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
- structure materials for aircraft engine:

  low densities, strong, stiff, abrasion and impact resistant and corrosion resistant.

GE engine:

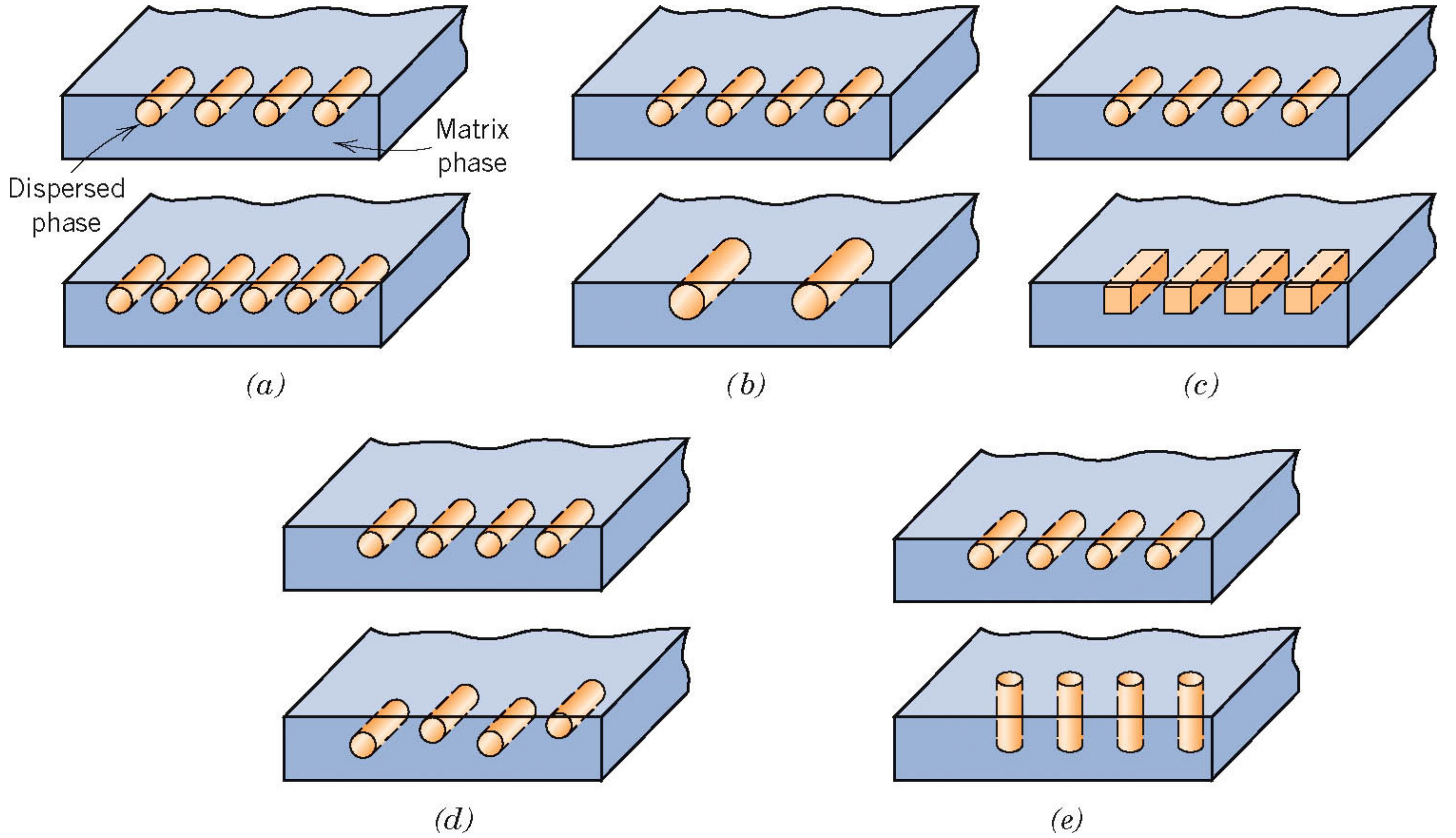
http://www.geae.com/education/theatre/genx/

http://www.geae.com/education/theatre/ge90/

- Principle of combined action
  - Mixture gives “averaged” properties

    better property combinations are fashioned by the combination of 2 or more distinct materials.

Composite is considered to be any multiphase materials that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realized.



Schematic representations of the various geometrical and spatial characteristics of particles of the dispersed phase that may influence the properties of composites: (1) concentration, (b) size, © shape, (d) distribution, and (e) orientation.

