# Chemical Engineering 378

## *Science of Materials Engineering*

### Lecture 28

### Composites: Fabrication

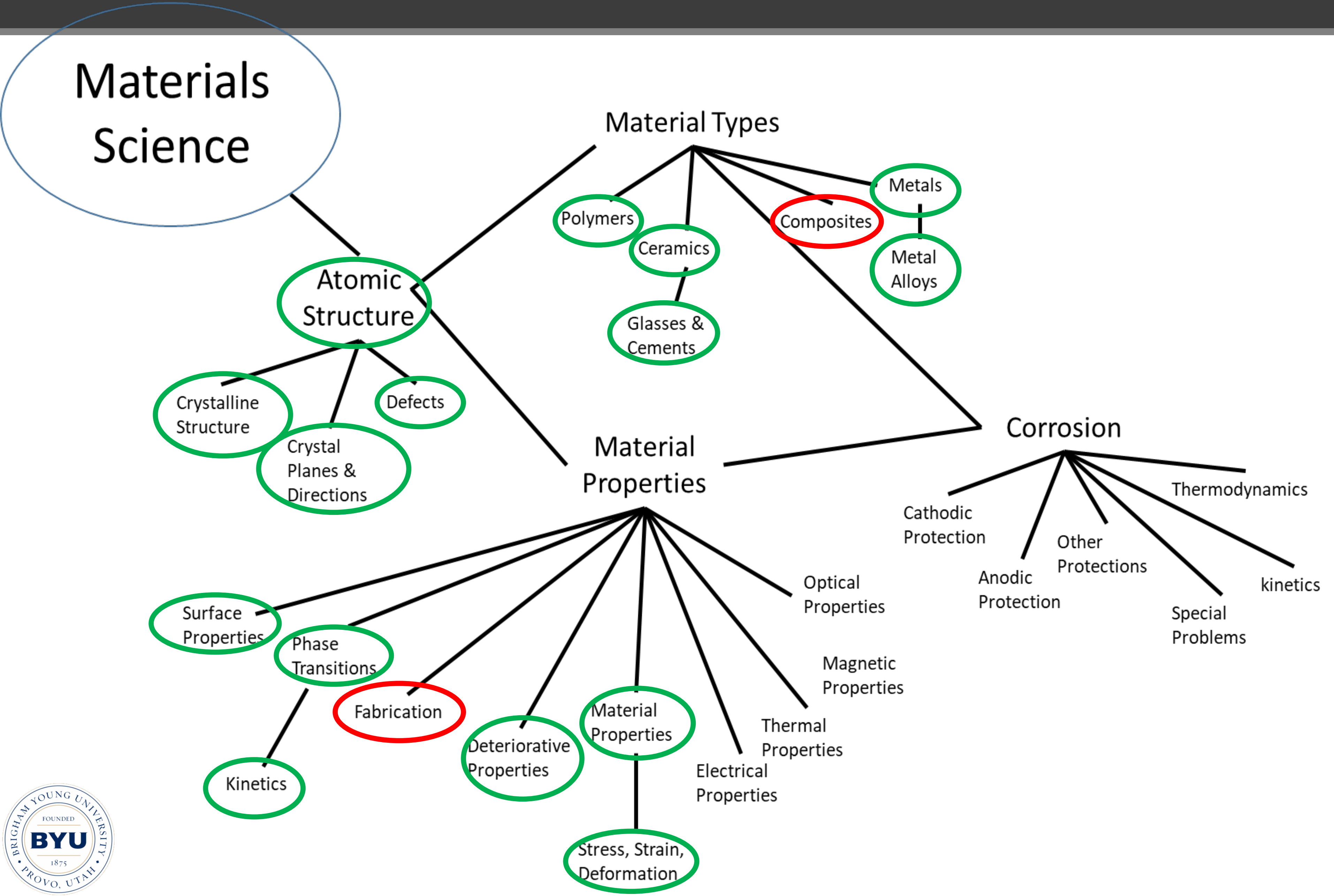
# Spiritual Thought

D&C 9-10

45 Thou shalt live together in love, insomuch that thou shalt weep for the loss of them that die, and more especially for those that have not hope of a glorious resurrection.

46 And it shall come to pass that those that die in me shall not taste of death, for it shall be sweet unto them;

# Materials Roadmap



Materials Science

Atomic Structure

- Crystalline Structure
- Crystal Planes & Directions
- Defects

Material Types

- Polymers
- Ceramics
  - Glasses & Cements
- Composites
- Metals
  - Metal Alloys

Corrosion

- Cathodic Protection
- Anodic Protection
- Other Protections
- Special Problems
- Thermodynamics
- kinetics

Material Properties

- Surface Properties
- Phase Transitions
  - Kinetics
- Fabrication
- Deteriorative Properties
- Material Properties
  - Stress, Strain, Deformation
- Electrical Properties
- Thermal Properties
- Magnetic Properties
- Optical Properties

# Composite Stiffness: Longitudinal Loading

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

- Longitudinal deformation

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

volume fraction

isostrain

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

$E_{cl}$ = 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 < $15\frac{\sigma_f d}{\tau_c}$

-- 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 $\sigma^*_{cd}$ 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 $l < l_c$

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

# Example

It is desired to produce an aligned carbon fiber-epoxy matrix composite having a longitudinal tensile strength of 750 MPa (109,000 psi). Calculate the volume fraction of fibers necessary if (1) the average fiber diameter and length are $1.2 \times 10^{-2}$ mm ($4.7 \times 10^{-4}$ in.) and 1 mm (0.04 in.), respectively; (2) the fiber fracture strength is 5000 MPa (725,000 psi); (3) the fiber-matrix bond strength is 25 MPa (3625 psi); and (4) the matrix stress at fiber failure is 10 MPa (1450 psi)

$$l_c = \frac{\sigma_f^* d}{2\tau_c} \qquad l_c = 1.2 \text{ mm}$$

$$\sigma_{cd'}^* = \frac{l\tau_c}{d} V_f + \sigma_m'(1 - V_f)$$

$$V_f = 0.357$$

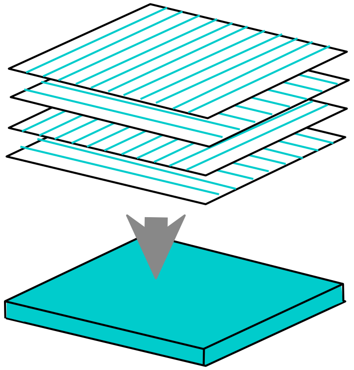
# Classification: Structural

Particle-reinforced　Fiber-reinforced　**Structural**

- Laminates -

  -- stacked and bonded fiber-reinforced sheets

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



- Sandwich panels

  -- honeycomb core between two facing sheets

  - benefits: low density, large bending stiffness

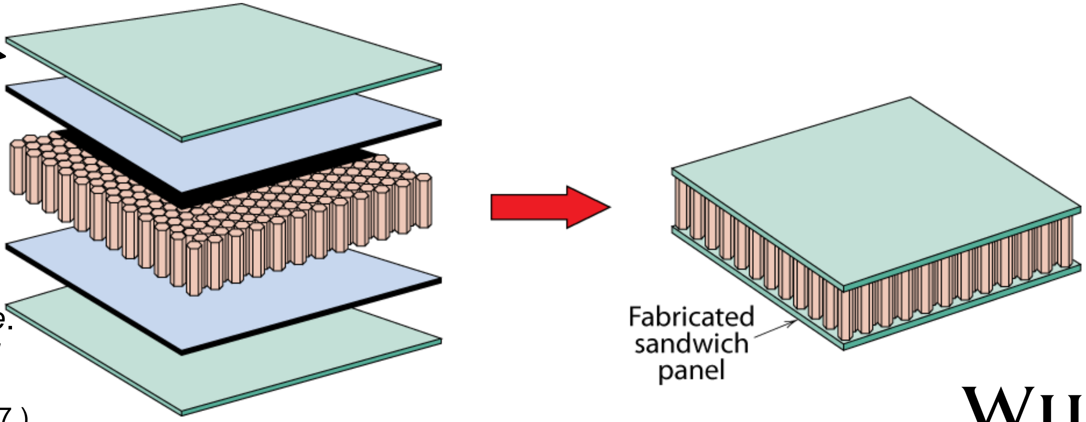
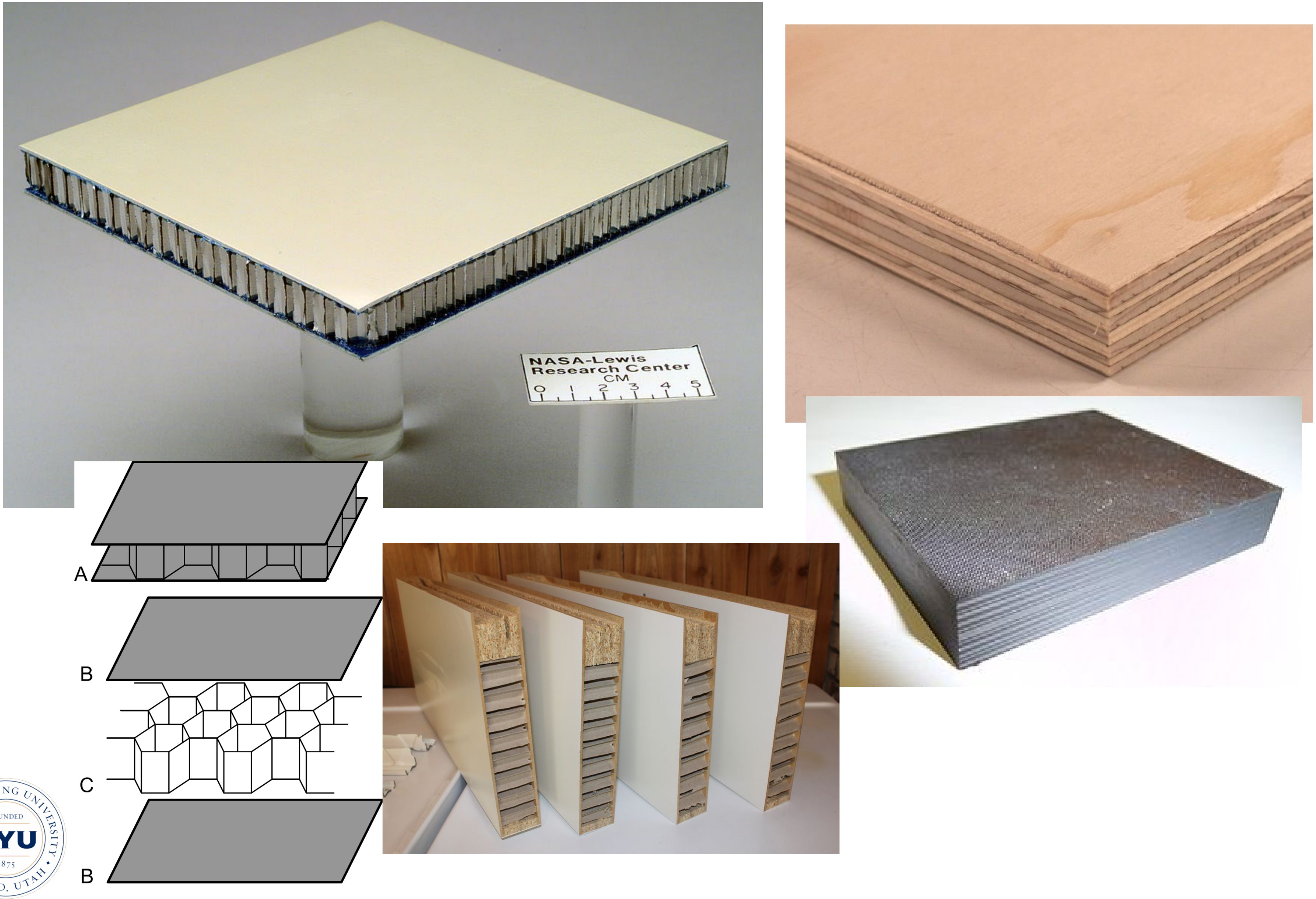


Fig. 16.18, *Callister & Rethwisch 10e*.
(Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, Composites, ASM International, Materials Park, OH, 1987.)

