Chemical Engineering 378

Science of Materials Engineering

Lecture 27

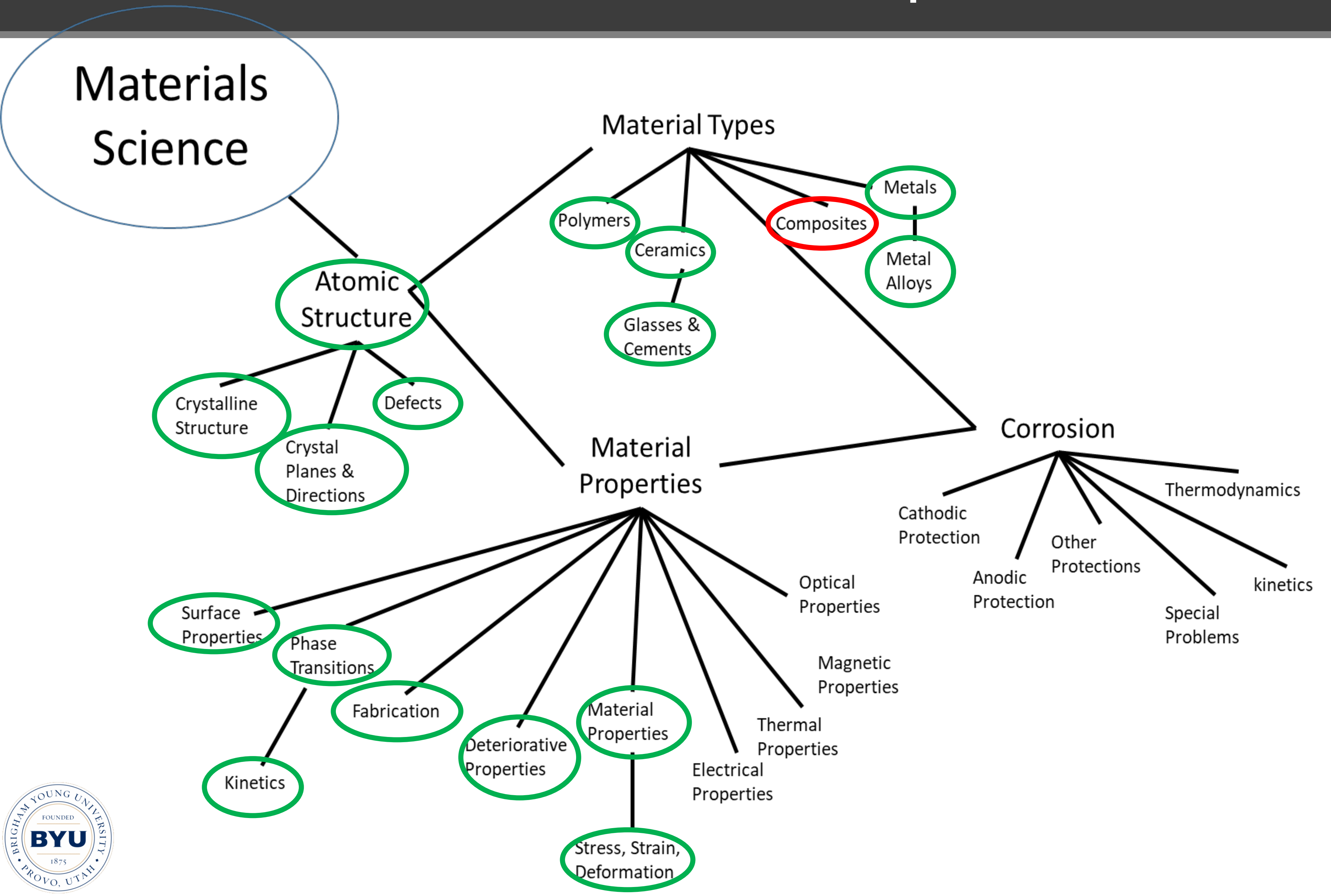
Composites: Fiber Orientation

Spiritual Thought

"The Lord's hand is guiding you. By 'divine design,' He is in the small details of your life as well as the major milestones. As it says in Proverbs, 'Trust in the Lord with all thine heart; … and he shall direct thy paths.' I testify that He will bless you, sustain you, and bring you peace."

-Elder Ronald A. Rasband

Materials Roadmap



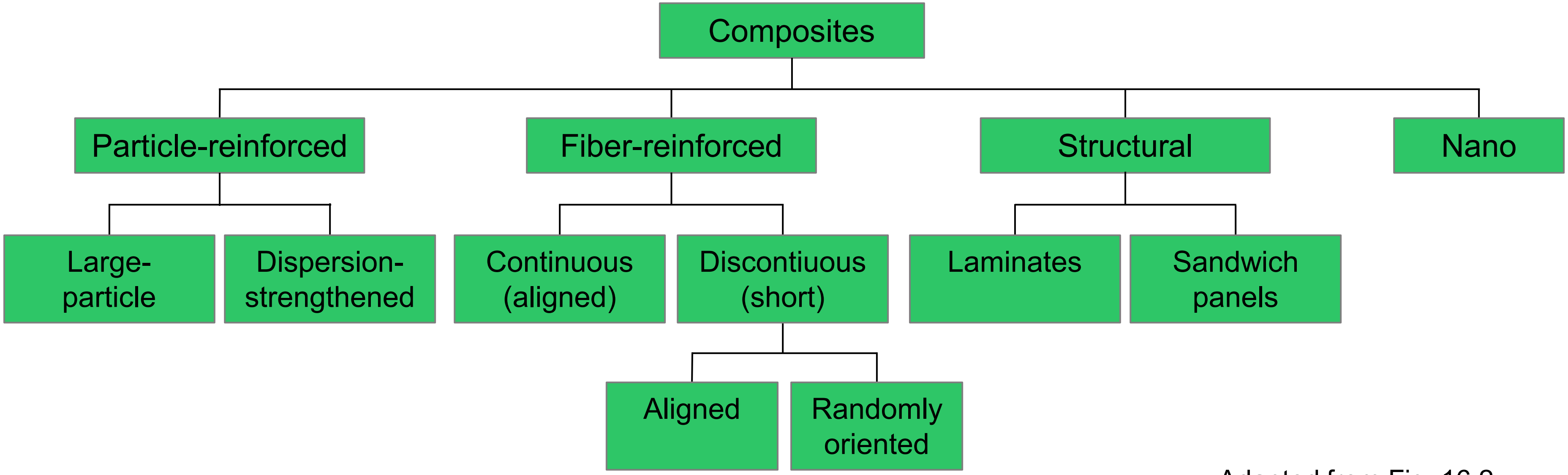

Top Sheet
Laminated Wood Core
Sidewalls
Composite Layers
Rubber Damping Strips
Edge
Base
Tip

Composite

- Combination of two or more individual materials

- Design goal: obtain a more desirable combination of properties (principle of combined action)
  - e.g., low density and high strength

Classification of Composites

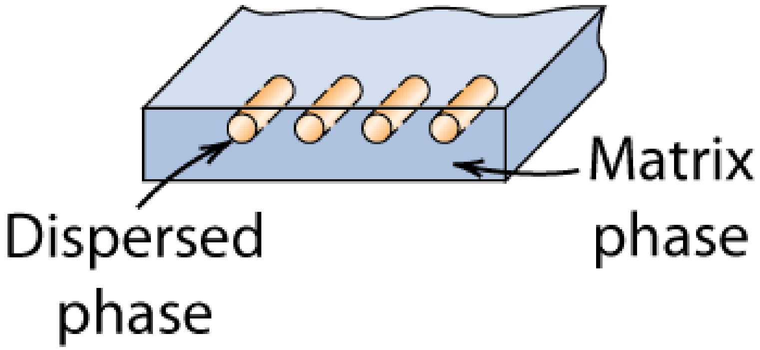


Adapted from Fig. 16.2,
Callister & Rethwisch 10e.

Terminology/Classification

- Composite:
  -- Multiphase material that is artificially made.

- Phase types:
  -- Matrix - is continuous
  -- Dispersed - is discontinuous and surrounded by matrix



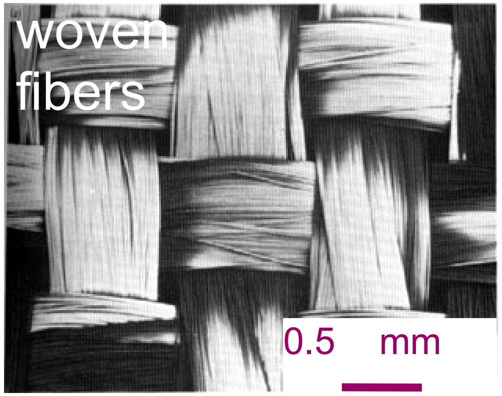
Adapted from Fig. 16.1(a), *Callister & Rethwisch 10e*.

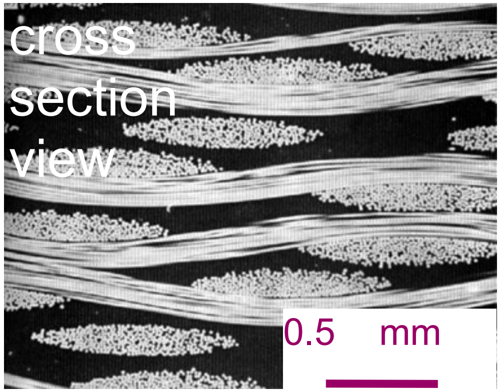
Terminology/Classification

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

metal ceramic polymer

- 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





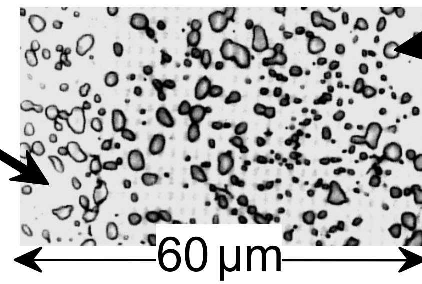
Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.

Classification: Particle-Reinforced (i)

Particle-reinforced | Fiber-reinforced | Structural

- Examples:
  - Spheroidite steel

matrix: ferrite (α) (ductile)

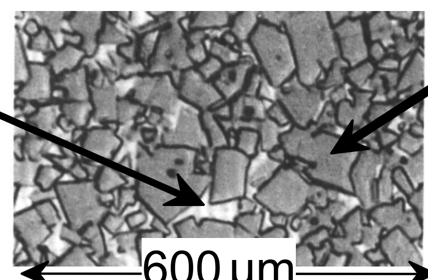


particles: cementite (Fe_3C) (brittle)

Fig. 10.19, *Callister & Rethwisch 10e*. (Copyright 1971 by United States Steel Corporation.)

  - WC/Co cemented carbide

matrix: cobalt (ductile, tough)

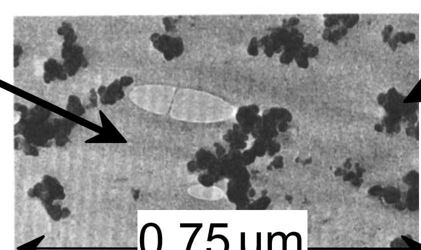


particles: WC (brittle, hard)

Fig. 16.4, *Callister & Rethwisch 10e*. (Courtesy of Carboloy Systems Department, General Electric Company.)

  - Automobile tire rubber

matrix: rubber (compliant)



particles: carbon black (stiff)

Fig. 16.5, *Callister & Rethwisch 10e*. (Courtesy of Goodyear Tire and Rubber Company.)

Classification: Particle-Reinforced (ii)

Particle-reinforced | Fiber-reinforced | Structural

Concrete – gravel + sand + cement + water

- Why sand *and* gravel? Sand fills voids between gravel particles

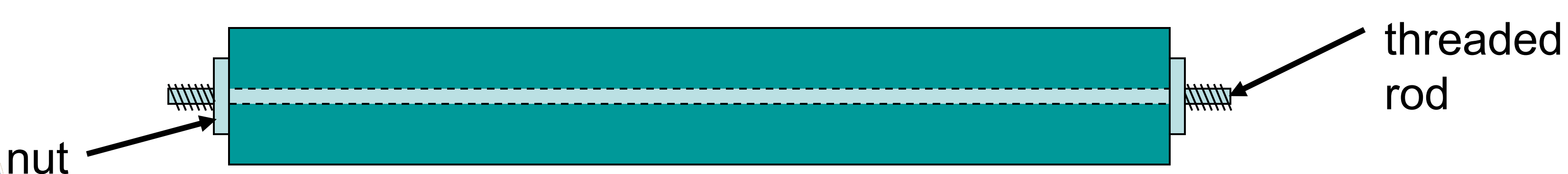
Reinforced concrete – Reinforce with steel rebar or remesh

- increases strength - even if cement matrix is cracked

Prestressed concrete

- Rebar/remesh placed under tension during setting of concrete
- Release of tension after setting places concrete in a state of compression
- To fracture concrete, applied tensile stress must exceed this compressive stress

Posttensioning – tighten nuts to place concrete under compression



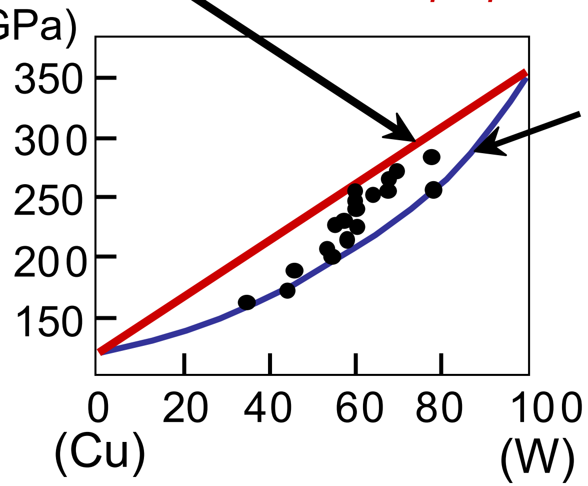
Classification: Particle-Reinforced (iii)

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:

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

Fig. 16.3, *Callister & Rethwisch 10e*. (Reprinted with permission from R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM International, 100 Barr Harbor Drive, West Conschohocken, PA 19428.)

- 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.

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

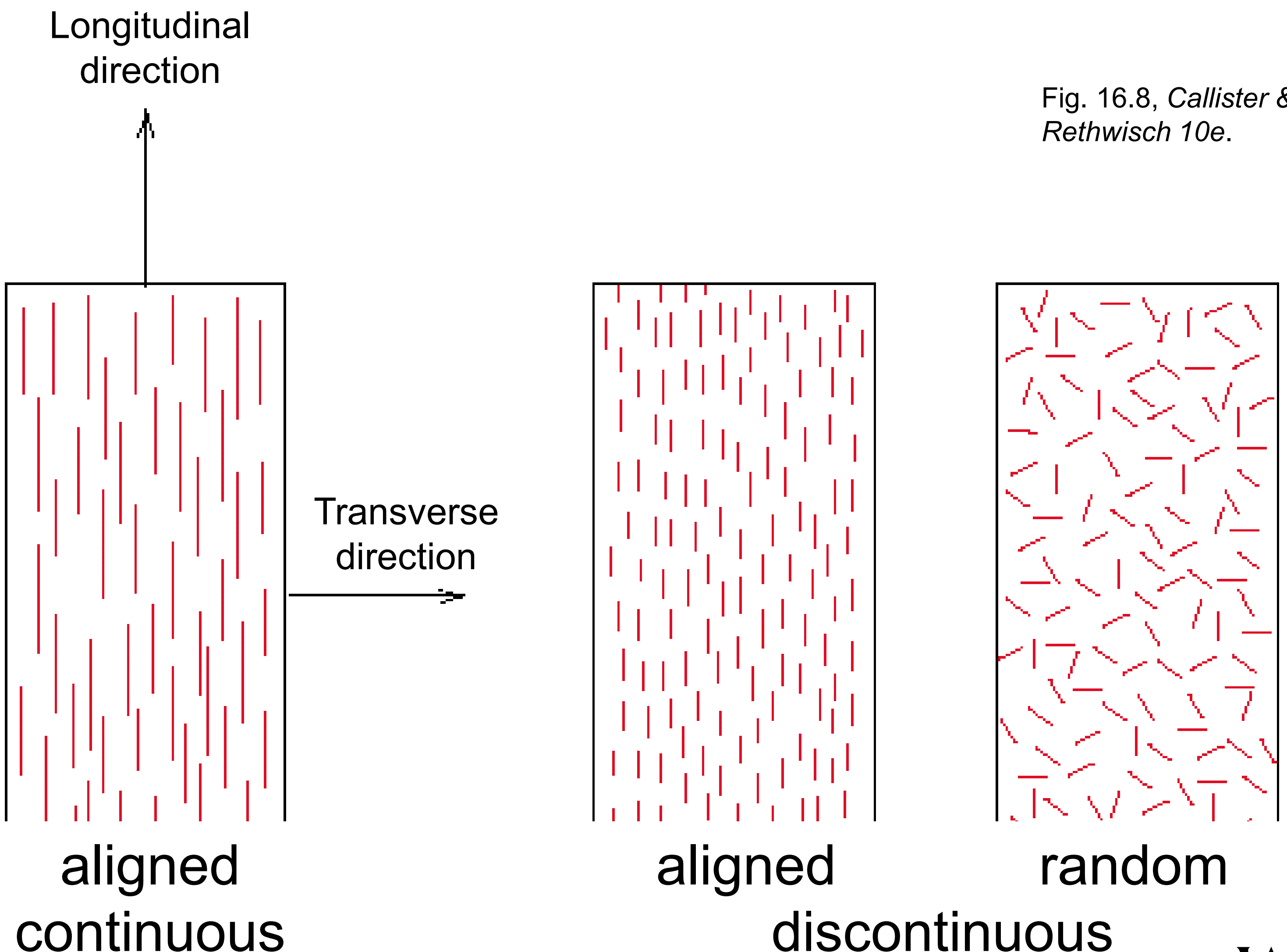
Classification: Fiber-Reinforced (ii)

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

- Fiber Types
  - Whiskers - thin single crystals - large length to diameter ratios
    - graphite, silicon nitride, silicon carbide
    - high crystal perfection – extremely strong, strongest known
    - very expensive and difficult to disperse
  - Fibers
    - polycrystalline or amorphous
    - generally polymers or ceramics
    - Ex: alumina, aramid, E-glass, boron, UHMWPE
  - Wires
    - metals – steel, molybdenum, tungsten

Fiber Alignment

Fig. 16.8, *Callister & Rethwisch 10e*.



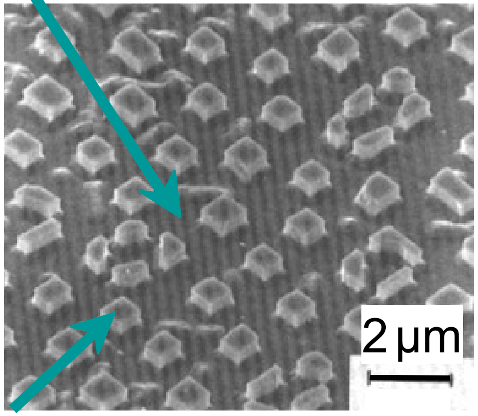
Classification: Fiber-Reinforced (iii)

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

- Aligned Continuous fibers
- Examples:

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

matrix: α(Mo) (ductile)

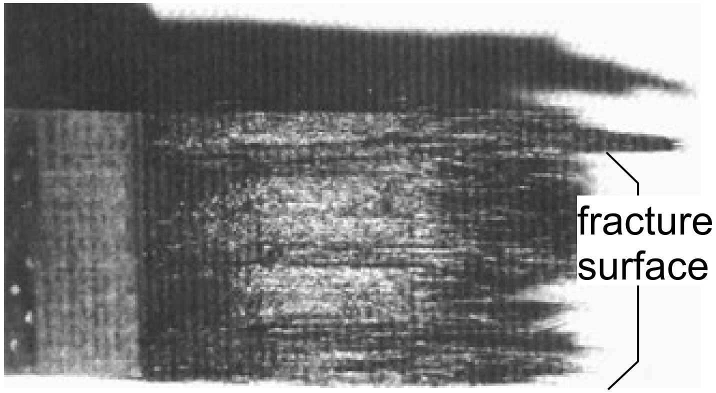


fibers: γ' (Ni_3Al) (brittle)

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

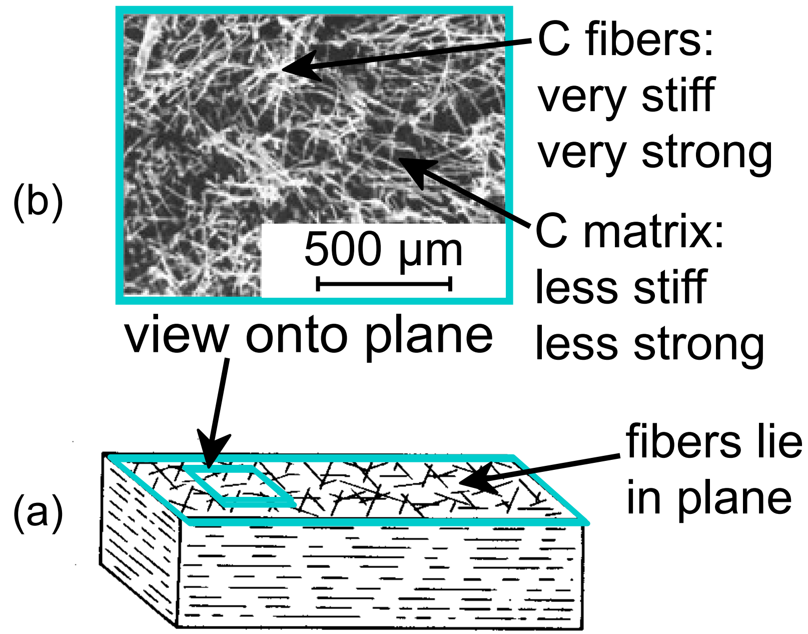


From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. Used with permission of CRC Press, Boca Raton, FL.

Classification: Fiber-Reinforced (iv)

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 2500° C.
  - -- 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.

Classification: Fiber-Reinforced (v)

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

- Critical fiber length for effective stiffening & strengthening:

fiber ultimate tensile strength

fiber diameter

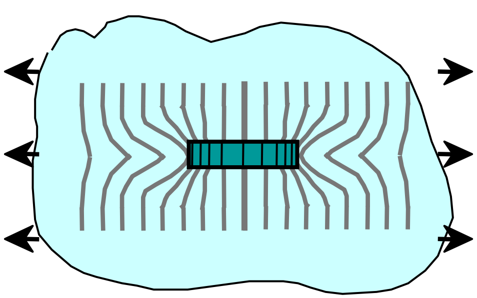
$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

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:

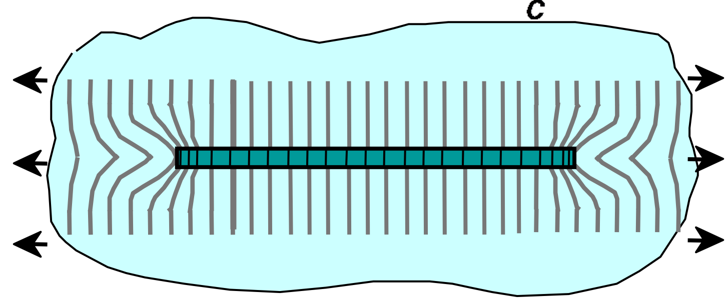
$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$



Low fiber efficiency

Long, thin fibers:

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



High fiber efficiency

Composite Stiffness: Longitudinal Loading

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

- Longitudinal deformation

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

volume fraction (the V_m and V_f terms) isostrain ($\varepsilon_c = \varepsilon_m = \varepsilon_f$)

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

E_{cl} = longitudinal modulus

c = composite
f = fiber
m = matrix

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

c = composite

f = fiber

m = matrix

Composite Stiffness

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

- Estimate of E_{cd} for discontinuous fibers:

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

  -- Elastic modulus in fiber direction:

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

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)

Table 16.3, *Callister & Rethwisch 10e*.
(Source is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

Composite Strength

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

- Estimate of σ^*_{cd} for discontinuous fibers:

1. When $l > l_c$

$$\sigma^*_{cd'} = \sigma^*_f V_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m (1 - V_f)$$

2. When $l < l_c$

$$\sigma^*_{cd'} = \frac{l\,\tau_c}{d} V_f + \sigma'_m (1 - V_f)$$