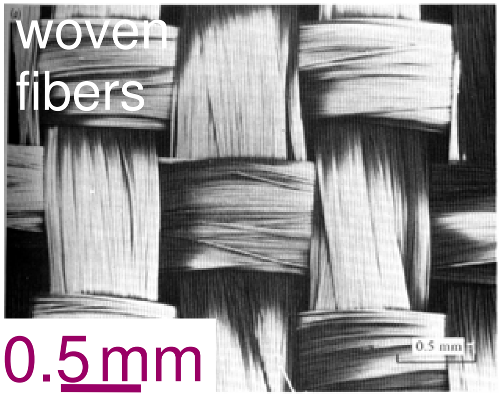
Terminology/Classification

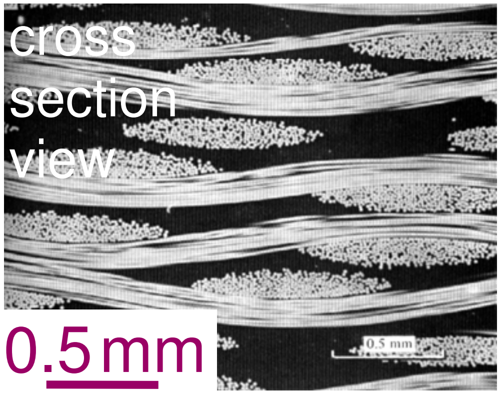
- Composites:
  -- Multiphase material w/significant proportions of each phase.
- Matrix:
  -- The continuous phase
  -- Purpose is to:
    - transfer stress to other phases
    - protect phases from environment

  -- 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.

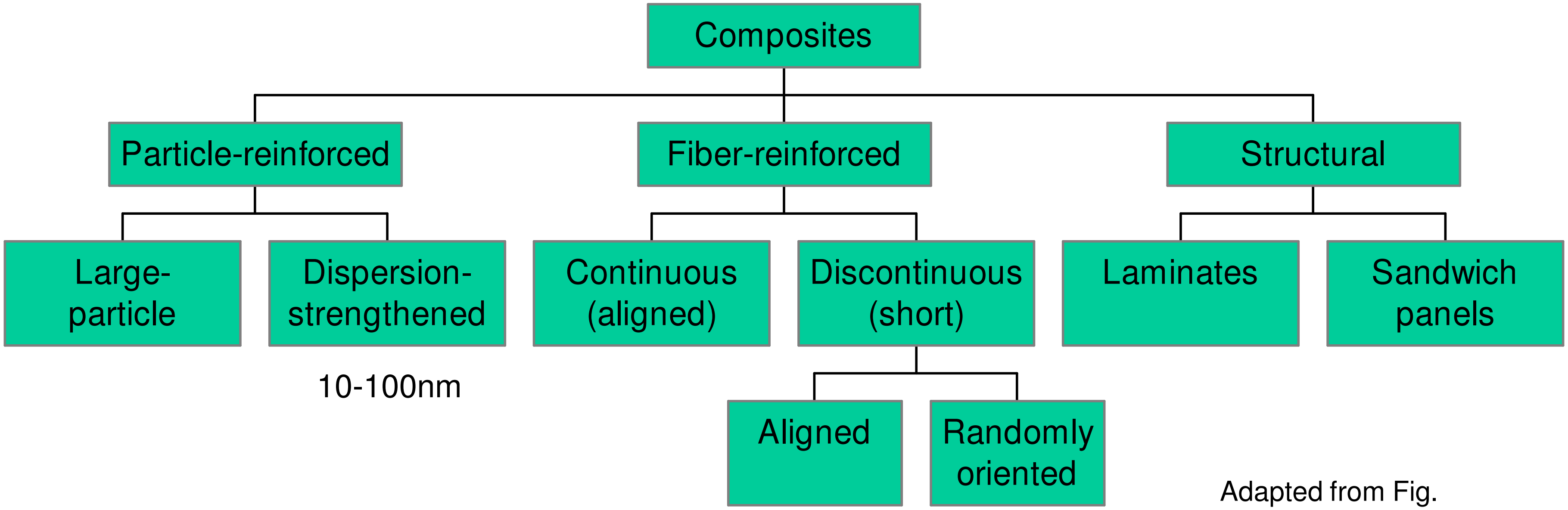
  -- Classification: Particle, fiber, structural





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
Fiber-reinforced
Structural
Large-particle
Dispersion-strengthened
Continuous (aligned)
Discontinuous (short)
Laminates
Sandwich panels
10-100nm
Aligned
Randomly oriented

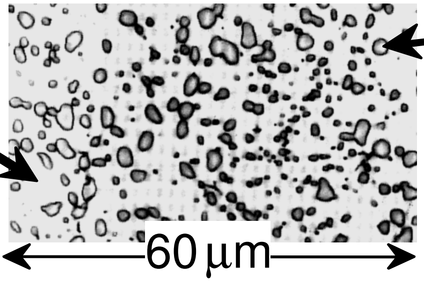
Adapted from Fig. 16.2, *Callister 7e*.

Composite Survey: Particle-I

Particle-reinforced Fiber-reinforced Structural

- Examples:
  - Spheroidite steel

matrix: ferrite (α) (ductile)



particles: cementite (Fe_3C) (brittle)

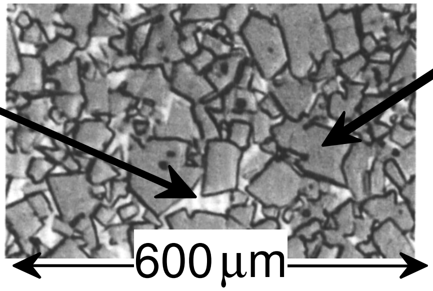
Adapted from Fig. 10.19, *Callister 7e*. (Fig. 10.19 is copyright United States Steel Corporation, 1971.)

