e*. (Fig. 10.19 is copyright United States Steel Corporation, 1971.)

  - WC/Co cemented carbide

matrix: cobalt (ductile)

V_m:

10-15 vol%!

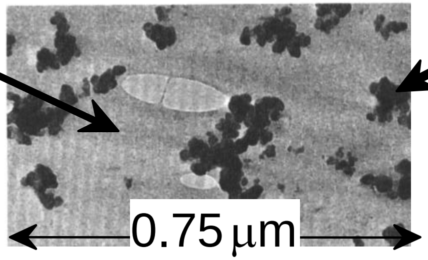


particles: WC (brittle, hard)

Adapted from Fig. 16.4, *Callister 7e*. (Fig. 16.4 is courtesy Carboloy Systems, Department, General Electric Company.)

  - Automobile tires

matrix: rubber (compliant)



particles: C (stiffer)

Adapted from Fig. 16.5, *Callister 7e*. (Fig. 16.5 is courtesy Goodyear Tire and Rubber Company.)

Composite Survey: Particle-II

Particle-reinforced · Fiber-reinforced · Structural

Concrete – gravel + sand + cement

- Why sand *and* gravel? Sand packs into gravel voids

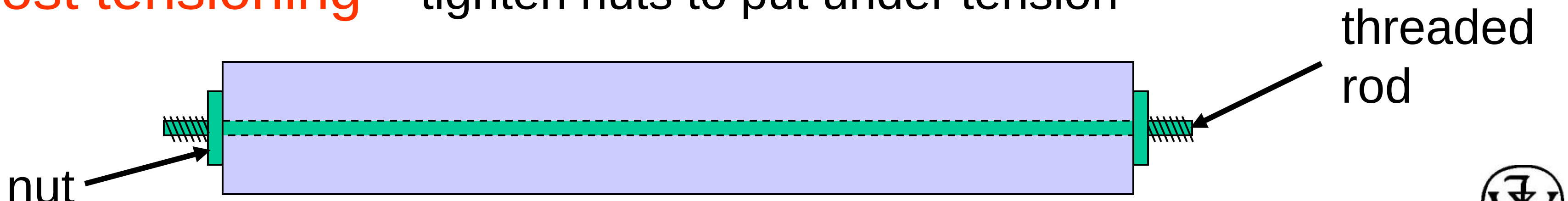
Reinforced concrete - Reinforce with steel rerod or remesh

- increases strength - even if cement matrix is cracked

Prestressed concrete - remesh under tension during setting of concrete. Tension release puts concrete under compressive force

- Concrete much stronger under compression.
- Applied tension must exceed compressive force

Post tensioning – tighten nuts to put under tension



Composite Survey: Particle-III

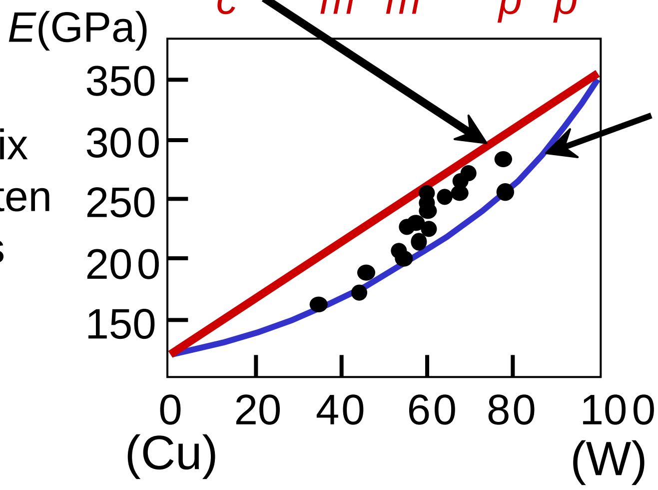
Particle-reinforced | Fiber-reinforced | Structural

- Elastic modulus, E_c, of composites:
  - -- two approaches.

