Module #27

Composite Materials

(an overview)

READING LIST

►DIETER: Ch. 6, Pages 220-226.

- Chapter 15 in Meyers & Chawla.
- N. Chawla & K.K. Chawla, Metal Matrix Composites, Springer (2006)
- D. Hull & T.W. Clyne, An Introduction to Composite Materials, 2nd Edition, Cambridge (1996)

Introduction

- So far, we've considered the improvement of the mechanical properties of materials by modifying the internal structure of the material system either by alloying or processing.

- We can also develop materials with even different properties by introducing additional phases/materials into a host material. This mixture of phases is termed a *composite*.

- In general, composites are *relatively macroscopic mixtures of phases/materials*. These mixtures are sometimes natural, but are generally artificial.

- By mixing two different phases or materials, we can develop materials that have properties which are an average of those of the two components.

Introduction (2)

- In a composites, strength/properties = average of strength/properties of the individual materials.

- We design composites so as to obtain the best attributes of the individual constituents.

- Microstructure of a composite = matrix + reinforcement

  – Matrix:
    - phase that holds reinforcement together
    - protects the reinforcement
    - transmits load to the reinforcement.

  – Reinforcement:
    - filaments, fibers, whiskers, etc., which have intrinsically high strength and modulus; reinforcements are often too brittle to use in monolithic forms. Sometimes “soft” reinforcements are used too.

Introduction (3)

- Interface between reinforcement and matrix is often the most critical element in determining materials properties and performance.
  - Is interface strong or weak?
    - Influences transfer of stress from matrix to fiber
    - Influences crack propagation
    - Etc.
  - Is there reaction at the interface? Is there no reaction?
    - Reactions change the properties of the fiber and matrix locally. Chemistry change
    - Stress concentration
    - Etc.

Classification of Composites (1)

- On basis of matrix:
  - **Polymer** matrix composites (**P**MCs)
  - **Metal** matrix composites (**M**MCs)
  - **Ceramic** matrix composites (**C**MCs)
- Purpose of reinforcement
  - PMC: increase stiffness (E), yield strength, tensile strength, and creep resistance
  - MMC: increase yield strength, tensile strength, and creep resistance
  - CMC: increase fracture toughness (K_c)

Classification of Composites (2)

- On basis of reinforcement
  - Particle reinforced composites
    - Natural
      - Ex., precipitates
    - Artificial
      - Addition of immiscible phases
  - Short fiber or whisker reinforced composites
    - Artificial
  - Continuous fiber or sheet reinforced MMCs
    - Natural ("sort of")
      - Ex., DS eutectics
    - Artificial

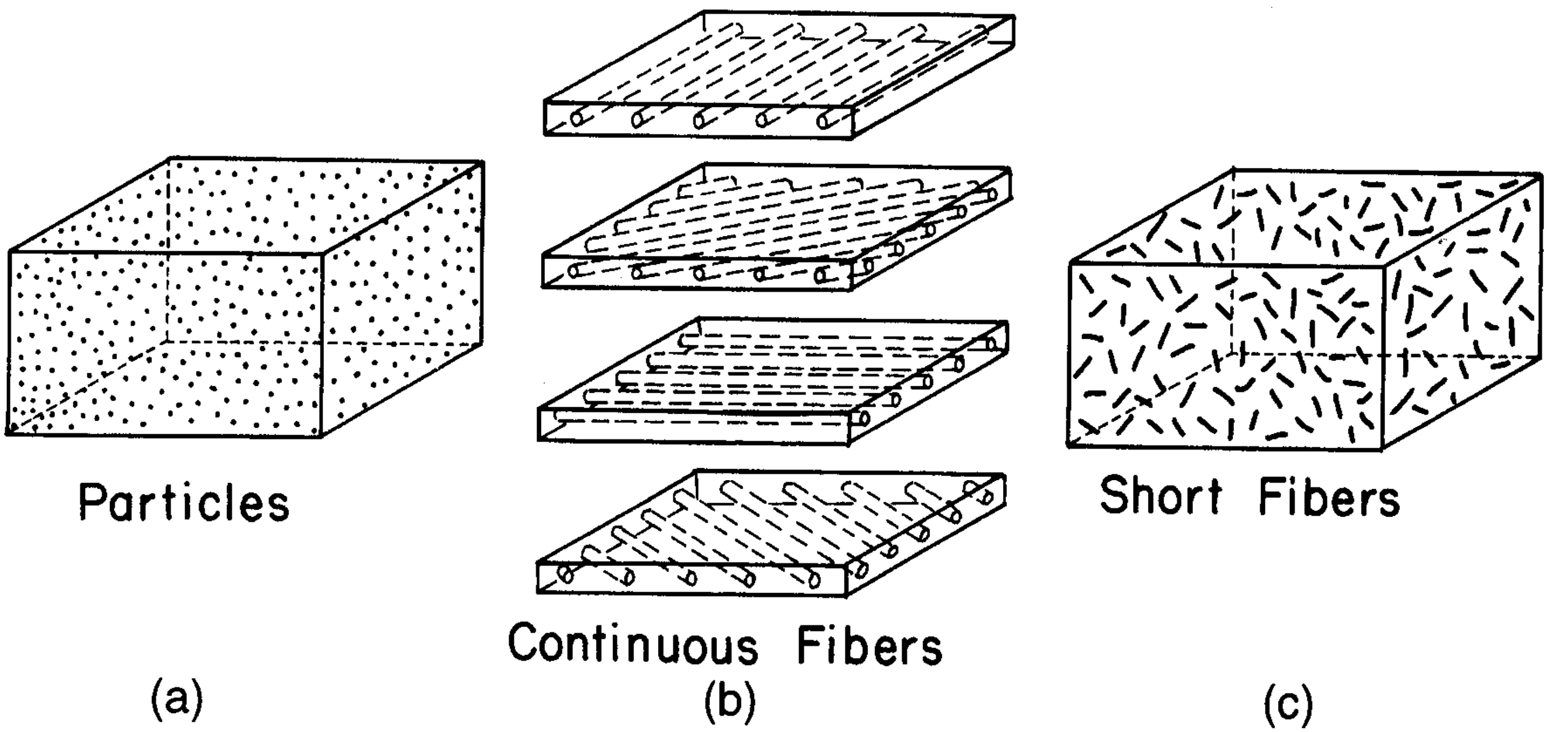


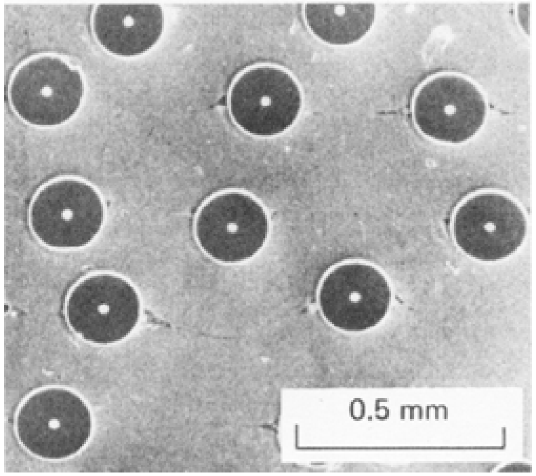
Figure 1.4 Different kinds of reinforcement in composite materials. (a) Composite with particle reinforcement. (b) Composite with continuous fibers with four different orientations (shown separately for clarity). (c) Composite reinforced with short, discontinuous fibers.

[Meyers & Chawla]

What can composites look like?

MMC

Fiber reinforced

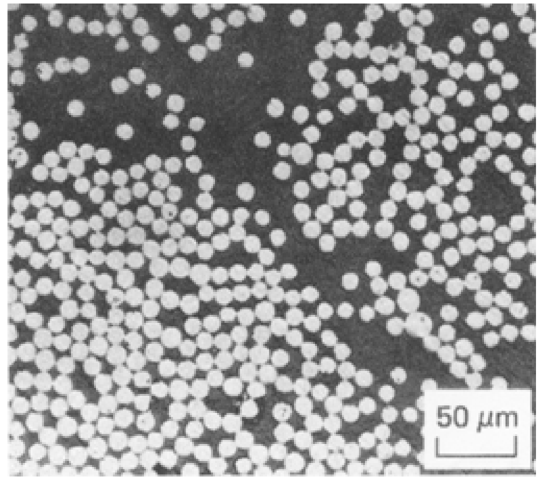


[Meyers & Chawla]

(a)

PMC

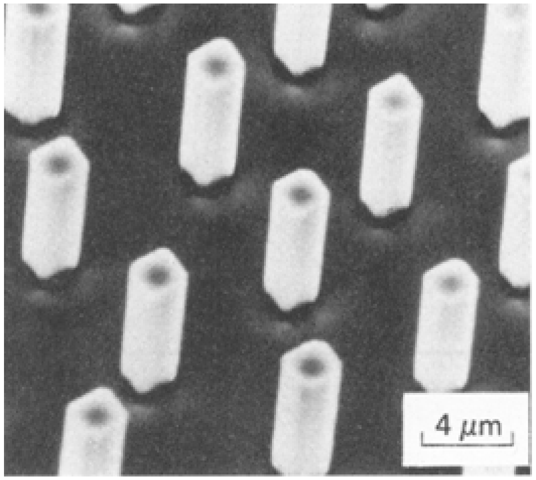
Fiber reinforced



(b)

MMC

Fiber reinforced (eutectic)

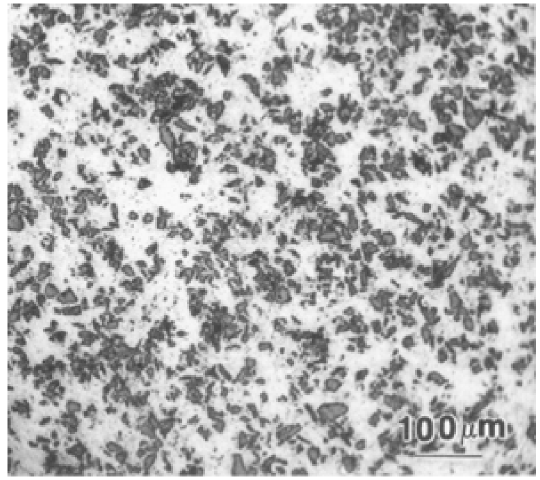


[Meyers & Chawla]