  - WC/Co cemented carbide

matrix: cobalt (ductile)

V_m:

10-15 vol%!

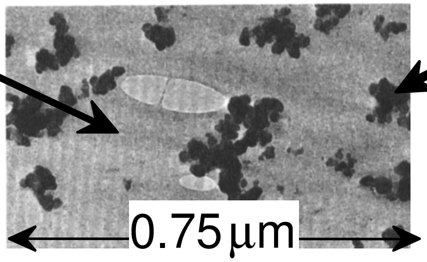


particles: WC (brittle, hard)

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

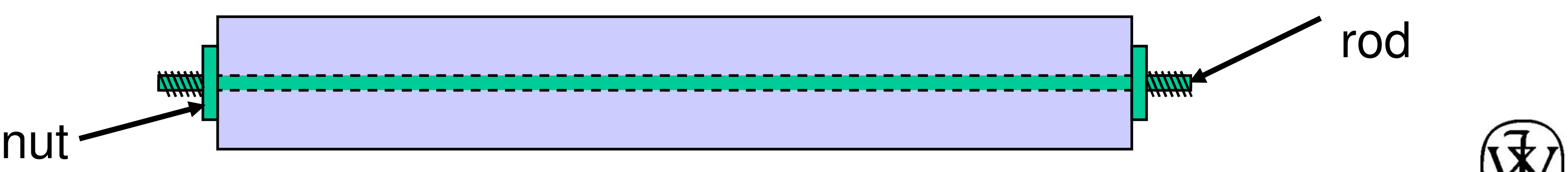
- increases strength - even if cement matrix is cracked

http://www.metacafe.com/watch/338535/concrete_forming_system_showing_reinforced_concrete_housing/

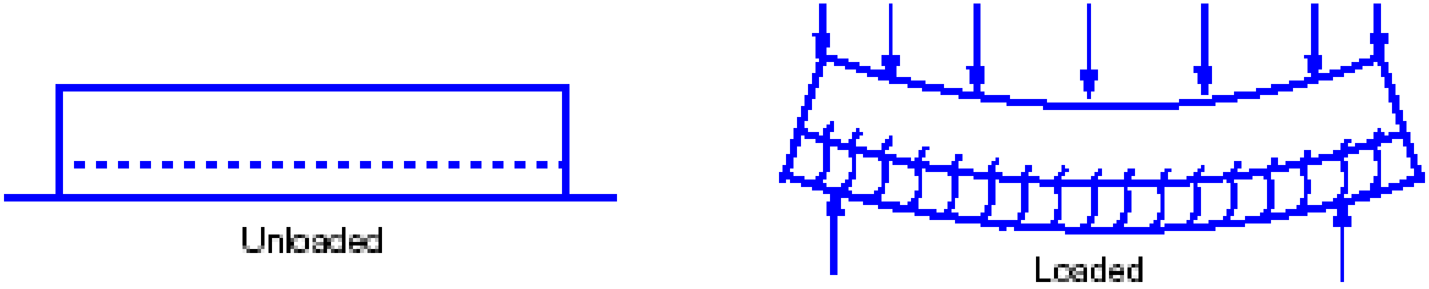
Prestressed concrete - remesh under tension during setting of concrete. Tension release puts concrete under compressive force

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

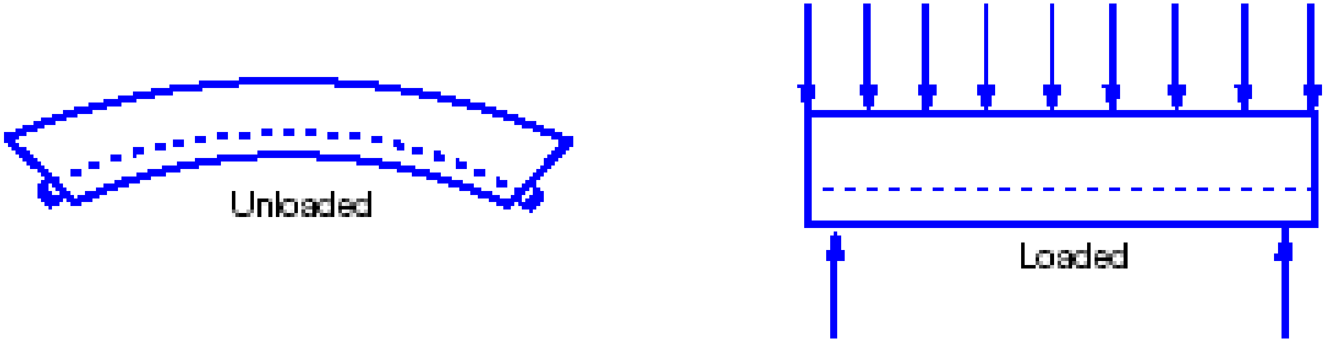
Post tensioning – tighten nuts to put under tension



Fractured reinforced concrete



Reinforced

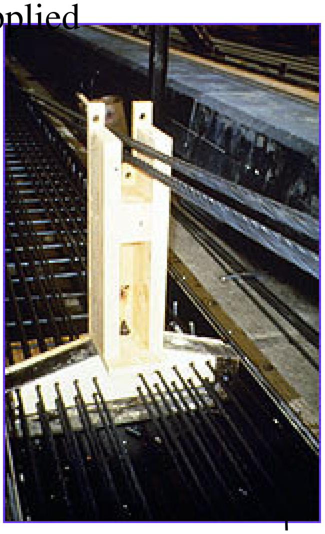


Prestressed

How prestressed concrete is made ?