upper limit: “rule of mixtures”

$$E_c = V_m E_m + V_p E_p$$

Data:
Cu matrix
w/tungsten
particles



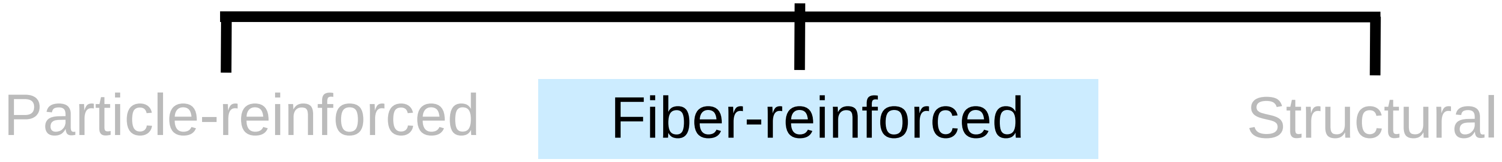
lower limit:

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

Adapted from Fig. 16.3, *Callister 7e*. (Fig. 16.3 is from R.H. Krock, *ASTM Proc*, Vol. 63, 1963.)

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

Composite Survey: Fiber-I



Particle-reinforced

Fiber-reinforced

Structural

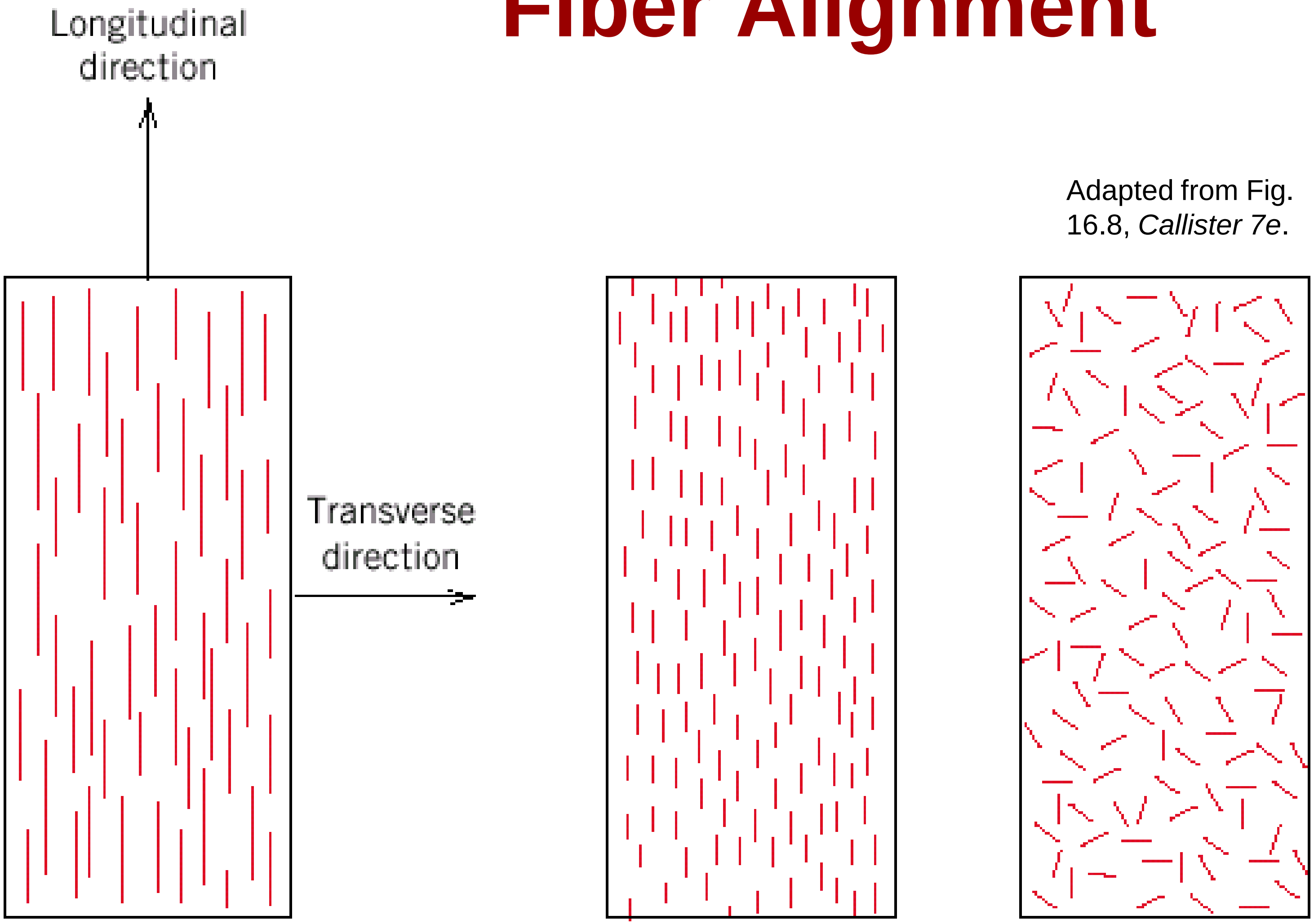
- Fibers very strong
  - – Provide significant strength improvement to material
  - – Ex: fiber-glass
    - Continuous glass filaments in a polymer matrix
    - Strength due to fibers
    - Polymer simply holds them in place