# Structural Composites



# 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

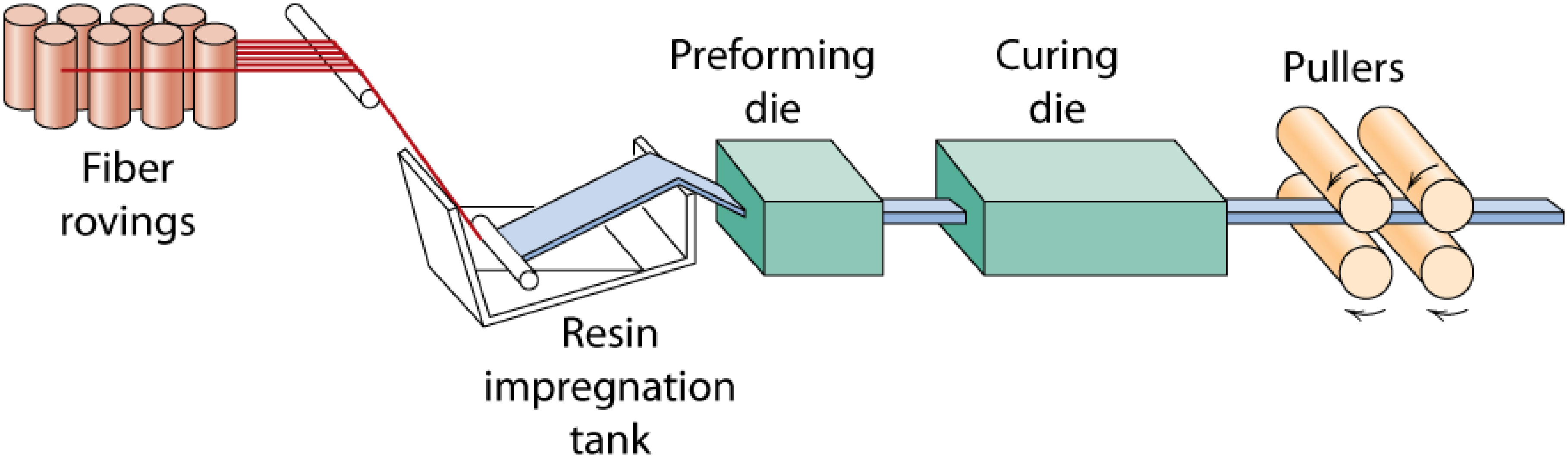


Fig. 16.13, *Callister & Rethwisch 10e*.

# 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

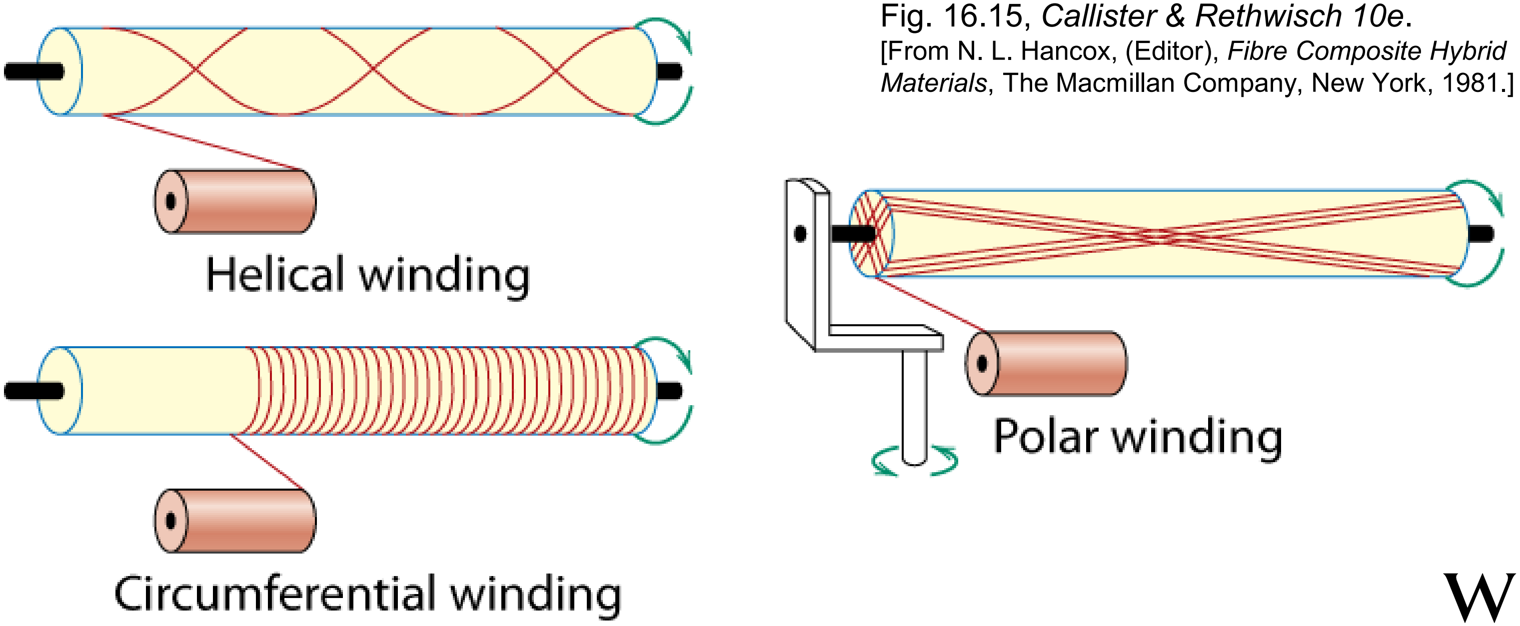
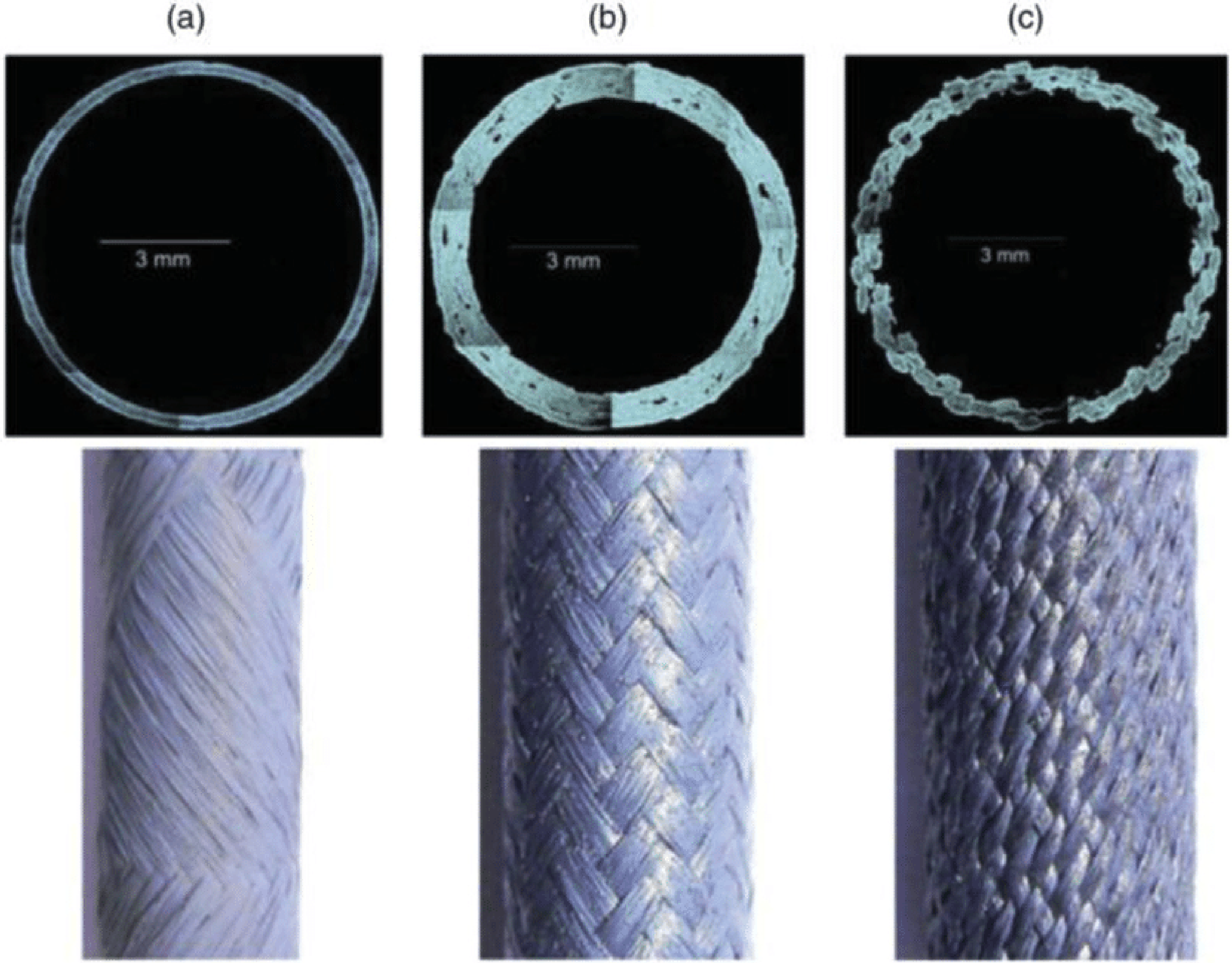
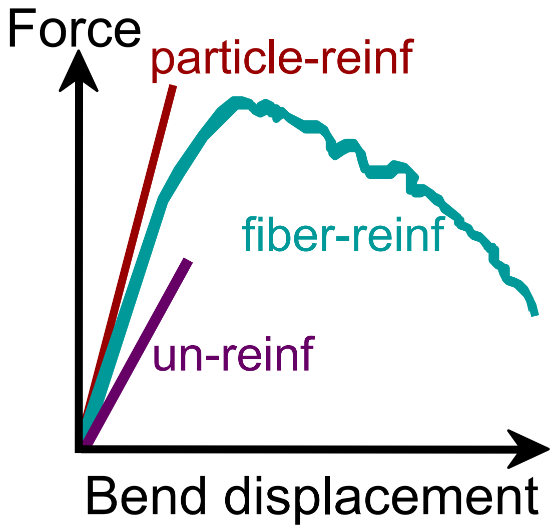


Fig. 16.15, *Callister & Rethwisch 10e*.
[From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]

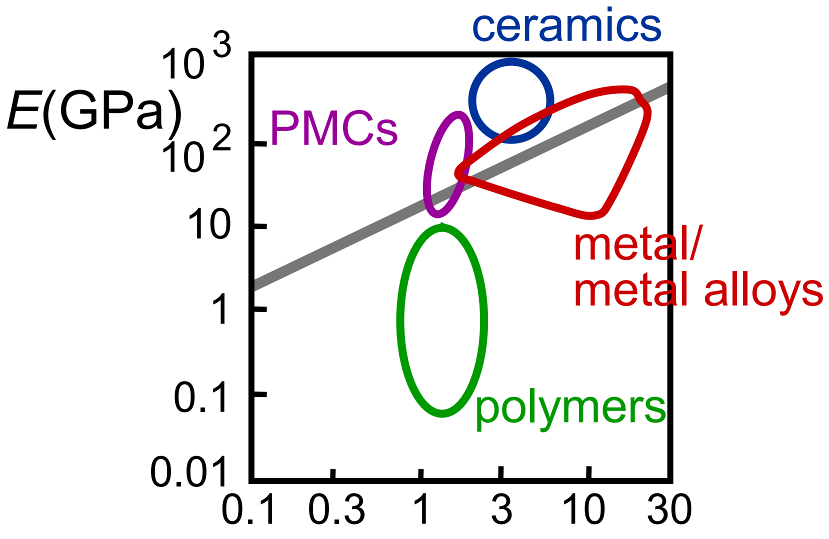

(a)
(b)
(c)
3 mm
3 mm
3 mm

# Composite Benefits

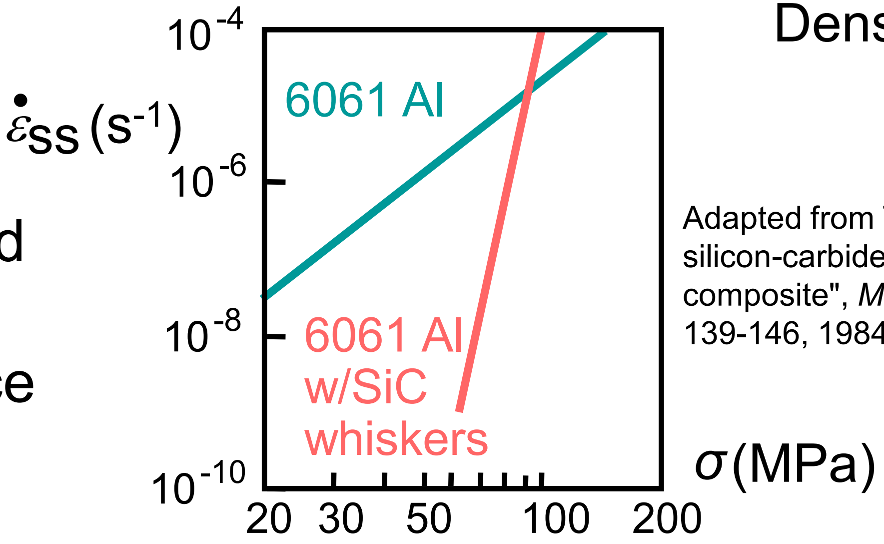
- CMCs: Increased toughness



- PMCs: Increased $E/\rho$



- 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 types are designated by:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement (particles, fibers, structural)
- Composite property benefits:
  -- MMC: enhanced $E$, $\sigma^*$, creep performance
  -- CMC: enhanced $K_{Ic}$
  -- PMC: enhanced $E/\rho$, $\sigma_y$, $TS/\rho$
- 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