High strength steel

The prestressing strand is stretched across the casting bed, 30000 pounds of tension will be applied

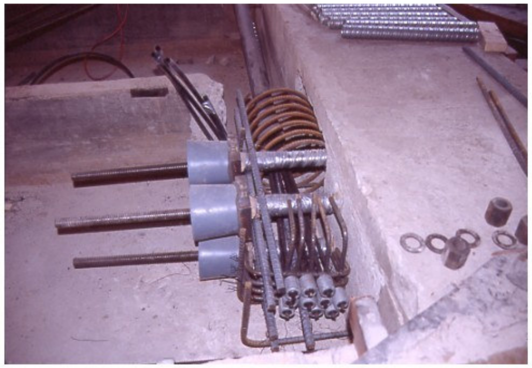


Cement, sand, stone, and water make up concrete

A tarp is placed over and heat is applied

The prestressing strands are cut and removed from the casting bed

Post-tensioning



- Post-tensioning is the method of achieving pre-stressing after the concrete has hardened and takes advantage of concrete's inherent compressive strength.
- Concrete is exceptionally strong in compression, but generally weak when subjected to tension forces or forces that pull it apart. These tension forces can be created by concrete shrinkage caused during curing or by flexural bending when the foundation is subjected to design loads (dead and live loads from the structure and/or expansive soil induced loads). This tension can result in cracking which can lead to large deflections that can cause distress in the building's structure.
- The application of an external force into the concrete, recompressing it before it is subjected to the design loads, makes the foundation less likely to crack.

http://www.youtube.com/watch?v=d51lciZRwF0

Composite Survey: Particle-III

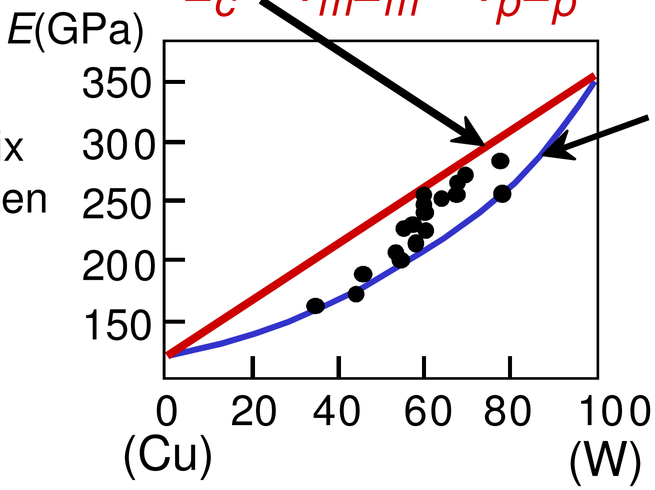
Particle-reinforced Fiber-reinforced Structural