Composite Survey: Fiber-II

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

- Fiber Materials
  - Whiskers - Thin single crystals - large length to diameter ratio
    - graphite, SiN, SiC
    - high crystal perfection – extremely strong, strongest known
    - very expensive
  - Fibers
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: Al_2O_3 , Aramid, E-glass, Boron, UHMWPE
  - Wires
    - Metal – steel, Mo, W

Fiber Alignment



Adapted from Fig. 16.8, *Callister 7e*.

aligned
continuous

aligned
discontinuous

random

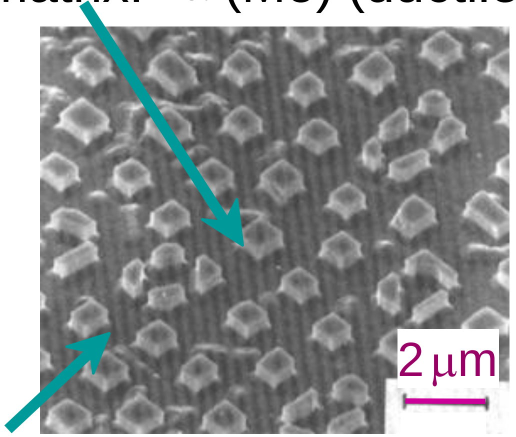
Composite Survey: Fiber-III

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

- Aligned Continuous fibers
- Examples:

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

matrix: α (Mo) (ductile)

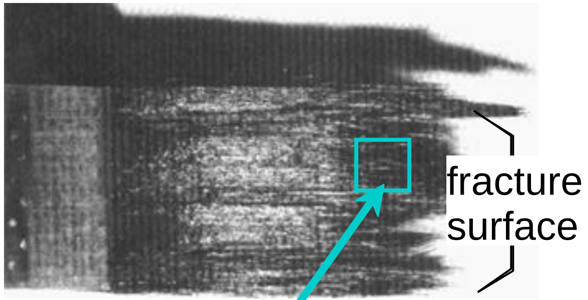


fibers: γ' (Ni_3Al) (brittle)

From W. Funk and E. Blank, "Creep deformation of Ni3Al-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)



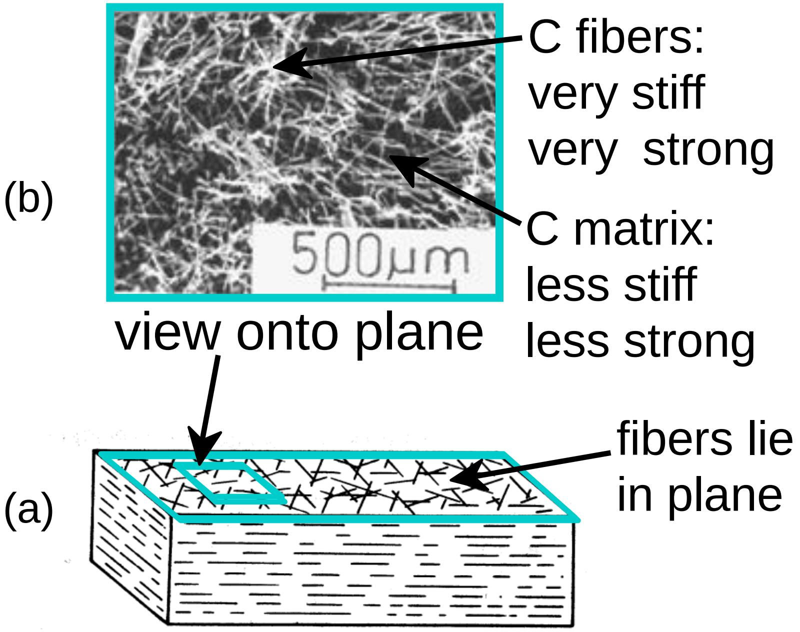
(b)

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.