(c)

MMC

Particle reinforced

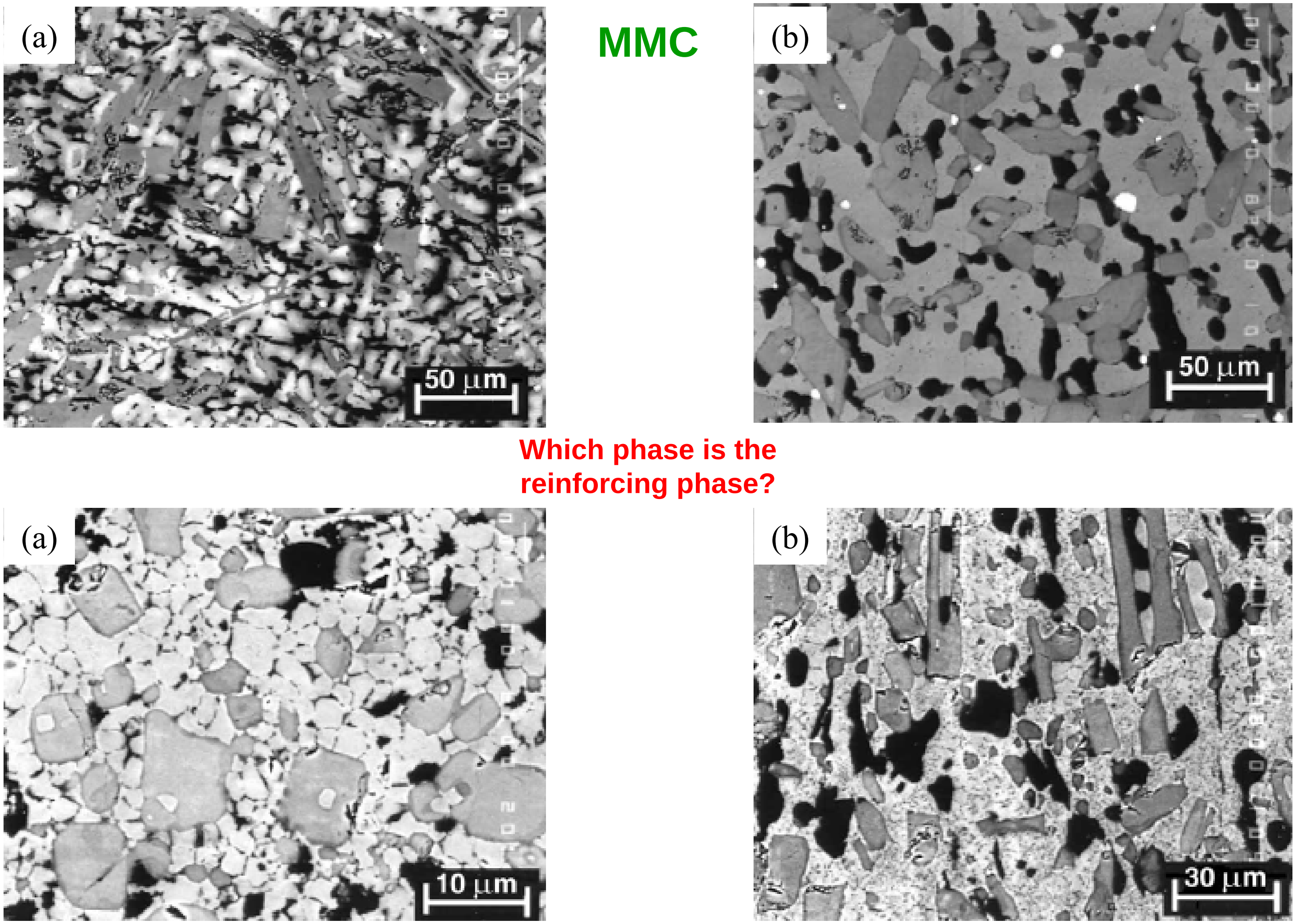


(d)

Figure 15.1 (a) Transverse section of a boron fiber reinforced aluminum composite. V_f = 10%. (b) Transverse section of a carbon fiber reinforced polyester resin. V_f = 50% (Optical). (c) Deeply etched transverse section of a eutectic composite showing NbC fibers in a Ni-Cr matrix. (d) SiC particles in an Al alloy matrix (SEM). V_f = 17%.

What can composites look like?

MMC



Which phase is the reinforcing phase?

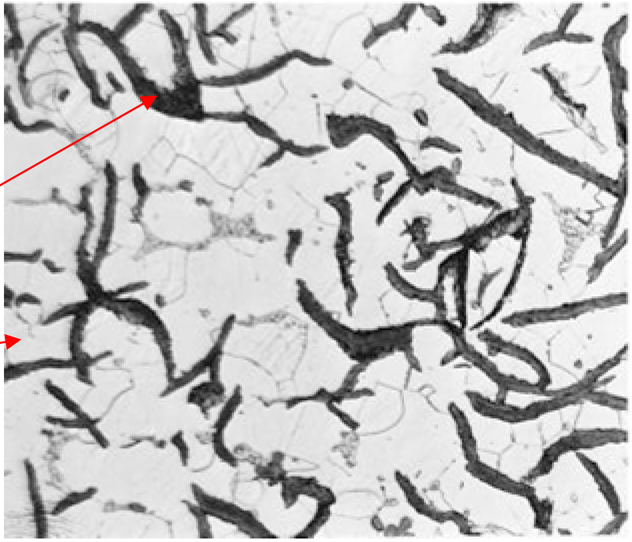
[Bewlay et al., MRS Bulletin, v.28, n.9 (2003) p. 646-653]

Figure 5. Microstructural evolution in Nb-19.5Ti-13Cr-2Hf-17.5Si-2Al-1.2Sn (at.%) in the following conditions: (a) as-cast, (b) homogenized (1300°C/24h + 1400°C/76 h), and (c), (d) extruded (1350°C at 6:1 ratio), transverse and longitudinal sections, respectively. The light phase is Nb, the gray phase in $(Nb)_5Si_3$, and the black phase is the $Cr_2(Nb)$-type Laves phase.

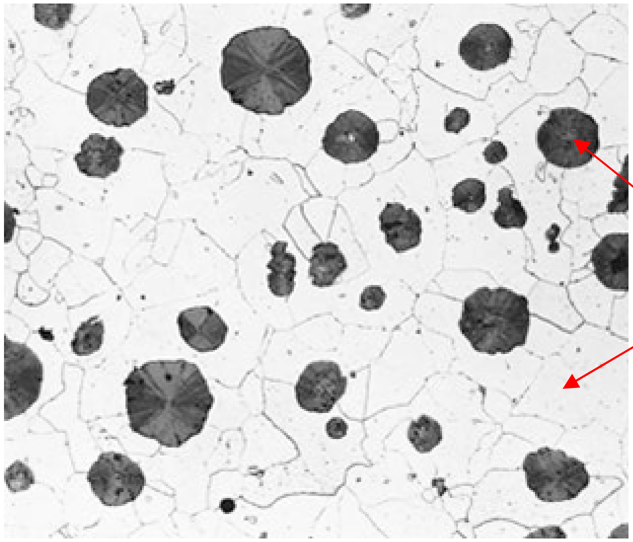
Cast Iron: another good example of a composite

Particle reinforced MMCs

GRAY

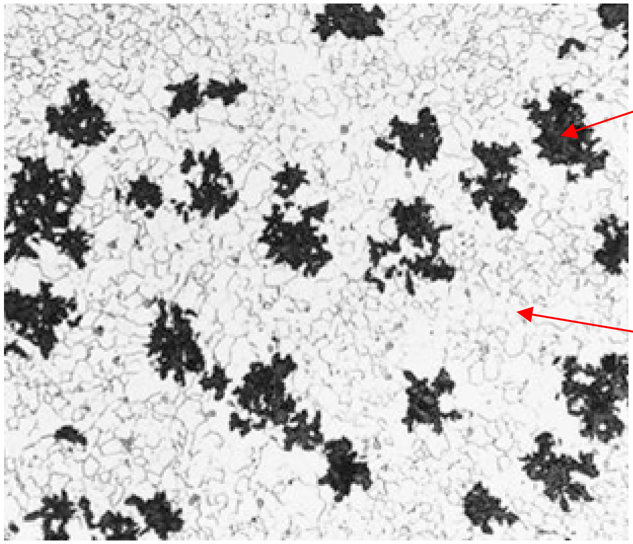


DUCTILE



WHITE

MALLEABLE



[From Callister, 7th Ed., Fig. 11.3, pages 367-368]

What do properties depend upon?

- Matrix type
  - Structure and intrinsic properties

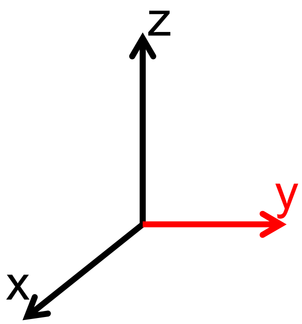
- Reinforcement:
  - Concentration
  - Shape
  - Size
  - Distribution
  - Orientation
  - Matrix/reinforcement interface

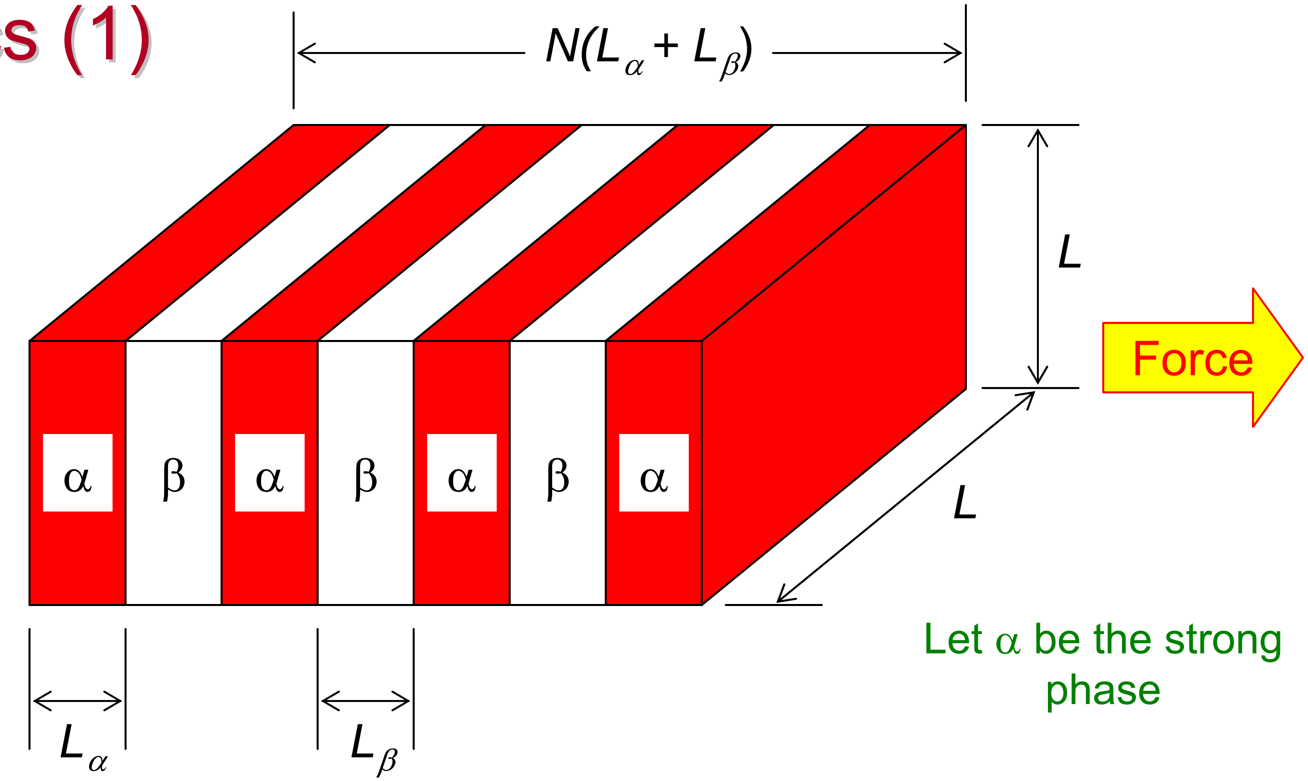
- To begin, we will consider a laminate composite in order to develop the basic principles of reinforcement.

Basic mechanics (1)

$$V_\alpha = \frac{L_\alpha}{(L_\alpha + L_\beta)}$$

$$V_\beta = \frac{L_\beta}{(L_\alpha + L_\beta)}$$





Let α be the strong phase

- Consider the case where a force is applied along the y-direction. In this instance, the stresses on the α and β lamellae are equal (i.e., σ = F/L²).
- The composite strain is the weighted average of the individual strains in each lamellae.

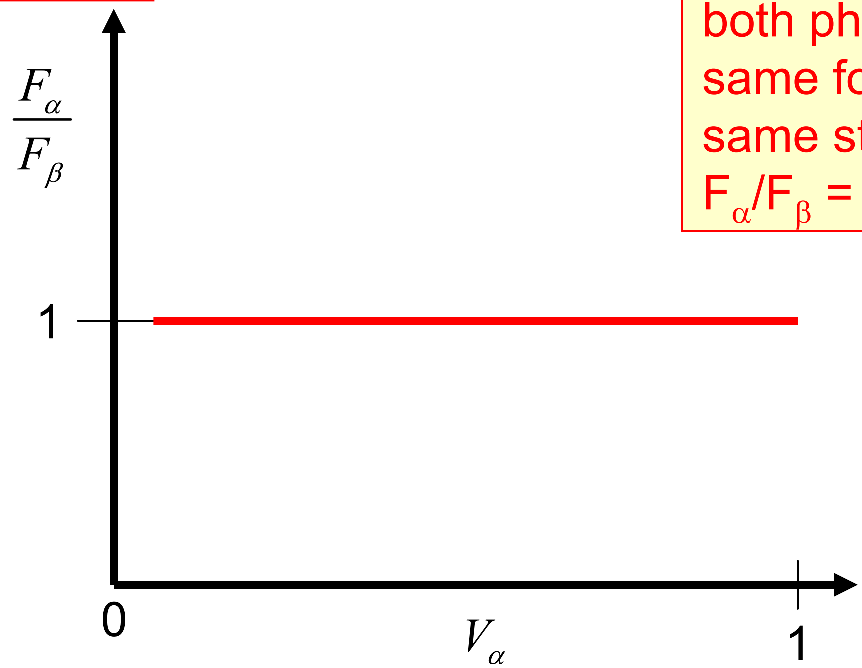
$$\varepsilon_c = V_\alpha \varepsilon_\alpha + V_\beta \varepsilon_\beta$$

- The composite modulus is given by:

$$E_c = \frac{E_\alpha E_\beta}{V_\alpha E_\beta + V_\beta E_\alpha}$$

Does strength change as we alter volume fraction of reinforcing phase?

Let F_α = strong phase.



With this type of loading, both phases experience the same force and thus the same stress. Therefore, $F_\alpha/F_\beta = 1$.

The force ratio is independent of V_α.

Answer: NOT FOR THIS ARRANGEMENT!

Does <u>modulus</u> change as we alter volume fraction of reinforcing phase?

- Point 1:
  - $V_\alpha = 0.5; V_\beta = 0.5$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

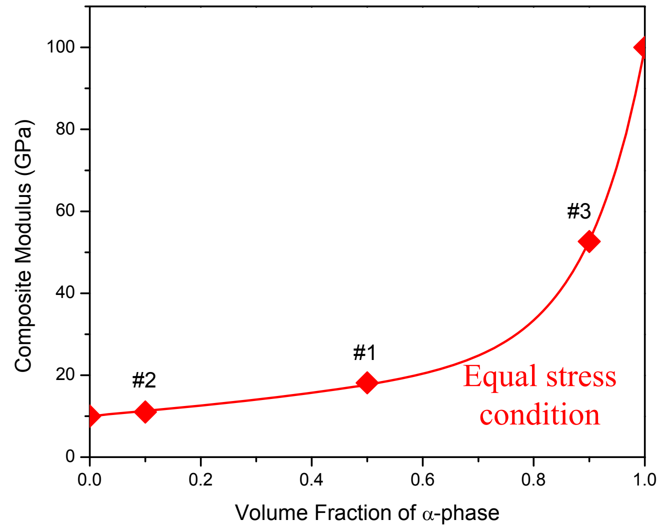
$$E_c = \frac{1000 \text{ GPa}^2}{(0.5 \times 10 \text{ GPa} + 0.5 \times 100 \text{ GPa})} = \frac{1000}{55} \text{ GPa} = 18.1 \text{ GPa}$$

- Point 3:
  - $V_\alpha = 0.9; V_\beta = 0.1$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

$$E_c = \frac{1000 \text{ GPa}^2}{(0.9 \times 10 \text{ GPa} + 0.1 \times 100 \text{ GPa})} = \frac{1000}{19} \text{ GPa} = 52.6 \text{ GPa}$$

- Point 2:
  - $V_\alpha = 0.1; V_\beta = 0.9$
  - $E_\alpha = 100$ GPa; $E_\beta = 10$ GPa

$$E_c = \frac{1000 \text{ GPa}^2}{(0.1 \times 10 \text{ GPa} + 0.9 \times 100 \text{ GPa})} = \frac{1000}{91} \text{ GPa} = 11 \text{ GPa}$$

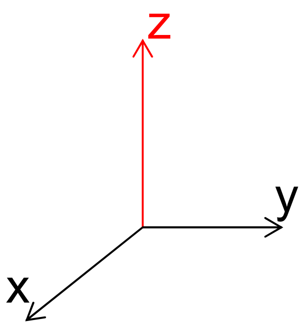


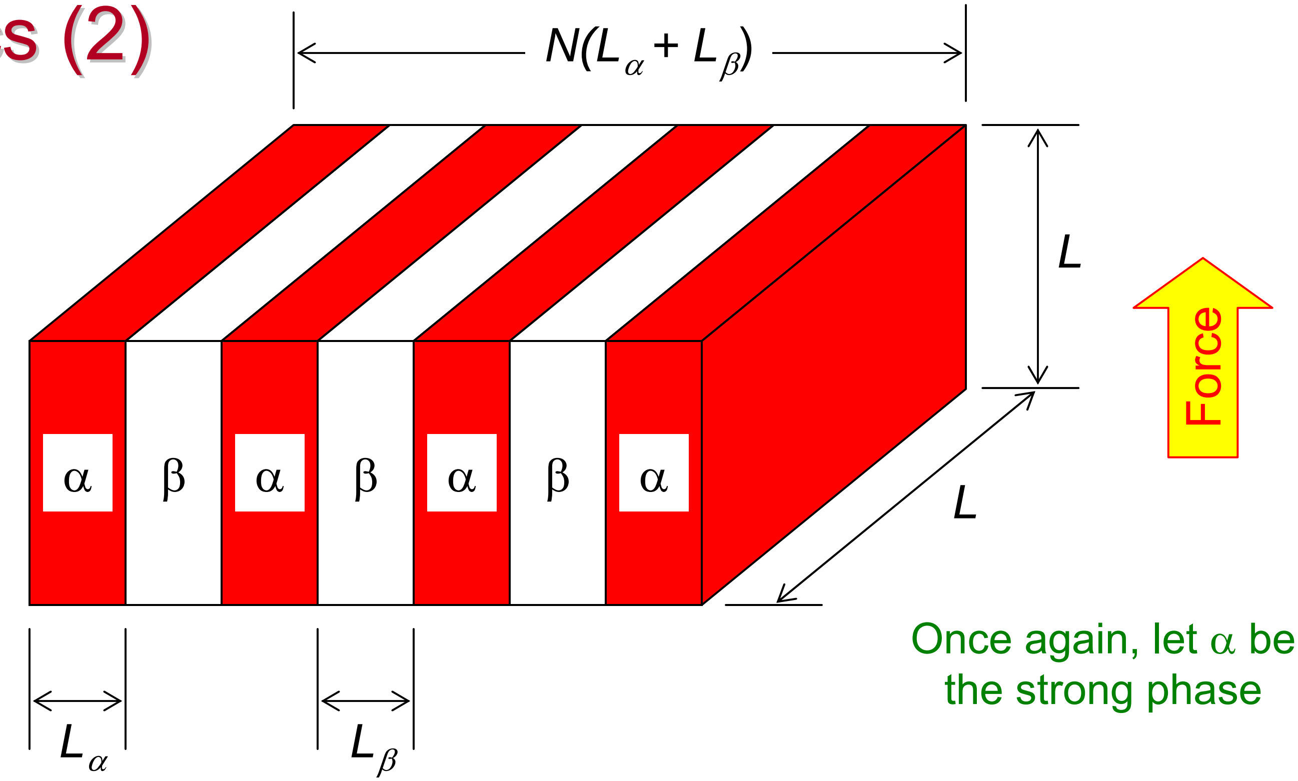
Answer: YES!

Basic mechanics (2)

$$V_\alpha = \frac{L_\alpha}{(L_\alpha + L_\beta)}$$

$$V_\beta = \frac{L_\beta}{(L_\alpha + L_\beta)}$$





- Consider the case where a force is applied along the z-direction. In this instance, the stresses on the α and β lamellae are different.
- The strains on the α and β lamellae are equal.

$$\varepsilon_c = \varepsilon_\alpha = \varepsilon_\beta$$

- The composite modulus is given by:

$$E_c = V_\alpha E_\alpha + V_\beta E_\beta$$

Does <u>modulus</u> change as we alter volume fraction of reinforcing phase?

- Point 1:
  - V_α = 0.5; V_β = 0.5
  - E_α = 100 GPa; E_β = 10 GPa

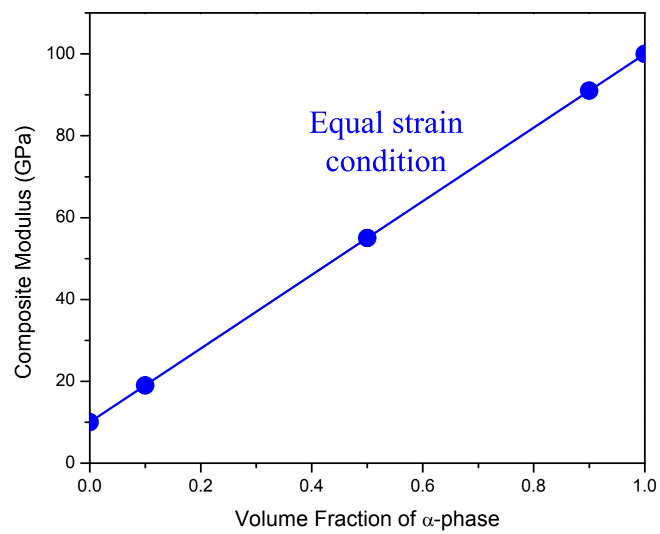
$$E_c = (0.5 \times 100 \text{ GPa} + 0.5 \times 10 \text{ GPa})$$
$$= 55 \text{ GPa}$$

- Point 3:
  - V_α = 0.9; V_β = 0.1
  - E_α = 100 GPa; E_β = 10 GPa

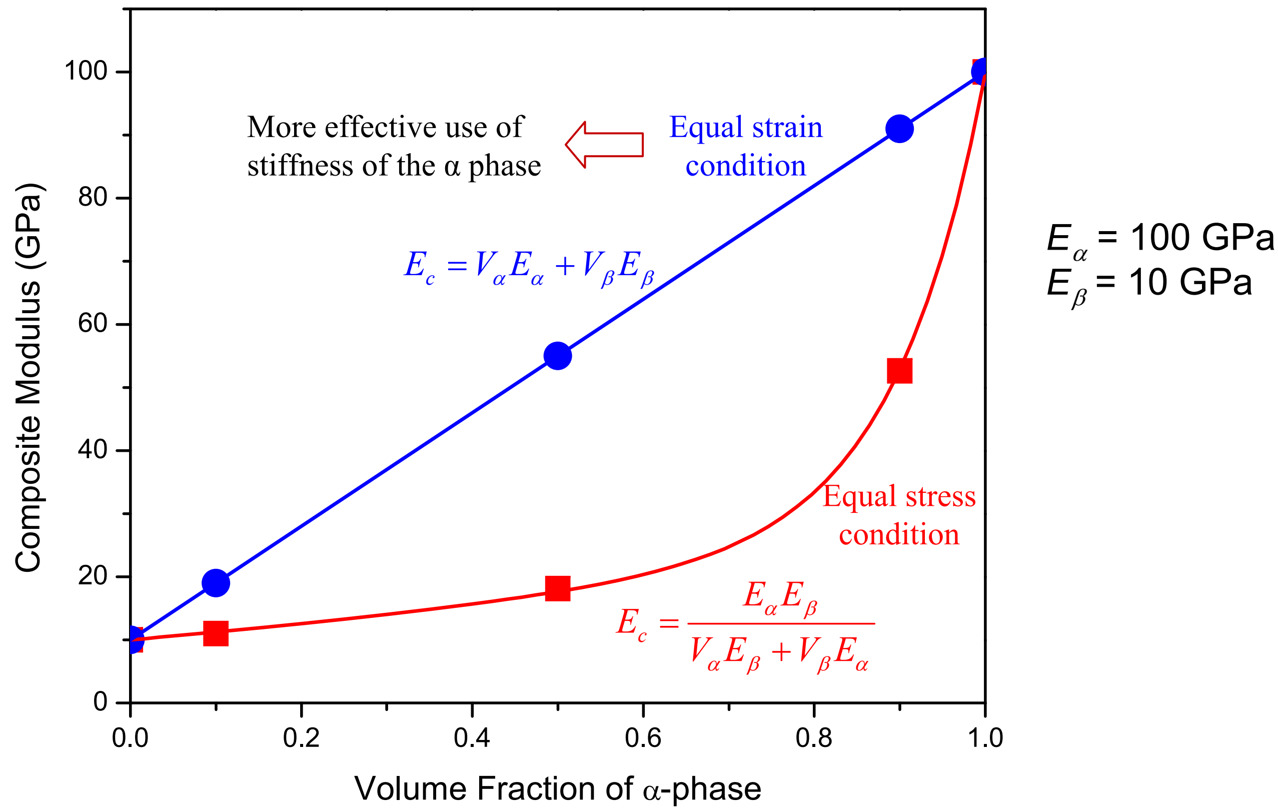
$$E_c = (0.9 \times 100 \text{ GPa} + 0.1 \times 10 \text{ GPa})$$
$$= 91 \text{ GPa}$$

- Point 2:
  - V_α = 0.1; V_β = 0.9
  - E_α = 100 GPa; E_β = 10 GPa

$$E_c = (0.1 \times 100 \text{ GPa} + 0.9 \times 10 \text{ GPa})$$
$$= 19 \text{ GPa}$$



Answer: YES!



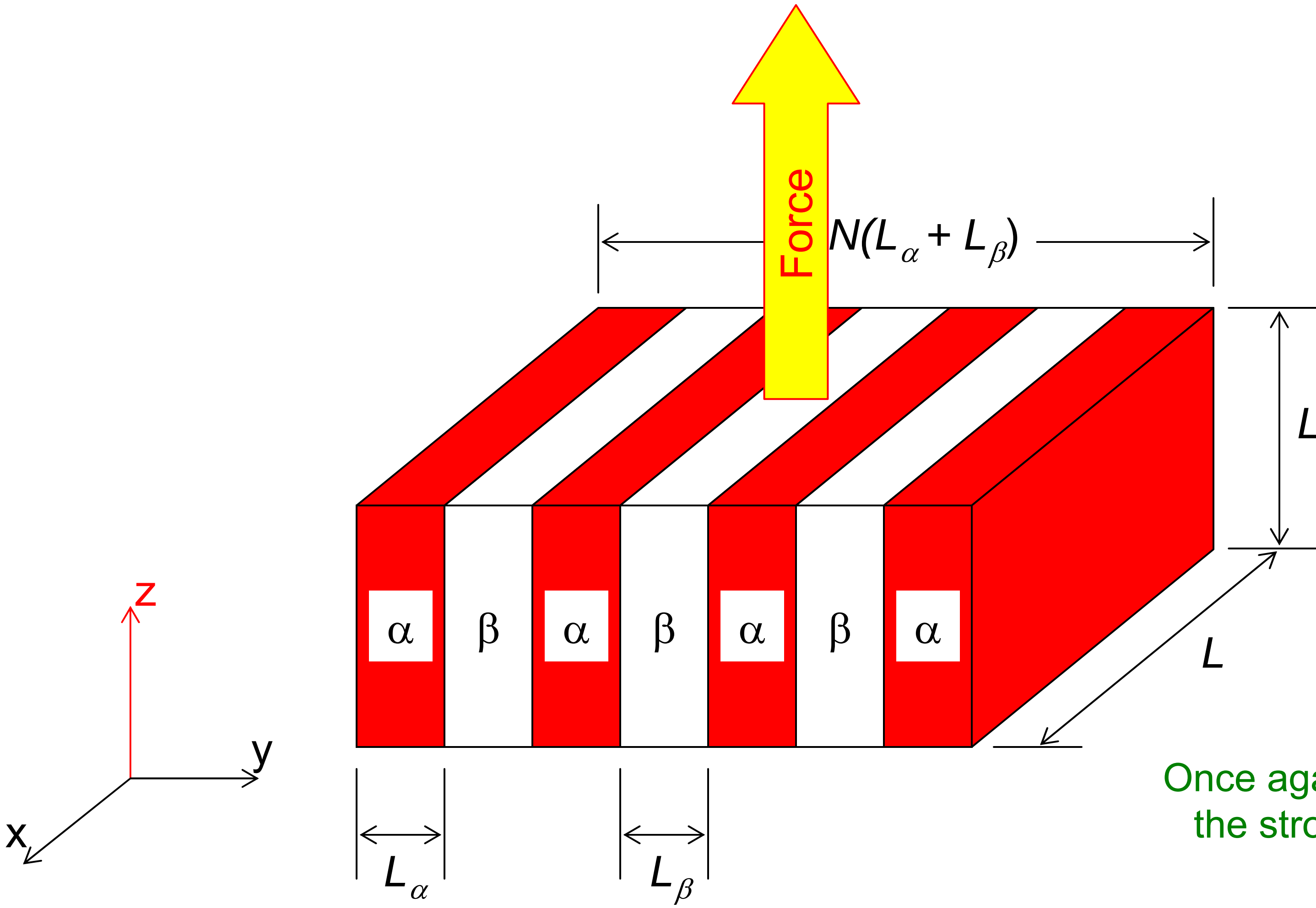
This is a composite plot of the elastic modulus for the composite that we used in the example. The blue curve shows the upper bound for modulus and the red curve shows the lower bound as calculated using the rule of mixtures. The moduli of particle-reinforced materials generally lies between the values predicted for laminate composites, but near the lower bound. In fact, for particle reinforced composites:

$$E_c = V_m E_m + K_c V_p E_p \quad \text{and} \quad \sigma_c = V_m \sigma_m + K_s V_p \sigma_p,$$

where K_c and K_s are empirical constants with values of less than 1

$$(K_c \neq K_s)$$

Basic mechanics (3)

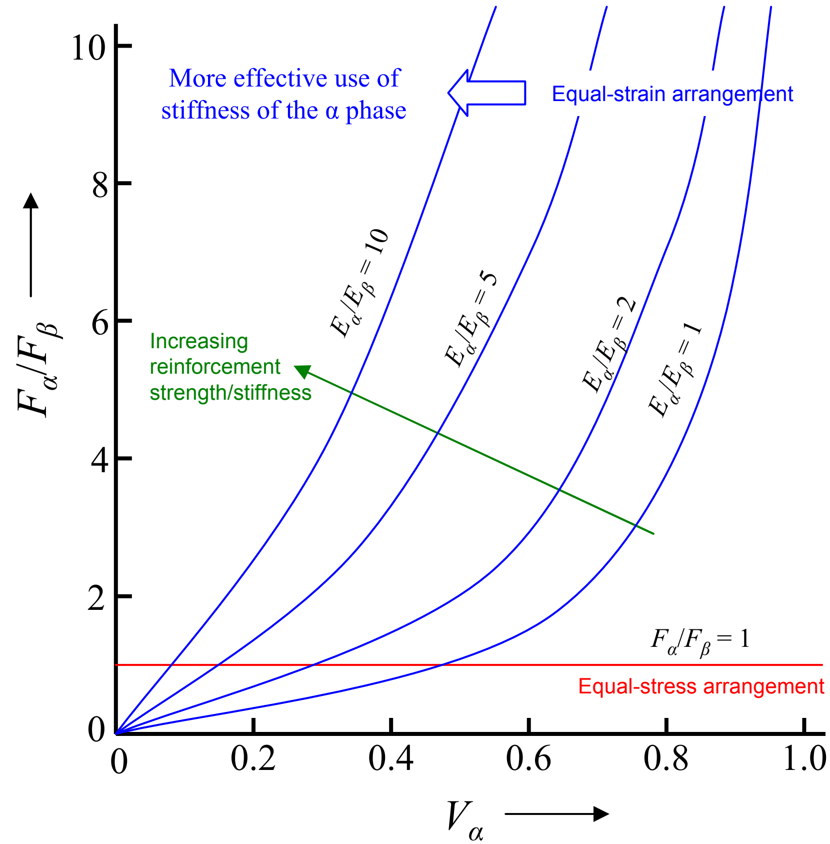


Once again, let α be the strong phase

- The composite stress for this arrangement is given by:

$$\sigma_c = V_\alpha \sigma_\alpha + V_\beta \sigma_\beta$$

Influence of reinforcement arrangement on strength



[after Courtney, p. 251]

- What this plot shows is that the equal-strain condition for reinforcement (i.e., strong phase aligned parallel to applied force) is most useful for reinforcement.
- Under these conditions, the strengthening phase (i.e., the reinforcement) is much more effective at carrying load.
- However, there must be a certain volume fraction of the reinforcing phase present.

Reinforcement with continuous fibers (1)

Material class	Material	E (GN/m^2)	T.S. (GN/m^2)	ρ (Mg/m^3)	E/ρ (MNm/kg)	T.S./ρ (MNm/kg)
Metals	Be	315	1.3	1.8	175	0.72
	Pearlitic steel	210	4.2	7.9	27	0.53
	Stainless steel	203	2.1	7.9	26	0.27
	Mo	343	2.1	10.3	33	0.20
	β-Ti	119	2.3	4.6	26	0.50
	W	350	3.9	19.3	18	0.20
Ceramics	Al_2O_3	380–480	1.4–2.4	3.9–4.0	95–123	0.35–0.62
	Al_2O_3 whiskers	300–1500	2–20	3.3–3.9	77–455	0.51–6.1
	B	386–400	3.1–7.0	2.6	148–154	1.2–2.7
	BN	90	1.4	1.9	47	0.74
	Graphite whiskers	700	20	2.2	318	9.1
	Graphite	390–490	1.5–4.8	1.95–2.2	177–251	0.68–2.5
	E Glass	72–76	3.5	2.55	28–30	1.4
	S Glass	72	6	2.5	29	2.4
	SiC	380–400	2.4–3.9	2.7–3.4	112–148	0.71–1.4
	SiC whiskers	400–700	3–20	3.2	125–219	0.94–6.3
	Si_3N_4	380	5–7	3.2–3.8	100–119	1.3–2.2
Polymer	Kevlar	133	2.8–3.6	1.4–1.5	89–95	1.9–2.6

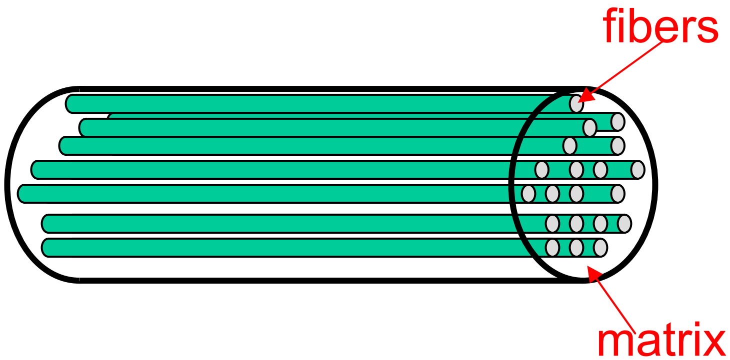
Notes: Variations in properties for a given material result from different processing conditions employed to manufacture them. *Data from*: (1) *Modern Composite Materials*, ed. L. J. Broutman and R. H. Krock, Addison-Wesley, Reading, Mass., 1967, articles of P. T. B. Shaeffer (p. 197), J. A. Roberts (p. 228), F. E. Wawner, Jr., (p. 244). (2) J. D. Embury, in *Strengthening Methods in Crystals*, ed. A. Kelly and R. B. Nicholson, Wiley, New York, 1971, p. 331. (3) *Metal Matrix Composites: Processing and Interfaces*, ed. R. K. Everett and R. J. Arsenault, *Treat. Matls. Sc. and Tech.*, Academic Press, San Diego, 1991, articles by W. C. Harrigan, Jr. (p. 1) and R. B. Bhagat (p. 43). (4) D. Hull, *Introduction to Composite Materials*, Cambridge University Press, Cambridge, England, 1981.

Table 6.1
Properties of Selected Fibers and Whiskers

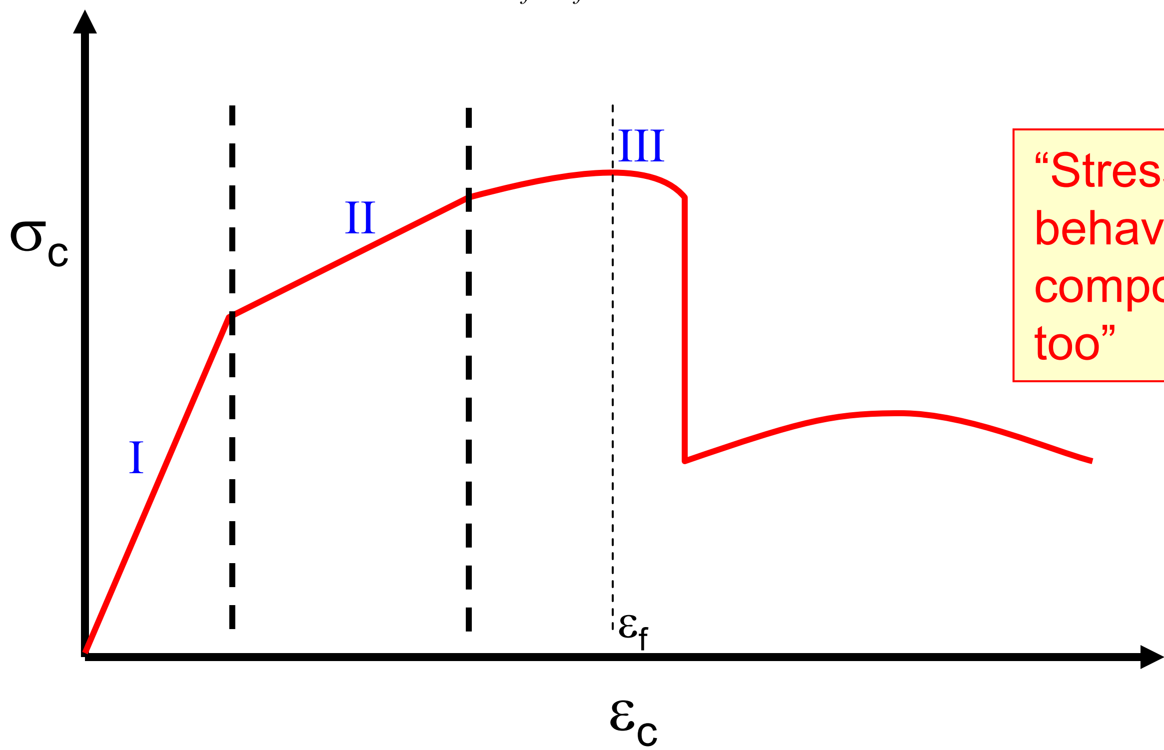
[Courtney]

- Most widely utilized phase geometry.
- WHY? Extraordinary strengths can be obtained in fibrous materials. Some particularly important ones are noted in this table.
- High strength fibers must be protected as their *fracture toughness* is generally low.

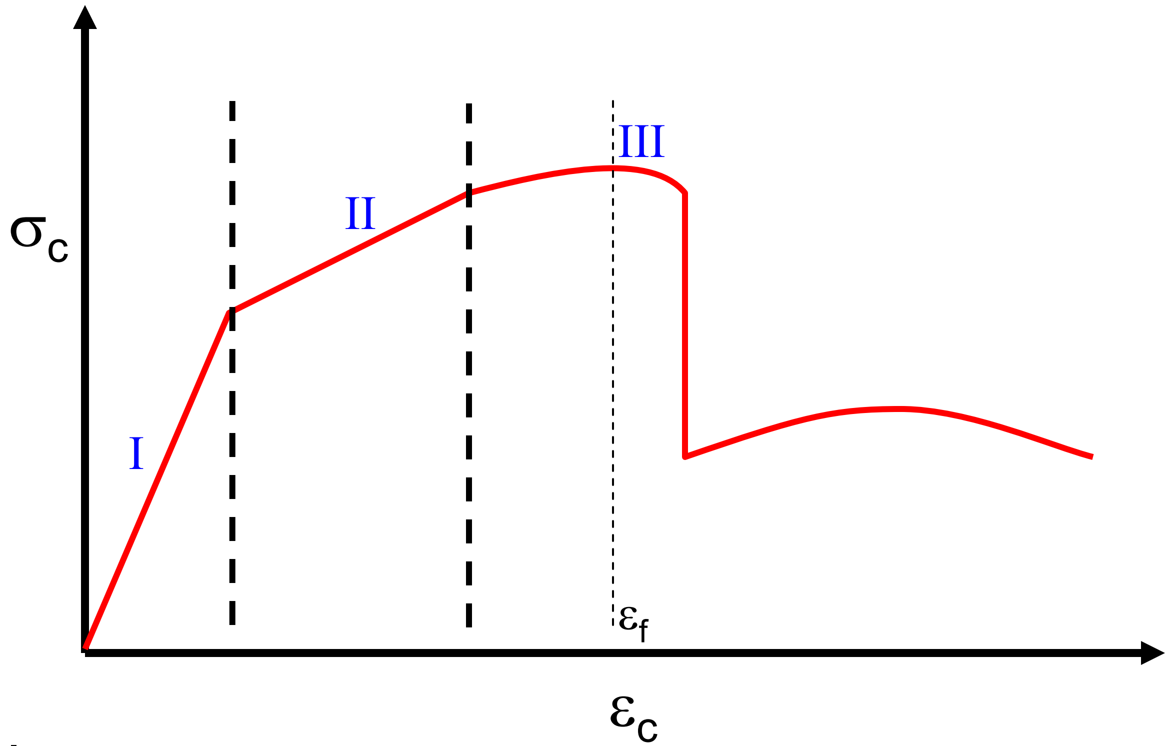
Reinforcement with continuous fibers (2)



$$\sigma_c = V_f \sigma_f + V_m \sigma_m$$



"Stress-strain behavior is a composite too"

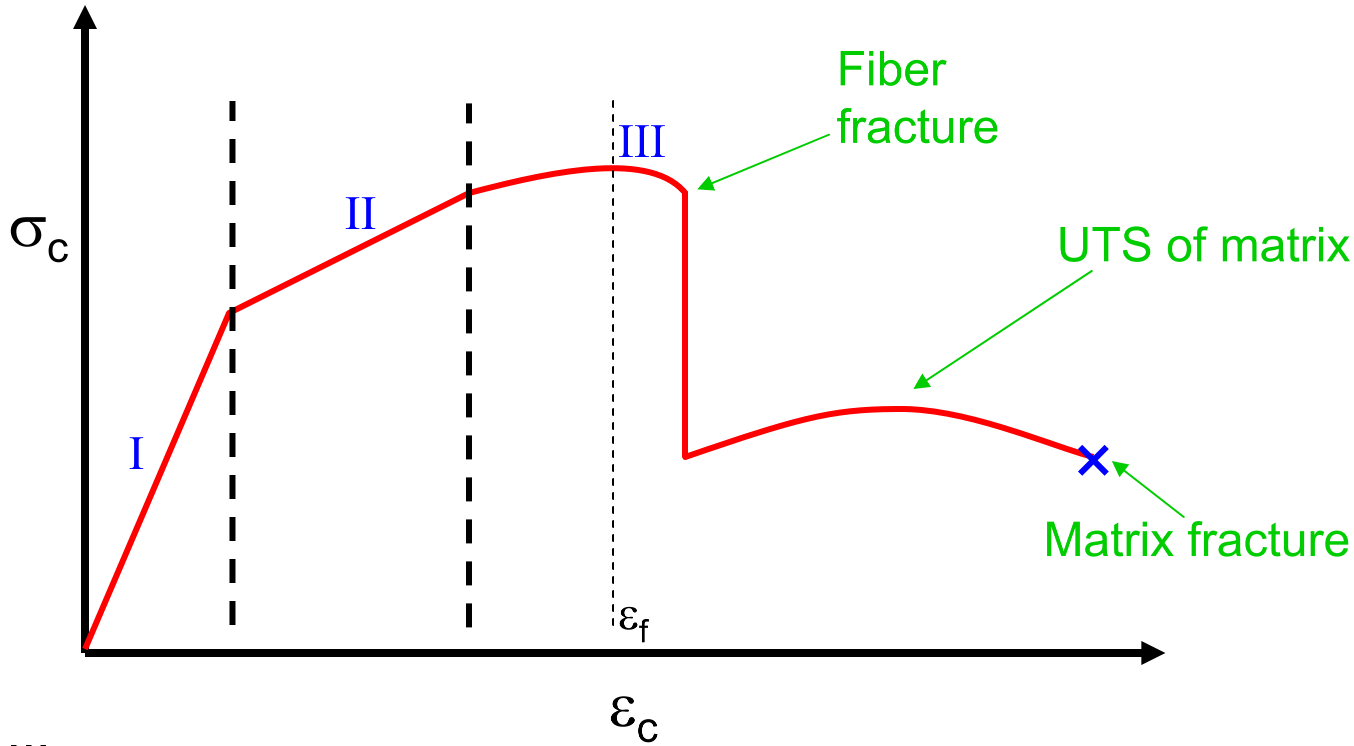


- Stage I
  - Both fiber and matrix deform elastically.

$$\sigma_c = \varepsilon_c E_c = \varepsilon_c \left[V_f E_f + V_m E_m \right]$$

- Stage II
  - Generally, the matrix will begin to deform plastically at a strain that is less than the elastic limit of the fiber.

$$\sigma_c = V_f \varepsilon_c E_f + V_c \underbrace{\sigma_m\left(\varepsilon_f\right)}_{\text{stress carried by matrix at strain } \varepsilon_c}$$

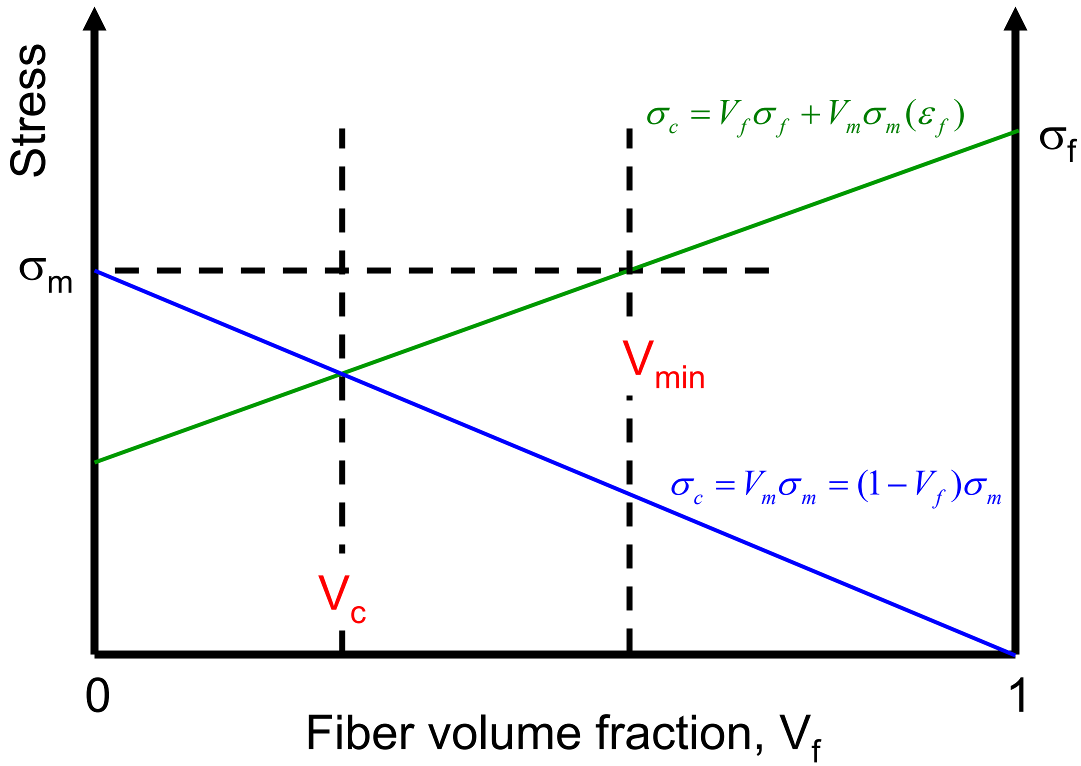


- Stage III
  - This stage only occurs if the fibers deform plastically prior to fracture

$$\sigma_c = V_f \sigma_f \left(\varepsilon_c\right) + V_m \sigma_m \left(\varepsilon_c\right)$$

- ε_f = fiber failure strain
  - Fibers begin to deform locally or fracture.

Critical fiber volume fraction needed to strengthen



- V_c = critical volume fraction of fibers

$$V_c = \frac{\sigma_m - \sigma_m(\varepsilon_f)}{\sigma_f + \sigma_m - \sigma_m(\varepsilon_f)}$$

- V_{min} = minimum fiber volume fraction required to increase strength of matrix

$$V_{min} = \frac{\sigma_m - \sigma_m(\varepsilon_f)}{\sigma_f - \sigma_m(\varepsilon_f)}$$

Typical values for V_c and V_{min} range from 0.02 to 0.10

Discontinuous fibers

- The equal strain volume fraction rule does not apply to composites containing discontinuous fibers.

- In discontinuous fibers, there is a critical fiber length L_c for effective strengthening.

$$L_c = \frac{\sigma_f d}{\tau_m}$$

where σ_f = tensile strength of fiber, τ_m = shear strength of fiber-matrix interface, and d = fiber diameter.

- For glass and carbon composites, $L_c \cong (20 - 150 \times d)$ mm.

- Fibers that are shorter than the critical length have less strengthening per unit volume than continuous fibers.

- WHY?

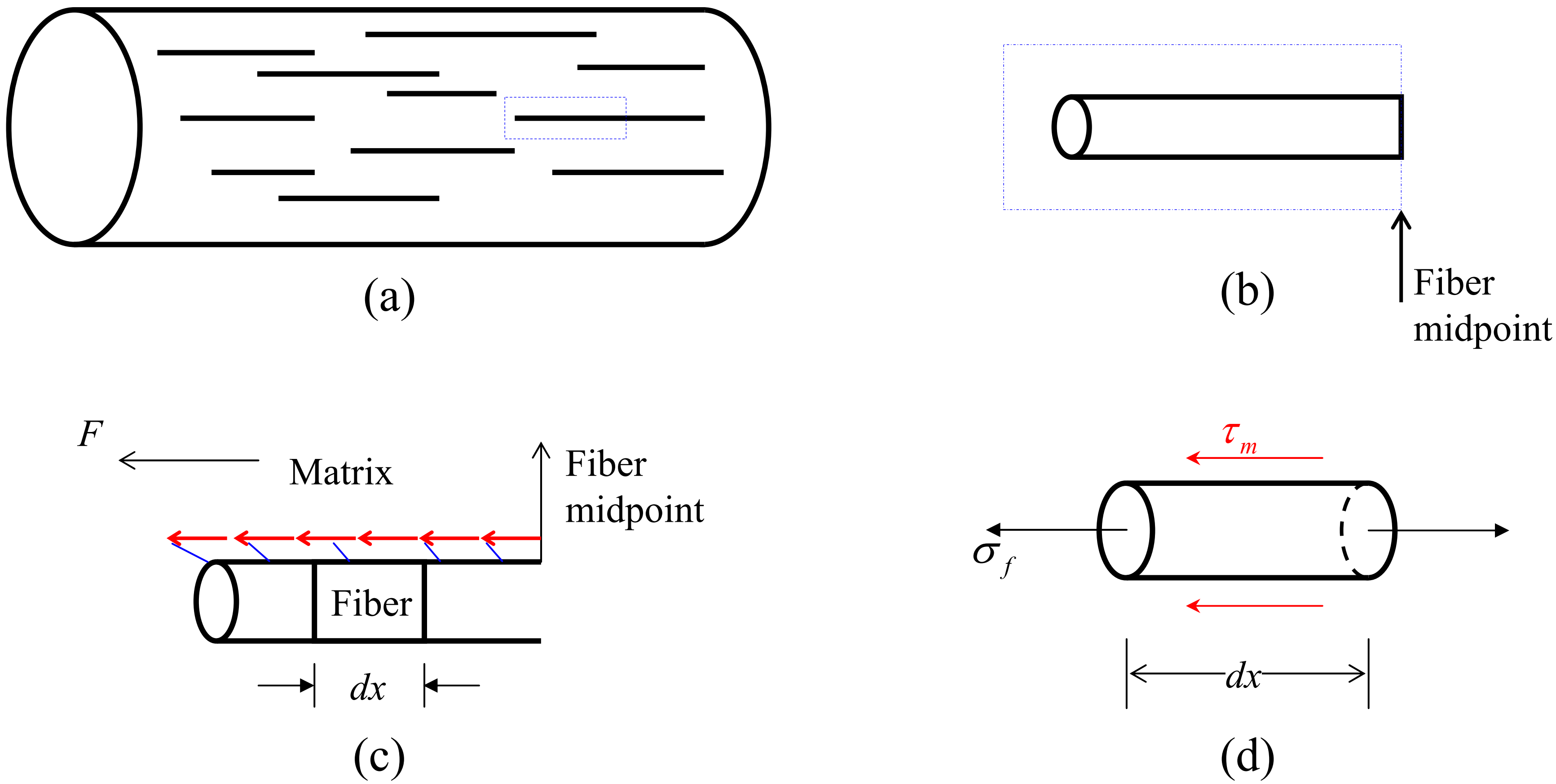
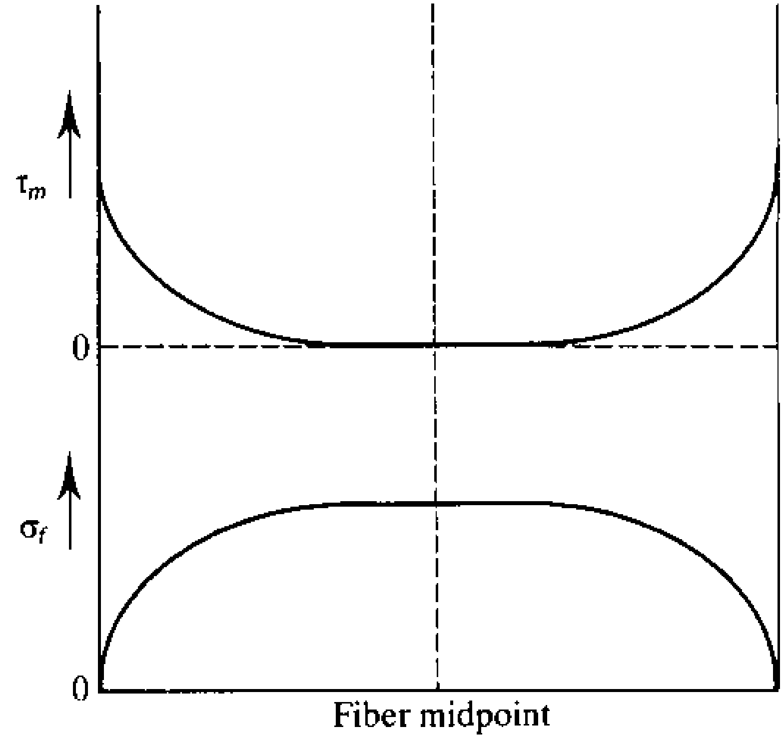


Figure 6.9 (a) A schematic of a matrix containing discontinuous fibers. (b) The geometry of one fiber is shown in the cross-hatched region. At the fiber end, tensile load can't be instantaneously transferred to the fiber from the matrix. (c) The tensile load-transfer process is accomplished by development of a shear stress at the fiber-matrix interface owing to the relative displacement of the fiber and matrix along this interface. The displacement is proportional to the arrows shown, and is zero at the fiber midpoint and a maximum at the fiber end. (d) A small increment of length *dx* of a fiber; the incremental fiber tensile stress ($d\sigma_f$) is obtained by a force balance; i.e., $(\pi d_f^2/4)\ d\sigma_f = \tau_m(\pi d_f^2 dx)$, where τ_m is the interfacial shear stress.

[after Courtney, p. 258]

[after Courtney, p. 259]



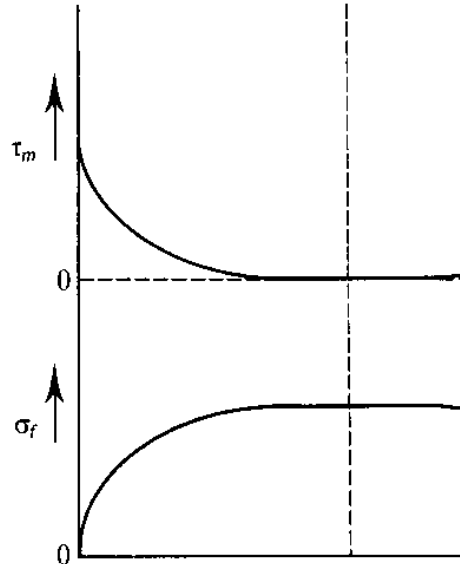
The variation of τ_m and σ_f with position along the fiber when the matrix (and fiber) deform elastically; τ_m is zero at the fiber midpoint and a maximum at the fiber end. The reverse is true for σ_f.

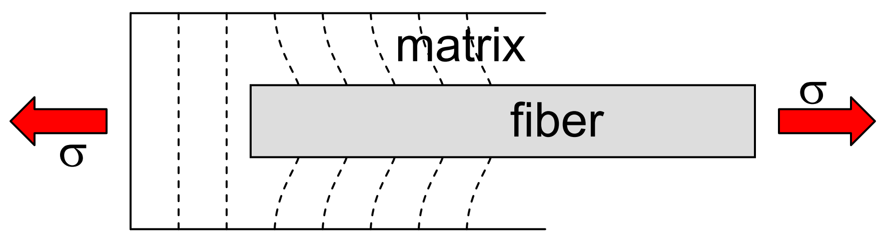
- The shear stress at the midpoint of a fiber is less than that at the ends.

- Fibers do work by transferring load from the “weak” matrix to the “strong/stiff” fiber. This requires a large interfacial area.

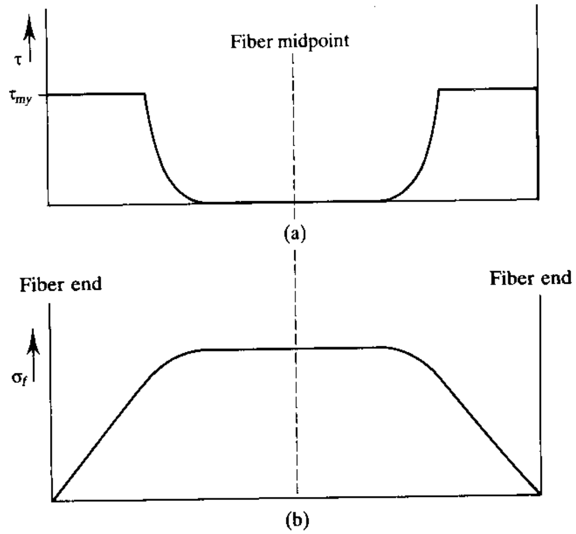
[after Courtney, p. 259]

The variation of τ_m and σ_f with position along the fiber when the matrix (and fiber) deform elastically; τ_m is zero at the fiber midpoint and a maximum at the fiber end. The reverse is true for



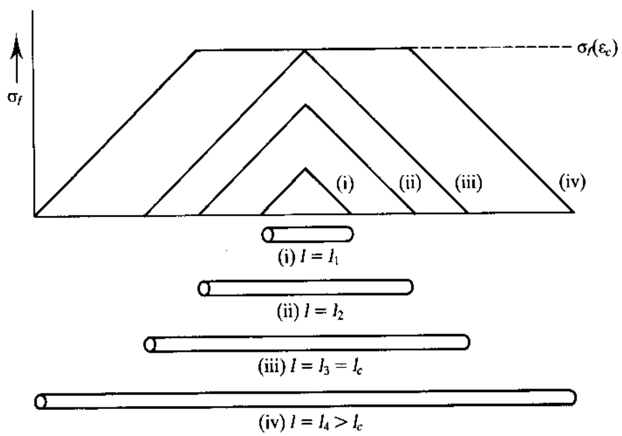


- No load is transferred to the fiber at its ends.
- Load is transferred along the length of the fiber



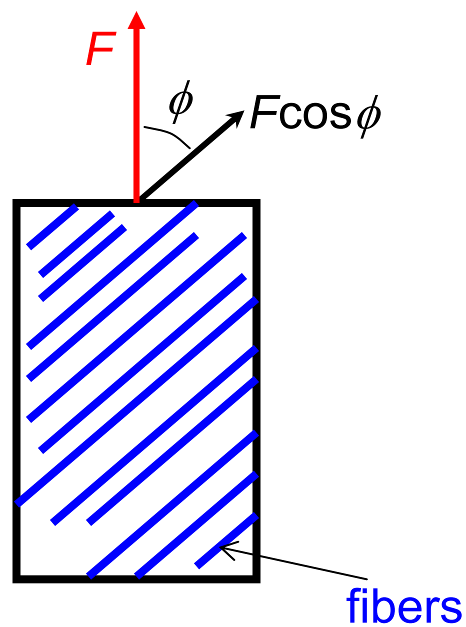
When the matrix flow stress is exceeded, τ_m of Fig. 6.10 attains the constant value τ_{my} (assuming the matrix does not work harden) near the fiber end. Thus (a) and (b) illustrate the variation of τ_m and σ_f for this case. For the most part, τ_m is constant ($= \tau_{my}$) or zero and this means that σ_f increases approximately linearly from the fiber ends and reaches a fixed value at the position where τ_m goes to zero.

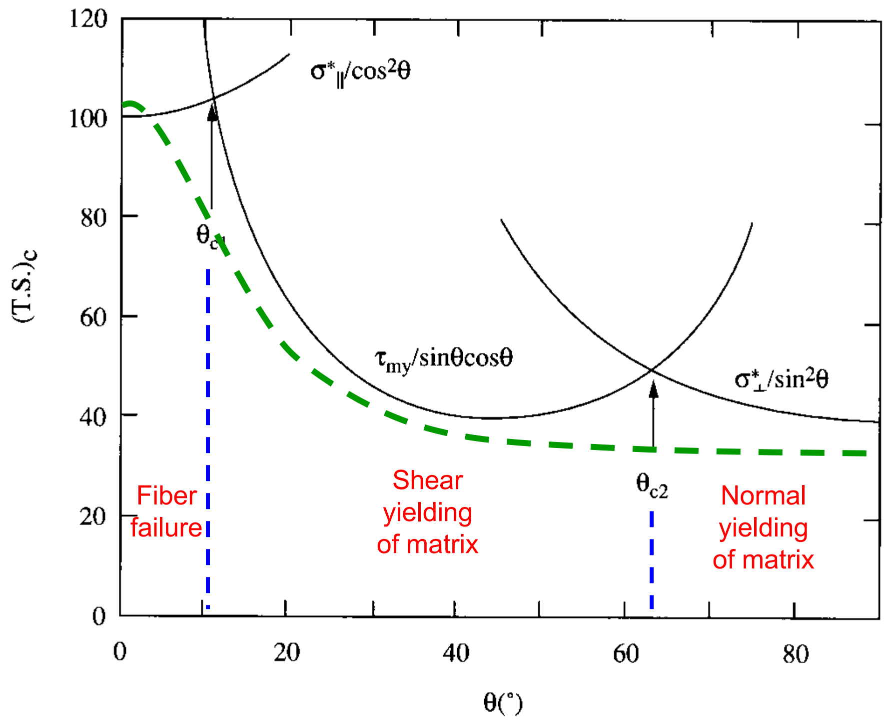
Whether the fiber midpoint carries the same stress it would if it were continuous depends on its length. If the fiber length (e.g., l_1, l_2) is less than a certain critical length l_c, then σ_f does not attain this value. When the fiber length is greater than l_c (e.g., l_4) it does. In this diagram $l_3 = l_c$.



[Courtney]

- Fibers need to be of a certain length to yield maximum strengthening.
- Read the captions for the two figures presented on the left.
- Fiber orientation is also important.





[Courtney]

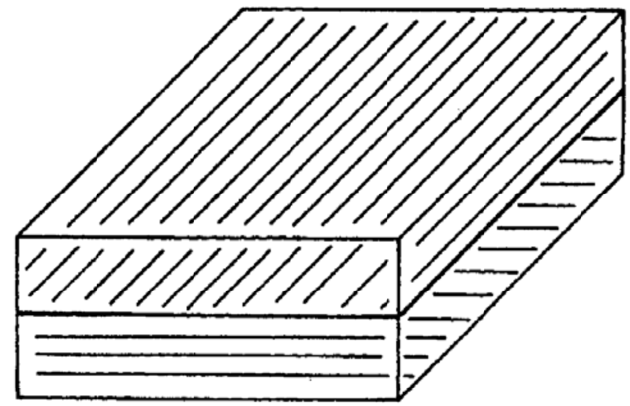
Figure 6.16
The variation of composite tensile strength with misorientation angle (θ) as predicted by Eqs. (6.31)–(6.33). For $\theta < \theta_{c1}$, tensile strength increases with θ and fracture occurs by "longitudinal" fracture. When $\theta > \theta_{c1}$, but is less than θ_{c2}, composite failure occurs by matrix shear (Eq. (6.32)). And when $\theta > \theta_{c2}$, composite fracture takes place by transverse fracture. For most fiber composites, the angle θ_{c1} is typically several degrees. (The graph is constructed for relative values of strength such that $\sigma_{\parallel}^{*} = 100$, $\sigma_{\perp}^{*} = 40$ and $\tau_{my} = 20$.)

Tsai-Hill failure criterion for fiber reinforce composites

$$\sigma_{UTS,c} = \sqrt{\frac{\cos^4\theta}{\left(\sigma_{\parallel}^{*}\right)^2} + \cos^2\theta\sin^2\theta\left(\frac{1}{\left(\tau_{my}\right)^2} - \frac{1}{\left(\sigma_{\parallel}^{*}\right)^2}\right) + \frac{\sin^4\theta}{\left(\sigma_{\perp}^{*}\right)^2}}$$

Cross-Plying

- Cross-plying aligned fibers to produce sandwich structures provides better utilization of composites.
- A 0-90° composite is illustrated to the right.
- Most composites contain more than two plies.



Schematic of a 0-90° cross-ply fiber composite. Such configurations are useful for biaxial loading of composites. Other configurations (e.g. 0-45°, 45-45°, or 0-45-90°) can be similarly employed. [Figure scanned from Courtney, p. 267].

- Other ply arrangements are possible and are used to improve in-plane loading.