- 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

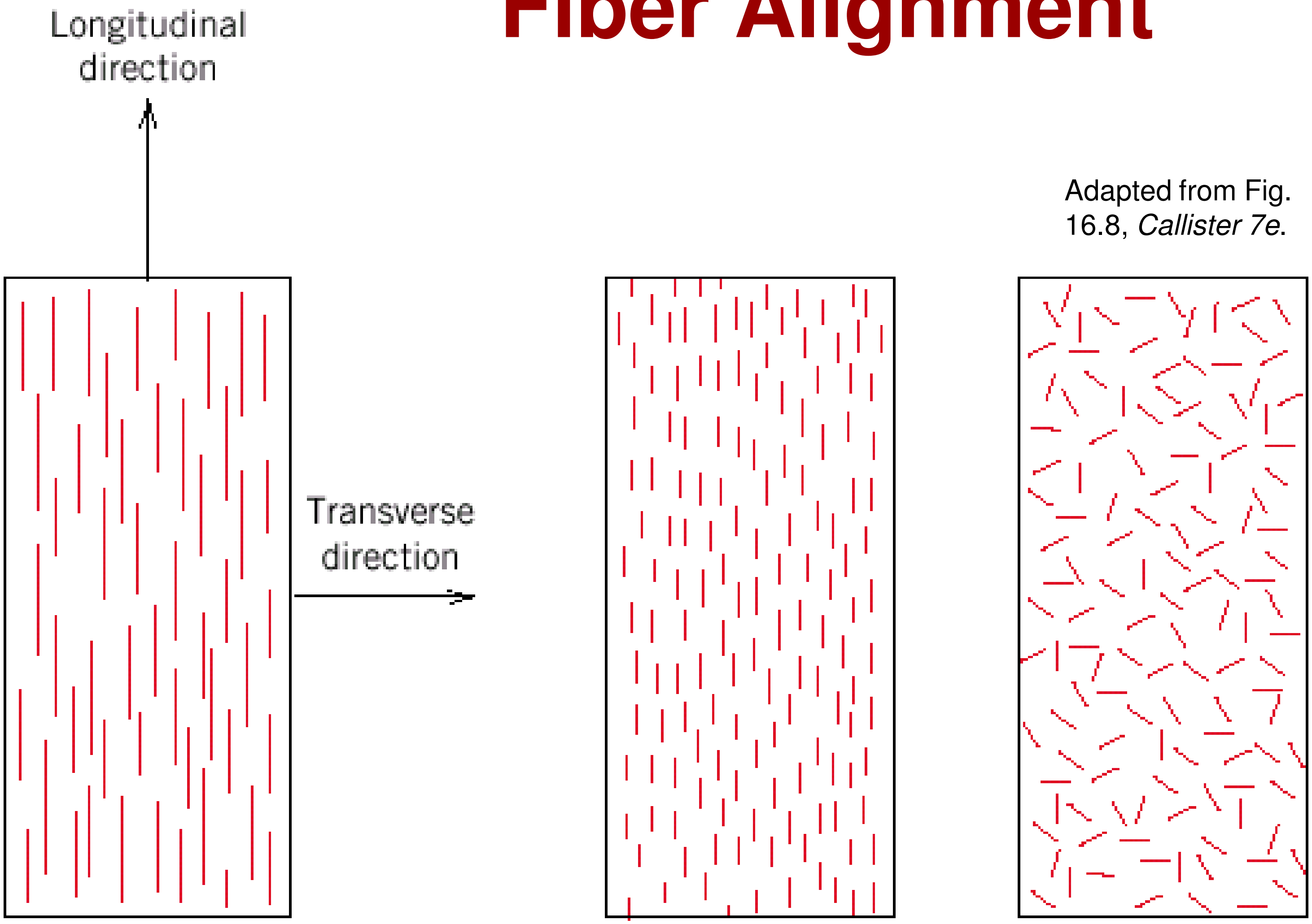
Influence of fiber materials, orientation, concentration, length, etc

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

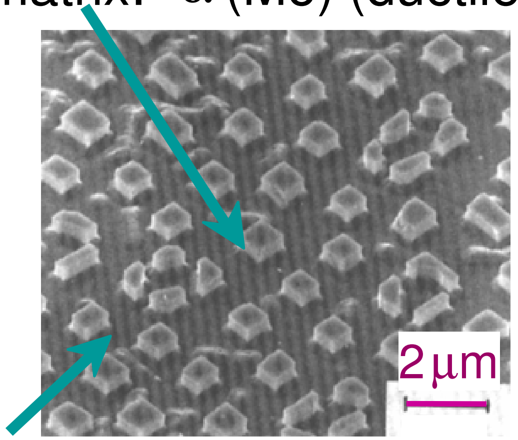
Composite Survey: Fiber-III

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

- Aligned Continuous fibers
- Examples:

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

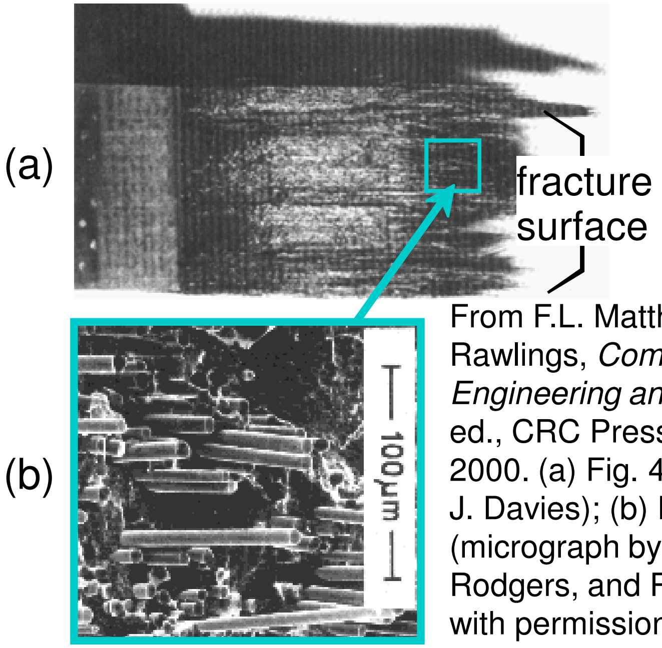
matrix: α (Mo) (ductile)



fibers: γ' (Ni_3Al) (brittle)

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

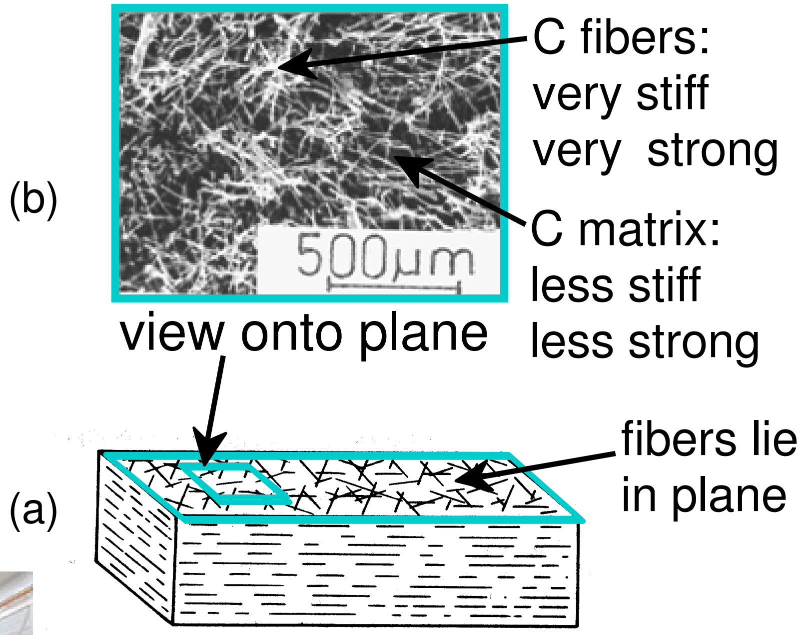


From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.22, p. 145 (photo by J. Davies); (b) Fig. 11.20, p. 349 (micrograph by H.S. Kim, P.S. Rodgers, and R.D. Rawlings). Used with permission of CRC Press, Boca Raton, 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.
- Other variations:
  - -- Discontinuous, random 3D
  - -- Discontinuous, 1D



C fibers:
very stiff
very strong

C matrix:
less stiff
less strong

view onto plane

fibers lie
in plane

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.

Carbon fiber-reinforced polymer composites

Composite Survey: Fiber-V

Particle-reinforced | Fiber-reinforced | Structural

- Critical fiber length for effective stiffening & strengthening:

fiber strength in tension

fiber diameter

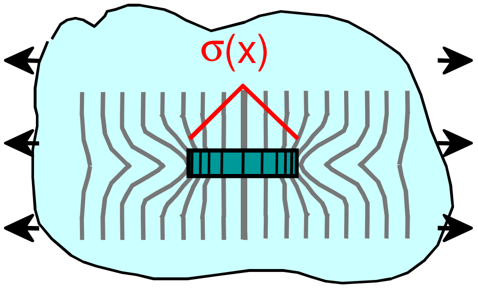
$$\text{fiber length} > 15\frac{\sigma_f d}{\tau_c}$$

shear strength of fiber-matrix interface

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

Shorter, thicker fiber:

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

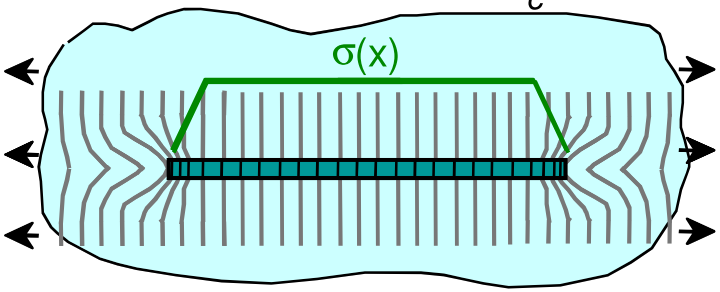


Poorer fiber efficiency

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

Longer, thinner fiber:

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



Better fiber efficiency

Load transmittance: the magnitude of the interfacial bond between the fiber and matrix phase

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

Modulus of elasticity

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

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

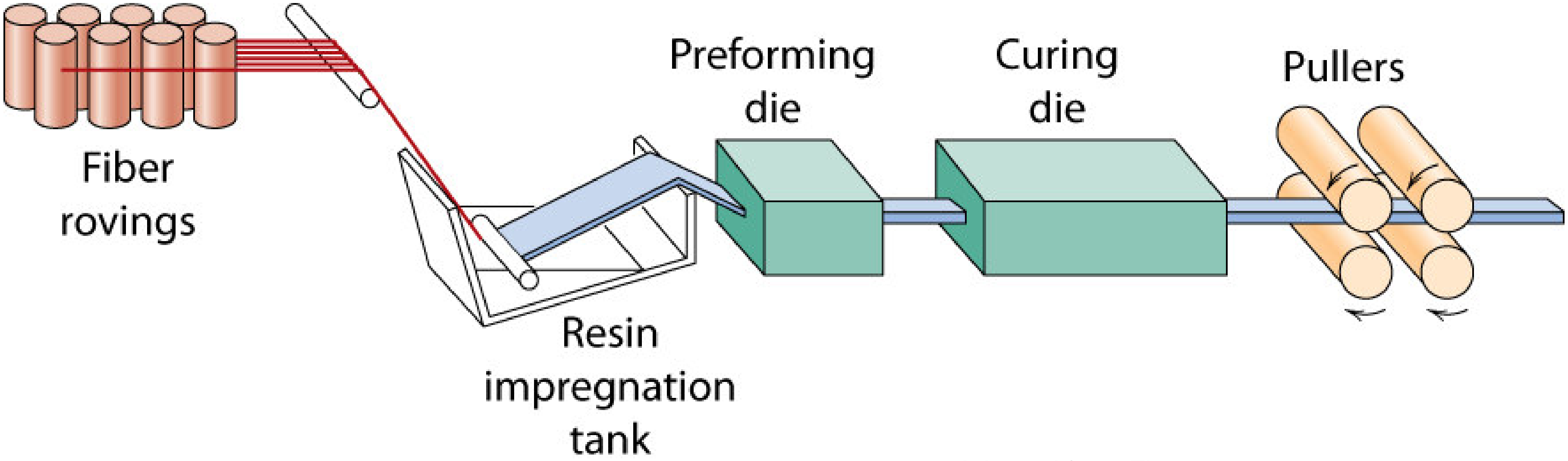
Values from Table 16.3, *Callister 7e*. (Source for Table 16.3 is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

-- 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 performing die & oven to cure

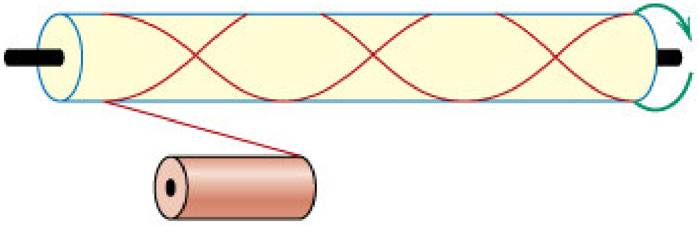


Adapted from Fig. 16.13, *Callister 7e*.

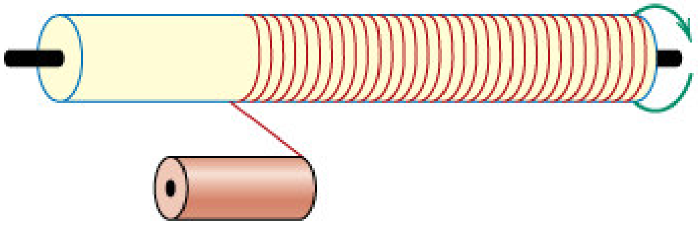
Composite Production Methods-II

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

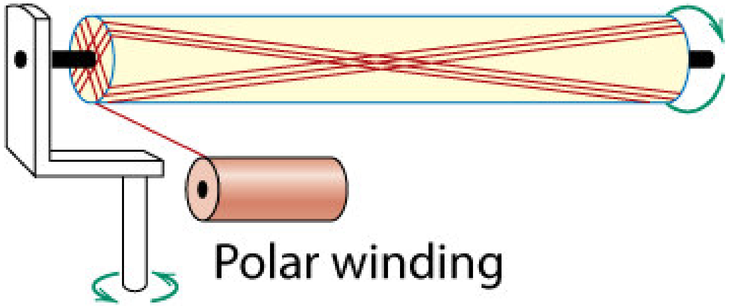
Adapted from Fig. 16.15, *Callister 7e*. [Fig. 16.15 is from N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials,* The Macmillan Company, New York, 1981.]



Helical winding



Circumferential winding



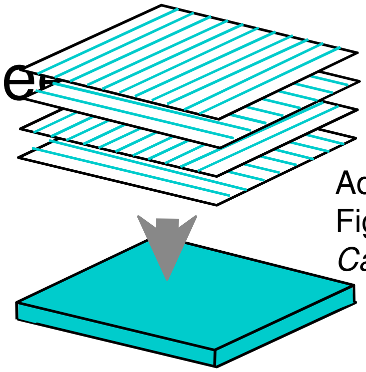
Polar winding

Composite Survey: Structural

Particle-reinforced   Fiber-reinforced   **Structural**

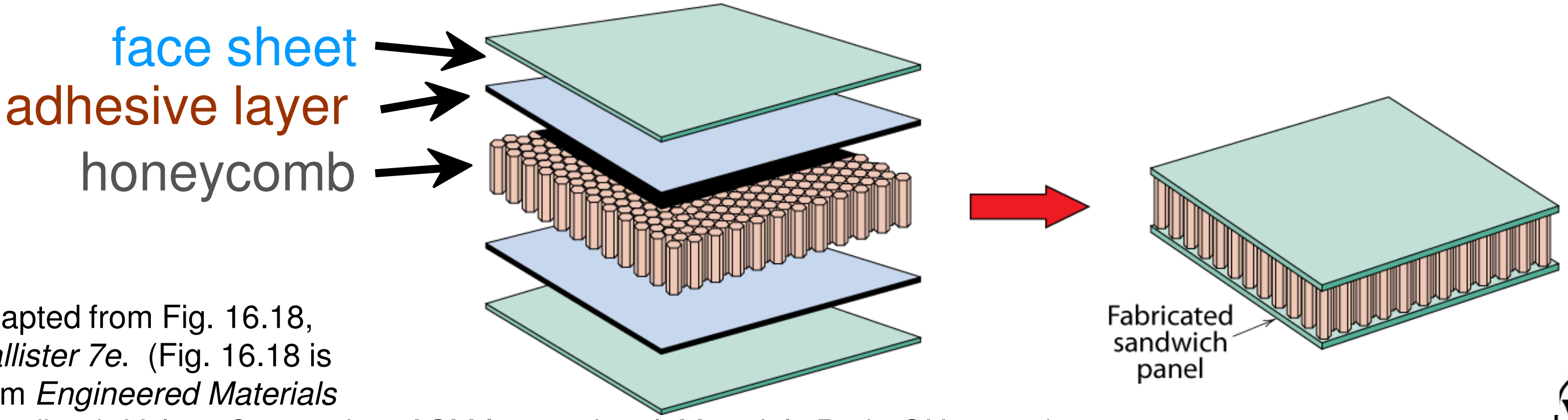
A structural composite is normally composed of both homogeneous and composite materials.

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



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

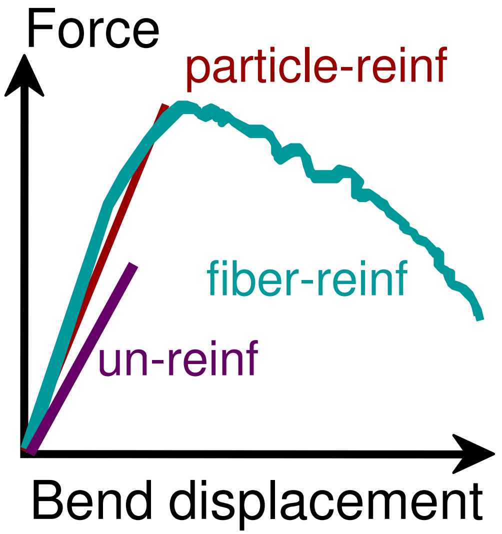
- Sandwich panels
  - -- low density, honeycomb core
  - -- benefit: small weight, large bending stiffness



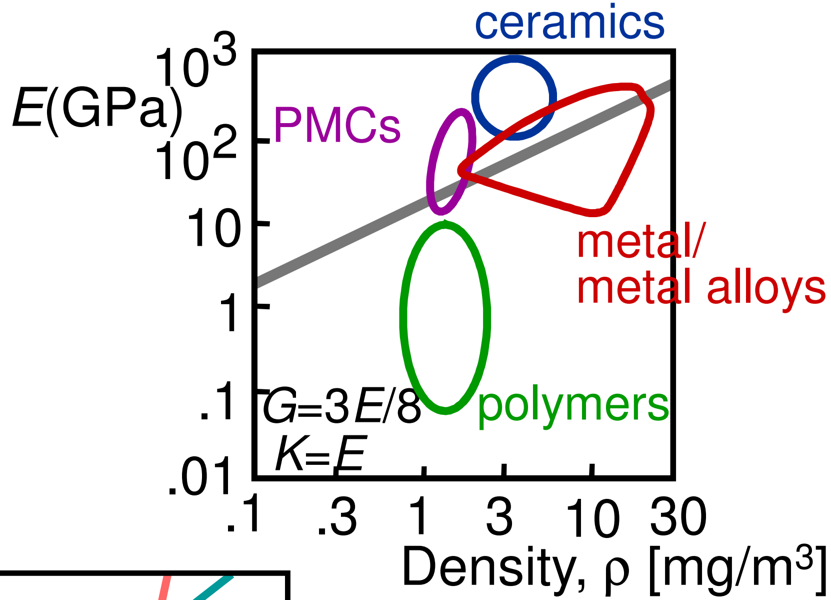
Adapted from Fig. 16.18, *Callister 7e*. (Fig. 16.18 is from *Engineered Materials Handbook*, Vol. 1, *Composites*, ASM International, Materials Park, OH, 1987.)

Composite Benefits

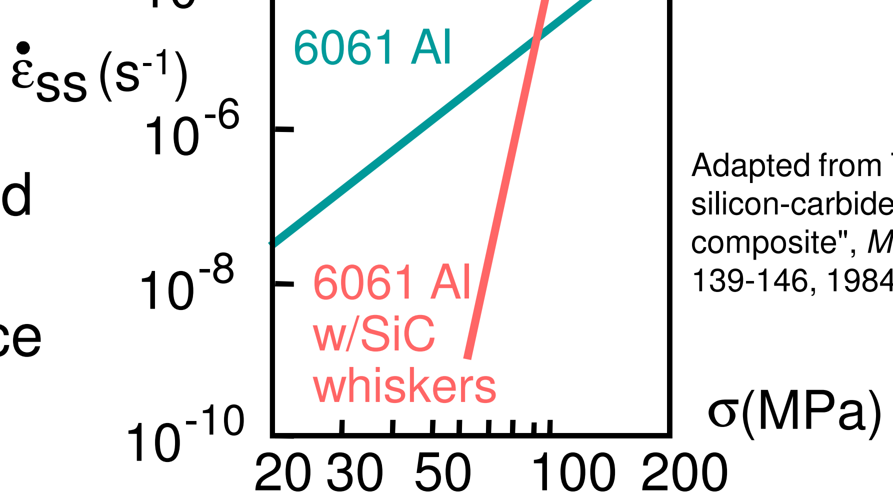
- CMCs: Increased toughness



- 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.