Composite Survey: Fiber-IV

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

- Discontinuous, random 2D fibers
- Example: Carbon-Carbon
  - -- process: fiber/pitch, then burn out at up to 2500ºC.
  - -- uses: disk brakes, gas turbine exhaust flaps, nose cones.



C fibers: very stiff very strong

C matrix: less stiff less strong

view onto plane

fibers lie in plane

- Other variations:
  - -- Discontinuous, random 3D
  - -- Discontinuous, 1D

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.

Composite Survey: Fiber-V

Particle-reinforced | Fiber-reinforced | Structural

- Critical fiber length for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

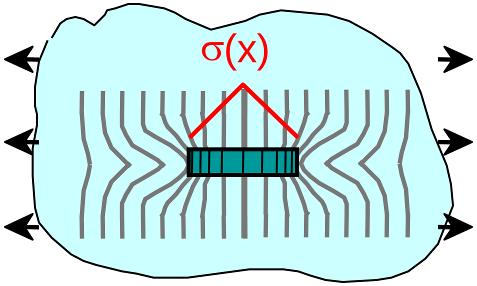
$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$

shear strength of fiber-matrix interface

- Ex: For fiberglass, fiber length > 15 mm needed
- Why? Longer fibers carry stress more efficiently!

Shorter, thicker fiber:

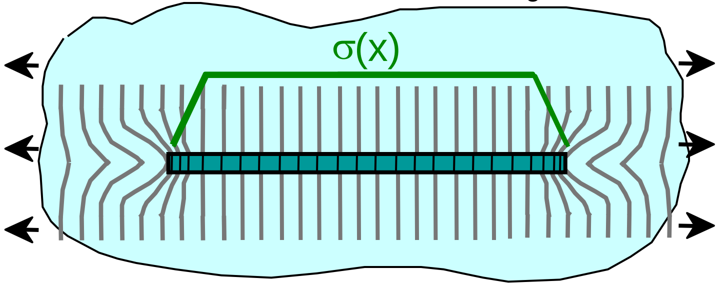
$$\text{fiber length} < 15\,\frac{\sigma_f d}{\tau_c}$$



Poorer fiber efficiency

Longer, thinner fiber:

$$\text{fiber length} > 15\,\frac{\sigma_f d}{\tau_c}$$



Better fiber efficiency

Adapted from Fig. 16.7, *Callister 7e*.

Composite Strength: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite strength for long continuous fibers in a matrix

- Longitudinal deformation

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \qquad \text{but} \qquad \varepsilon_c = \varepsilon_m = \varepsilon_f$$

volume fraction

isostrain

$$\therefore \qquad \boxed{E_{ce} = E_m V_m + E_f V_f}$$

longitudinal (extensional) modulus

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

f = fiber
m = matrix

Composite Strength: Transverse Loading

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

$\sigma_c = \sigma_m = \sigma_f = \sigma$

$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f$

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

transverse modulus

Composite Strength

Particle-reinforced | Fiber-reinforced | Structural

- Estimate of E_c and *TS* for discontinuous fibers:

-- valid when fiber length $> 15\dfrac{\sigma_f d}{\tau_c}$

-- Elastic modulus in fiber direction:

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

efficiency factor:

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

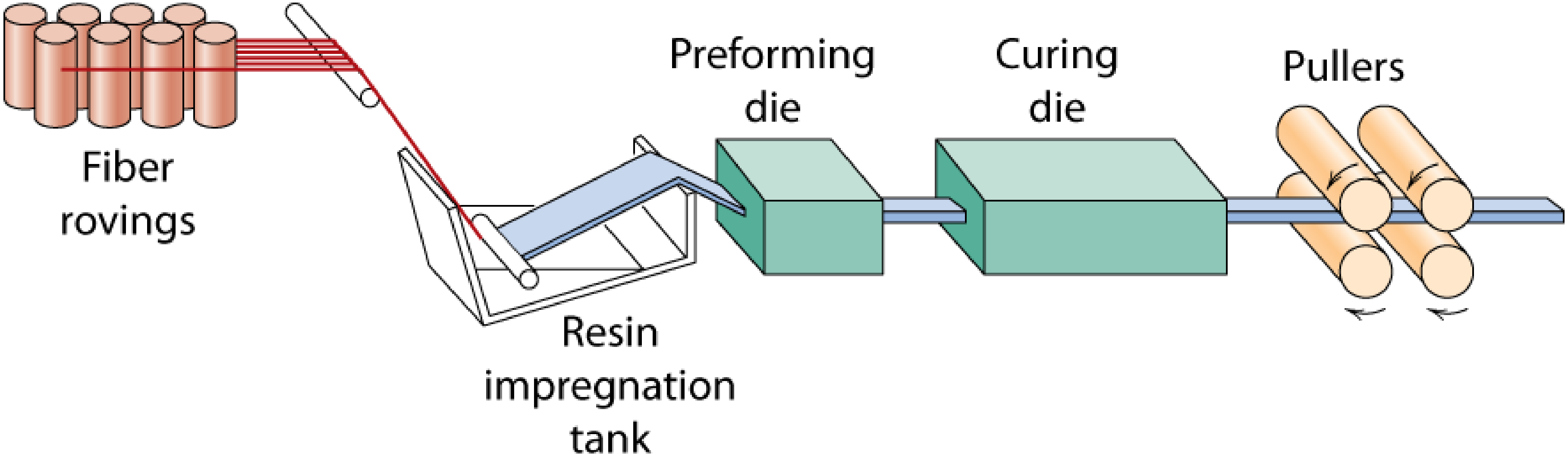
Values from Table 16.3, *Callister 7e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

-- *TS* in fiber direction:

$$(TS)_c = (TS)_m V_m + (TS)_f V_f \qquad \text{(aligned 1D)}$$

Composite Production Methods-I

- Pultrusion
  - Continuous fibers pulled through resin tank, then preforming die & oven to cure

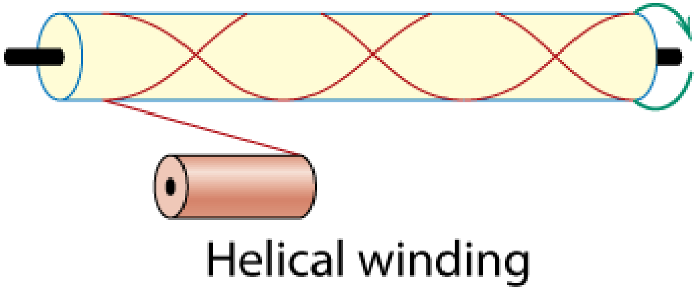


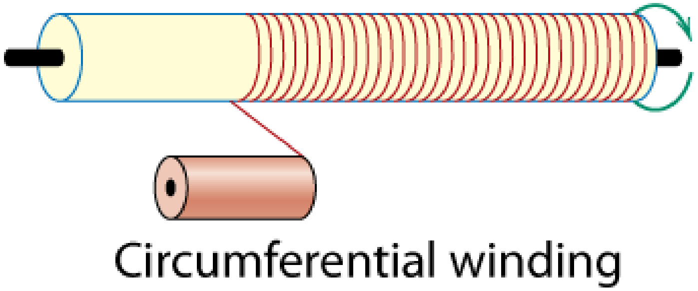
Adapted from Fig. 16.13, *Callister 7e*.

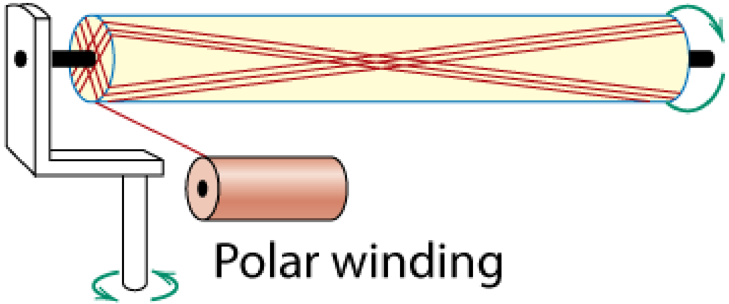
Composite Production Methods-II

- Filament Winding
  - Ex: pressure tanks
  - Continuous filaments wound onto mandrel

Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.]



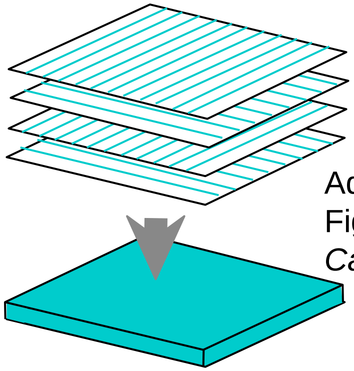




Composite Survey: Structural

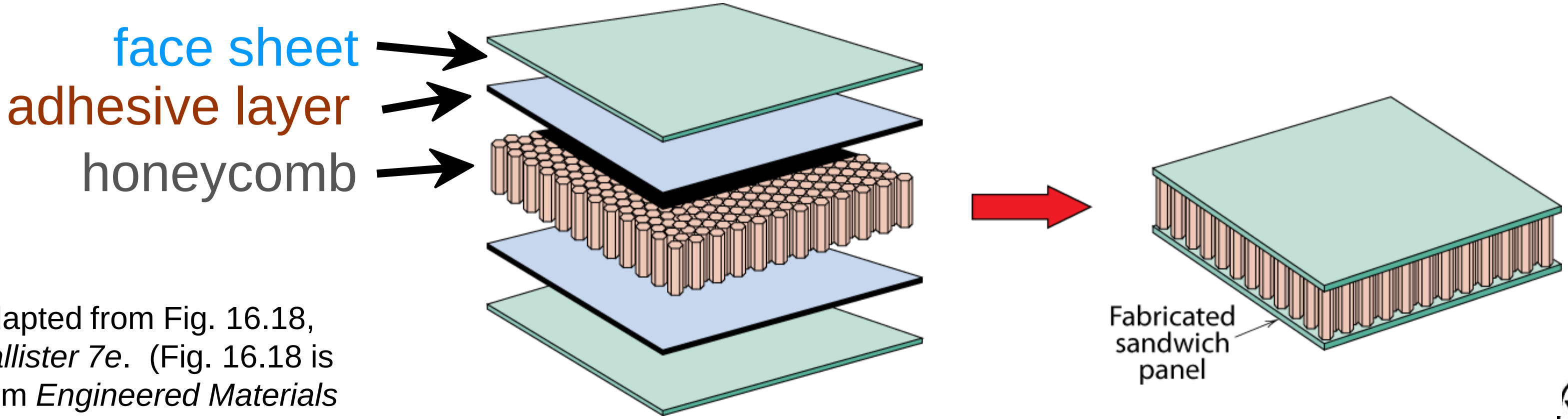
Particle-reinforced | Fiber-reinforced | **Structural**

- Stacked and bonded fiber-reinforced sheets
  - -- stacking sequence: e.g., 0º/90º
  - -- benefit: balanced, in-plane stiffness



Adapted from Fig. 16.16, *Callister 7e*.

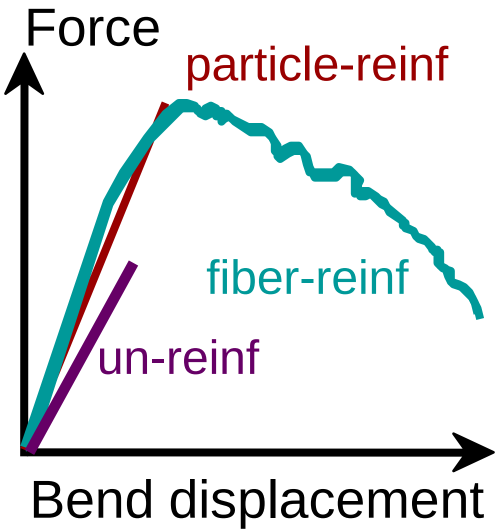
- Sandwich panels
  - -- low density, honeycomb core
  - -- benefit: small weight, large bending stiffness



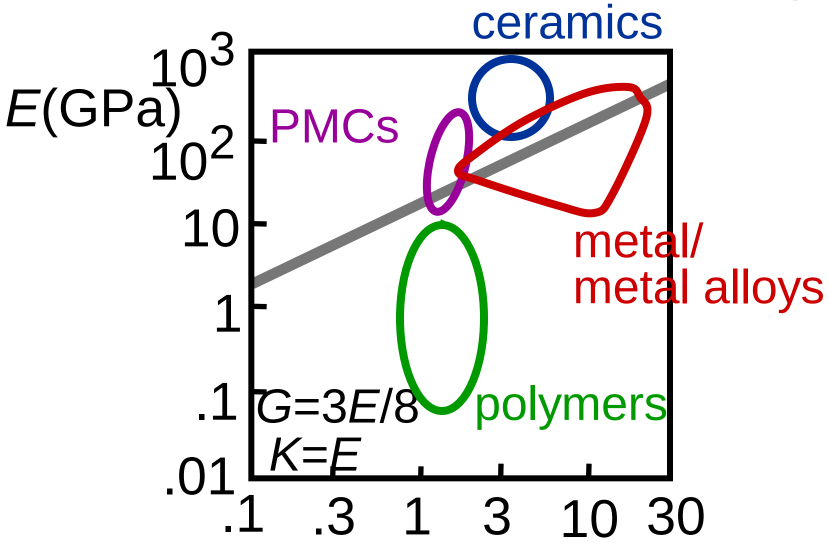
Adapted from Fig. 16.18, *Callister 7e*. (Fig. 16.18 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

Composite Benefits

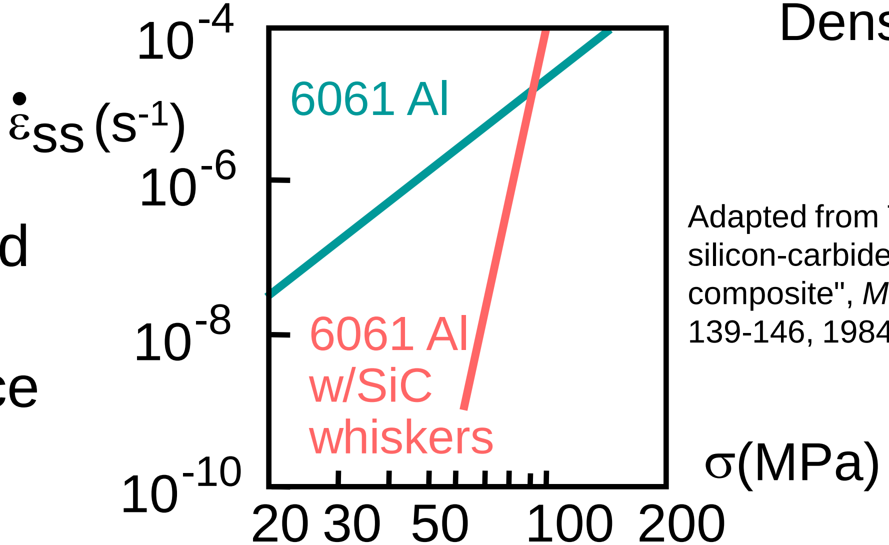
- CMCs: Increased toughness



- 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.

Summary

- Composites are classified according to:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement geometry (particles, fibers, layers).
- Composites enhance matrix properties:
  -- MMC: enhance σ_y, *TS*, creep performance
  -- CMC: enhance K_c
  -- PMC: enhance *E*, σ_y, *TS*, creep performance
- Particulate-reinforced:
  -- Elastic modulus can be estimated.
  -- Properties are isotropic.
- Fiber-reinforced:
  -- Elastic modulus and *TS* can be estimated along fiber dir.
  -- Properties can be isotropic or anisotropic.
- Structural:
  -- Based on build-up of sandwiches in layered form.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: