



Module #21

Strain Gradient Hardening and Multiphase Aggregates

READING LIST

DIETER: Ch. 6, pp. 185-188; pp. 207-211

Courtney, Pages 164-168, 210-218

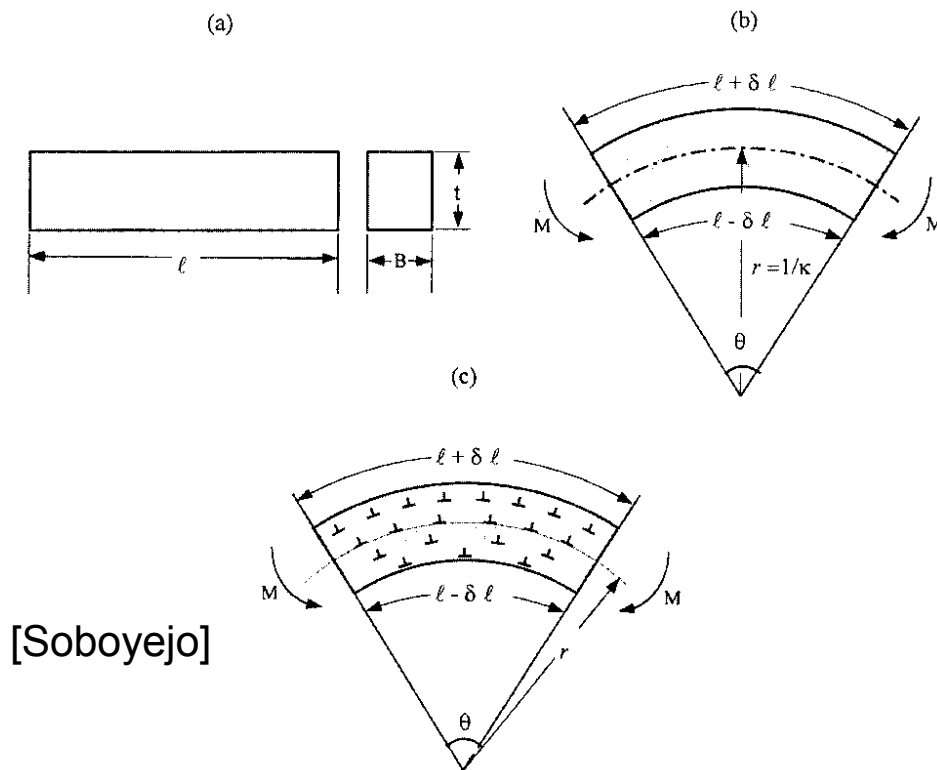


Strain Gradient Hardening (1)

- So far, we've limited our discussions to dislocation motion and the role of dislocation structures formed during deformation and processing. Such dislocations are generally nucleated at *dislocation sources* or are a direct result of *cross-slip* or some other process that we've discussed already.
- Those dislocations are termed *statistically stored dislocations (SSDs)*. SSDs account for the contribution of dislocations to plastic strain in the absence of large stress-gradients.
- When high stress gradients are encountered, another group of dislocations must be considered. They are called *geometrically necessary dislocations* (GNDs).
- Places where GNDs might be encountered include:
 - Grain boundaries
 - Thin films where film thickness \cong grain size
 - Etc...

Strain Gradient Hardening (2)

- GNDs develop in regions of high stress gradients to prevent overlap or void formation during plastic deformation. Consider the following explanation.



[Soboyejo]

FIGURE 7.32 Schematics of plastic bending of a rod to highlight the need for geometrically necessary dislocations: (a) before deformation; (b) curvature after bending; (c) geometrically necessary dislocations. (From Ashby, 1970. Reprinted with permission from Phil. Mag.)

- Consider the bending of a bar. Application of a bending moment results in a curved bar with a radius of curvature r .
- The outer surface of the bar increases in length while the inner surface decreases in length.
- This results in a tensile stress on the outer edge and a compressive stress on the inner edge.
- THUS, there is a stress gradient between the outer and inner surfaces.

Strain Gradient Hardening (3)

- There a strain gradient that is a direct result of the stress gradient. Remember, “strain is the result of stress.” From basic geometry the strain gradient can be expressed as:

$$\nabla \varepsilon = \frac{d\varepsilon}{dt} = \frac{2}{t} \frac{\delta l}{l} = \frac{2}{t} \left(\frac{t\theta}{2l} \right) = \frac{\theta}{l} = \frac{\ell}{r}$$

- NOTE: The original length of the sample is equal to the number of rows of atoms on the original sample $\times b$, the interatomic spacing.
- When the crystal is bent, the number of rows on the outer surface becomes:

$$\frac{(l + \delta l)}{b}$$

Strain Gradient Hardening (4)

- The difference in the total number of planes on the outer and inner surface can be accommodated by the introduction of an array of GNDs. In Fig. 7.32c this was illustrated as an array of edge dislocations of the same sign.
- The dislocations are GNDs. The GNDs maintain compatibility in the lattice in the presence of stress gradients.

- The density of GNDs is:

$$\rho_{GND} = \frac{2\Delta l}{b(lt)} = \frac{1}{rb} = \frac{\nabla \varepsilon}{b}$$

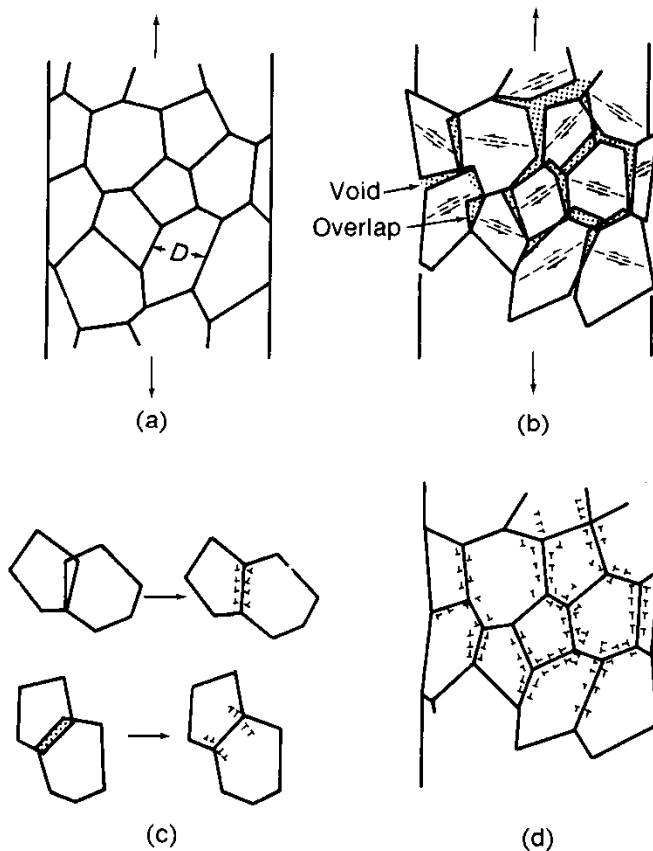
- The total density of dislocations is:

$$\rho_{\perp, total} = \rho_{SSD} + \rho_{GND}$$

- The implications of this increase in dislocation density are that materials will work harden more in the presence of a strain gradient.

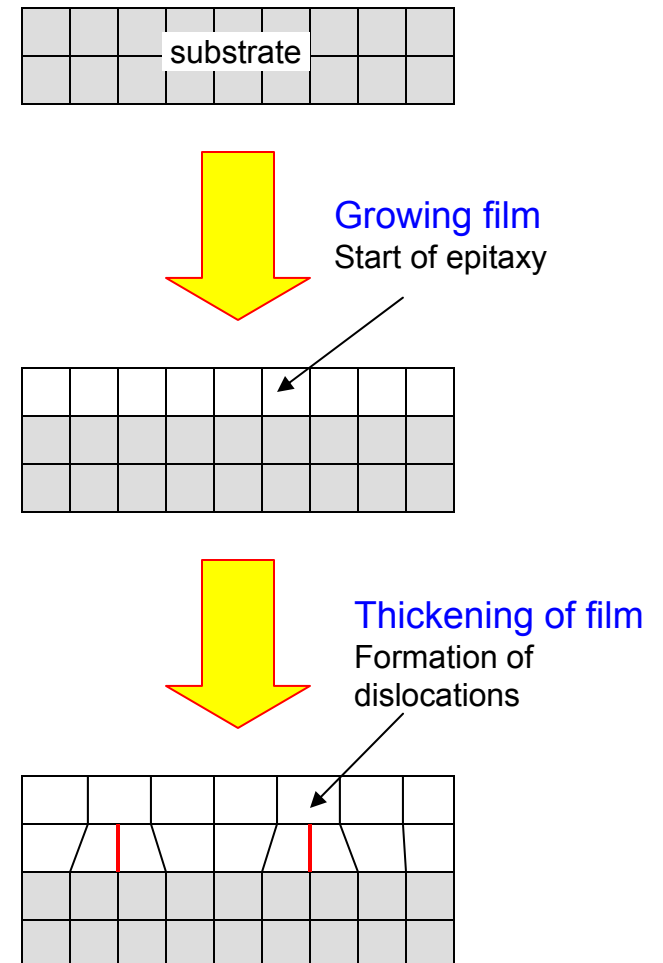
Strain Gradient Hardening (5)

- Some examples of where we might see GNDs are provided in the illustrations below.



[Dieter]

Figure 6-2 Ashby's model of deformation of a polycrystal (a). Polycrystal deforms in macroscopic uniform way, produces overlap, and voids at boundaries (b). These can be corrected by introducing geometrically necessary dislocations at (c) and (d). Note that statistical dislocations are not shown. (From M. F. Ashby, *Phil. Mag.*, vol. 21, p. 413, 1970.)



Strain Gradient Hardening (6)

- In cases where the density of geometrically necessary dislocations is high, the flow stress can be determined using a modified Taylor expression:

$$\tau = \tau_o + \alpha Gb \sqrt{\rho_{SSD} + \rho_{GND}}$$

- Strain gradient plasticity theories have been used in an attempt to explain the indentation size effect as observed during hardness testing. The theories are quite controversial. They are, however, quite elegant and may have some relevance in describing the behavior of crystalline solids.
- Strain gradient plasticity is likely to be very important in micro-electro-mechanical systems (MEMS), which are machines manufactured in the micro-scale regime.
- We will address this topic in greater detail when we discuss micro/nano-laminates and thin films.

Strain-gradient Hardening

- When materials are deformed such that plastic strain gradients are present, they work harden more than if such gradients are not present.
- Strength increases because geometrical dislocations accommodate the strain gradient. They interfere with dislocation flow much like “statistical” dislocations.
- However, strain gradients must exist over distances on the order of μm 's or less if values of ρ_G are high enough to significantly increase flow stress.
- A bent bar would have to be very thin to be stronger than a bar tested in tension.

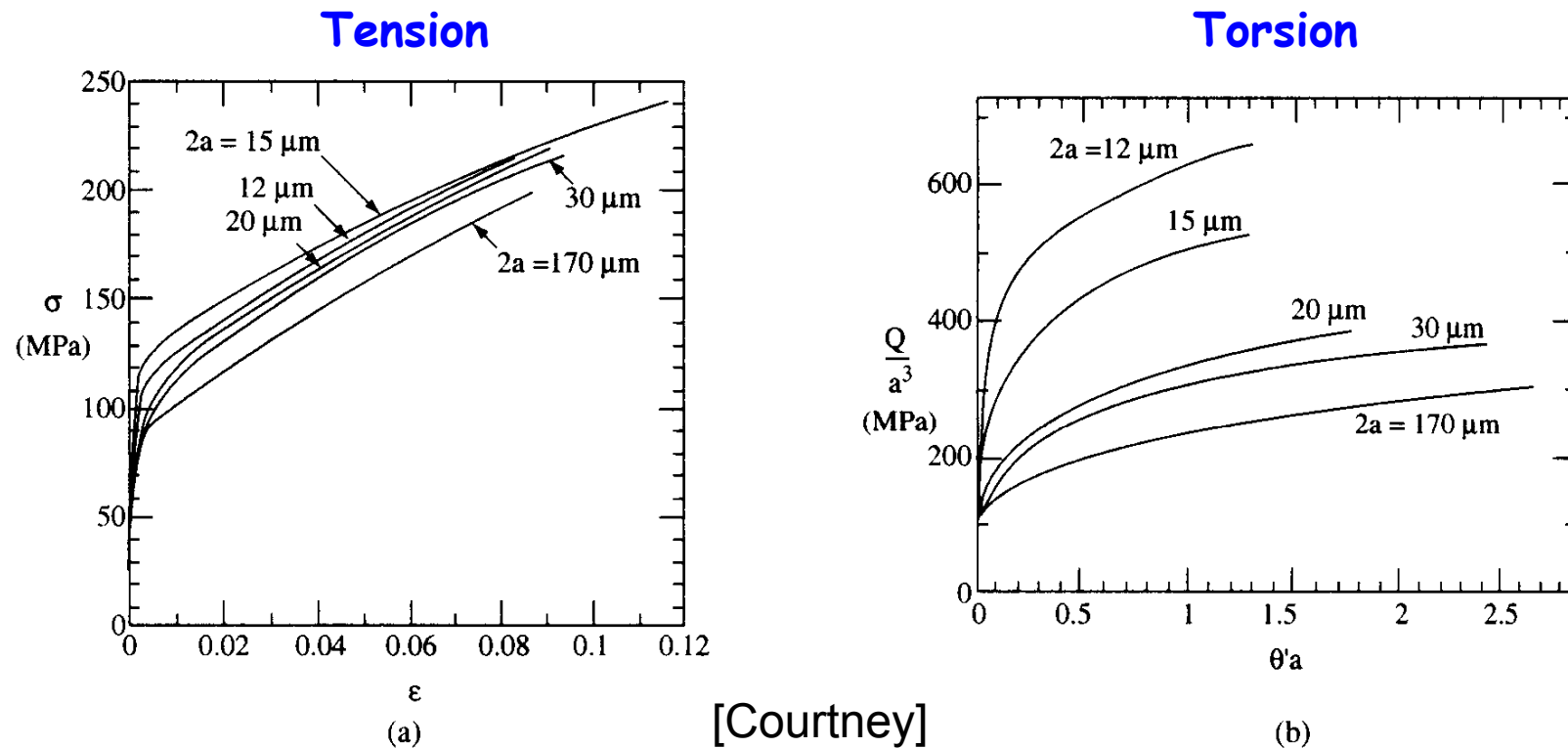
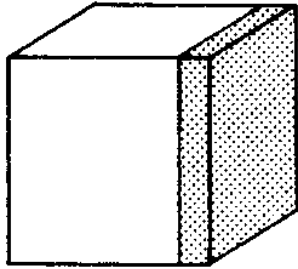


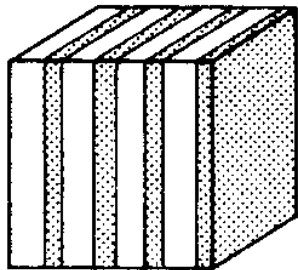
Figure 5.28

(a) Tensile true stress-true strain curves for fine copper wires (diameter ($2a$) in the range of 12–170 μm). There is a negligible effect of wire diameter on tensile behavior (except for the wire having the largest diameter; this wire likely has a coarser grain size than the others). (b) Torsional response of these same wires. The “normalized” torque (defined as the twisting moment (Q) divided by a^3) is plotted vs. normalized twist (twist per unit length (θ' (Eq. (1.37) multiplied by a)). In distinction to tensile behavior, torsional behavior depends greatly on wire diameter. The finer wires manifest significantly greater flow stresses. This is a result of the greater dislocation densities in the wires tested in torsion. (*Reprinted from N. A. Fleck, G. M. Muller, M. F. Ashby and J. W. Hutchinson, “Strain Gradient Plasticity: Theory and Experiment,” 475, copyright 1994, with permission from Elsevier Science.*) *Acta Metall. et Mater.*, 42.

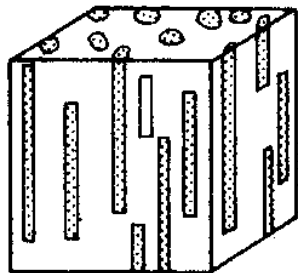
Multi-phase aggregates



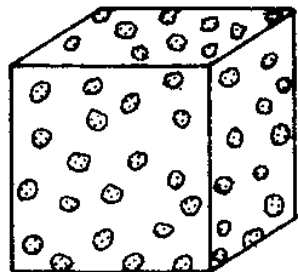
Coating



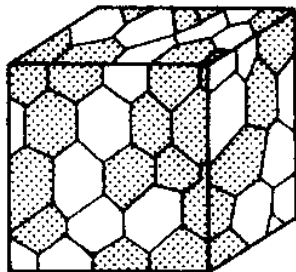
Lamellae



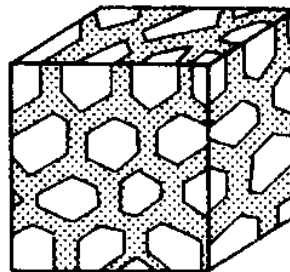
Fibers



Dispersion



Duplex



Skeleton

Sometimes, materials have complex multiphase microstructures

What distinguishes them?

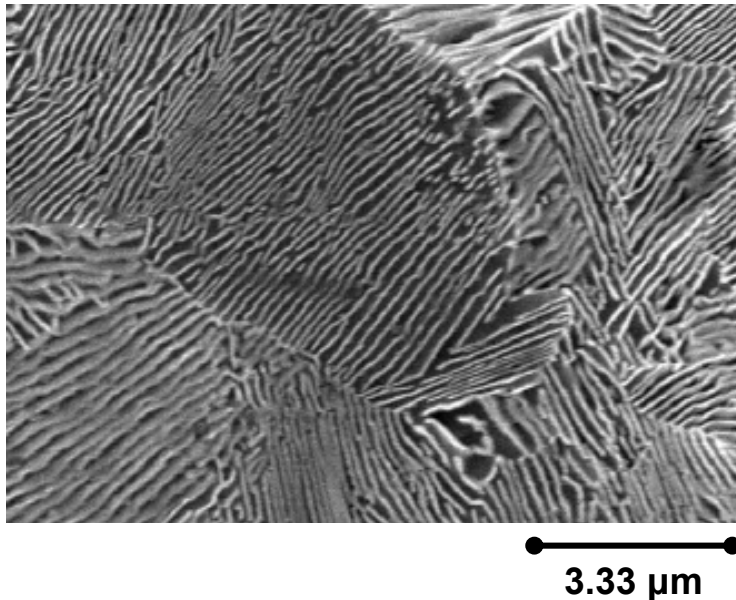
How do they deform?

How does this compare to single phase materials?

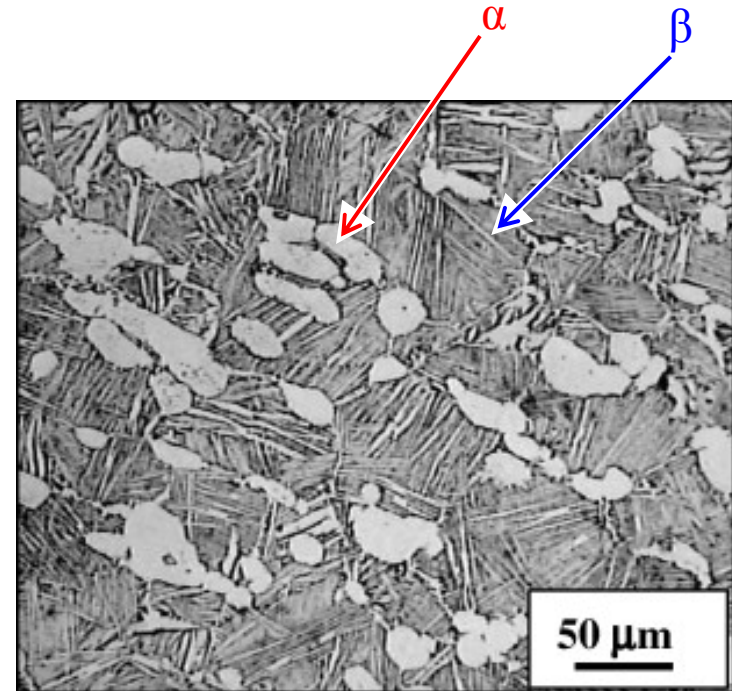
Is strain gradient plasticity a factor?

[Adapted from E. Hornbogen, "Overview No. 37: On the microstructure of alloys," *Acta Metallurgica* **32** (1984) P. 615-628]

Some typical examples



Pearlite in 1075 carbon steel. Figure from Taleff et al., *JOM*, v. 54 (2002) p. 25-30



Bimodal microstructure in IMI-834, a titanium alloy. Figure from Kumar et al., *Materials and Design*, v. 30 (2009) p. 1118-1123.

Can you think of others?

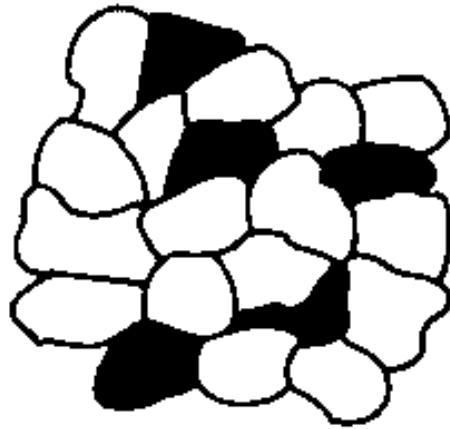
Deformation of multi-phase aggregates

- Similar to precipitation hardening, however, in aggregates the volume fractions of the constituent phases are comparable.
- With precipitation, volume fractions were on the order of a few percent.

Deformation of multi-phase aggregates

- Microstructural length scales are also larger than in precipitation.
 - Aggregates can be heterogeneous on a microscopic scale
 - Aggregates can be homogeneous on a macroscopic scale.
- When the reinforcing phase is formed via “equilibrium” processes such as solidification, the strengthening is generally additive to solid solution strengthening and work hardening.

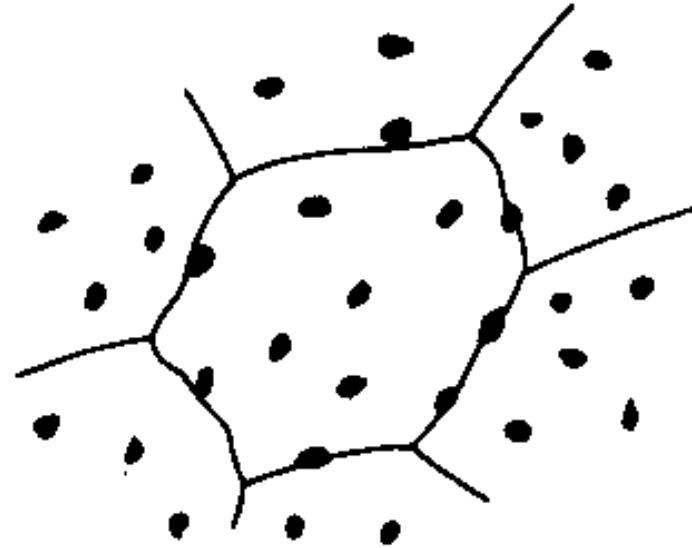
Types of 2-phase microstructure



(a)

Aggregated structure

- Second phase is of the order of the grain size of the matrix.



(b)

[Figure 6-14 from Dieter]

Dispersed structure

- Second phase is completely surrounded by matrix of a single orientation. Second phase is “large”.

Deformation of two-phase aggregates

- Second phase particles dispersed in a continuous matrix results in localized internal stresses which modify plastic deformation of the continuous phase. This will be related to:
 - Size, shape, number and distribution of second phase particles.
 - Strength, ductility and strain-hardening behavior of matrix and second phase.
 - Lattice matching between phases.
 - Interface between phases.
- When individual phase contributions are independent, then the properties are a weighted average of those of the individual phases.

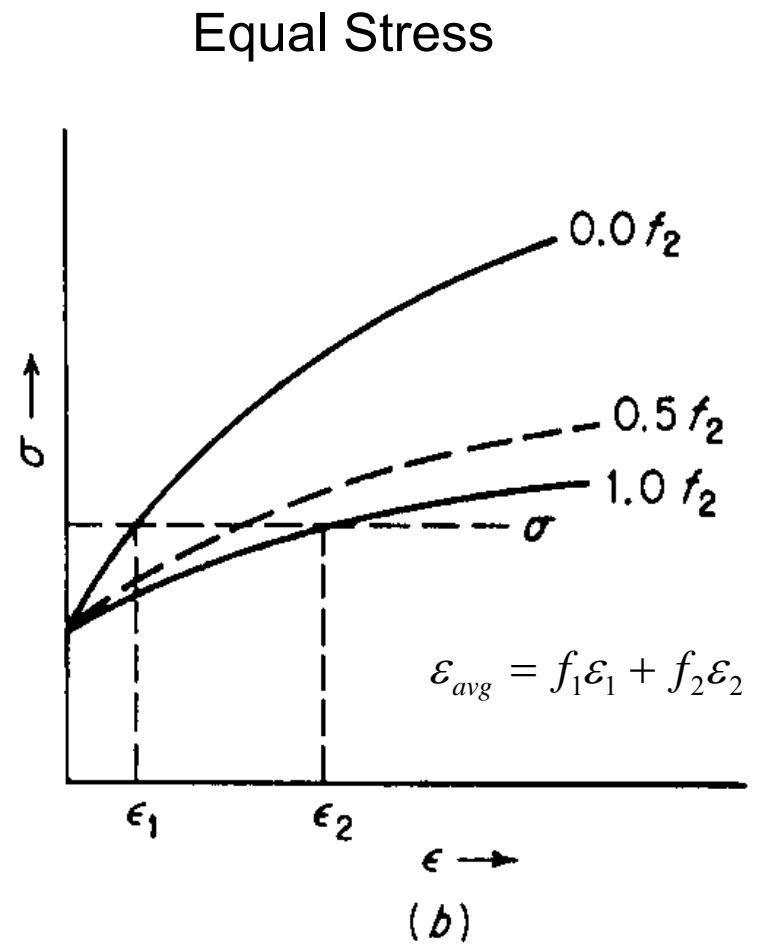
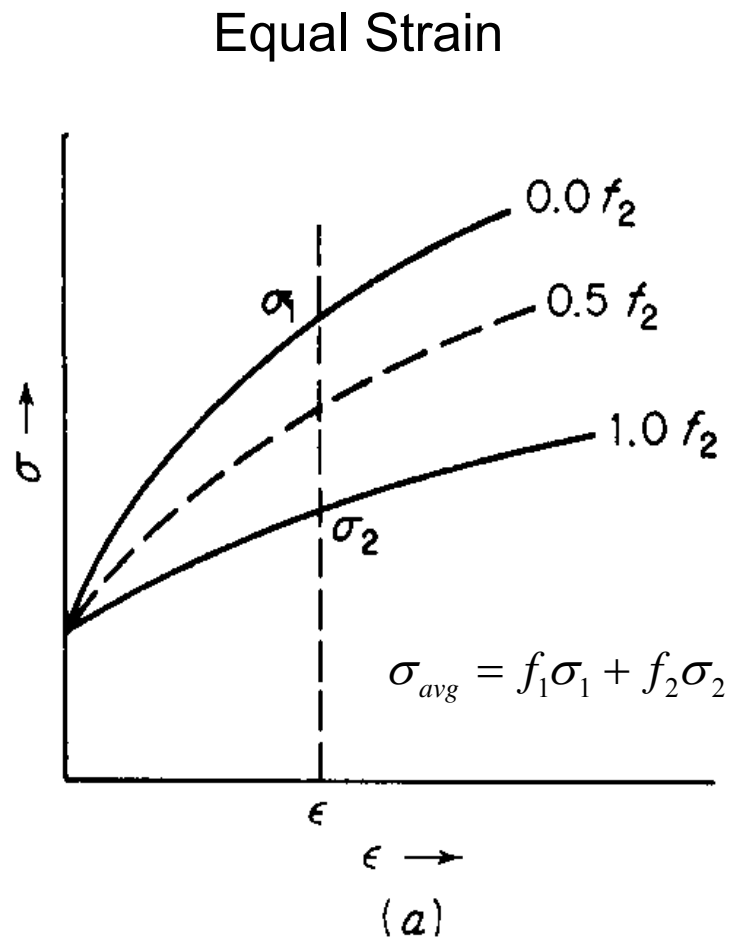
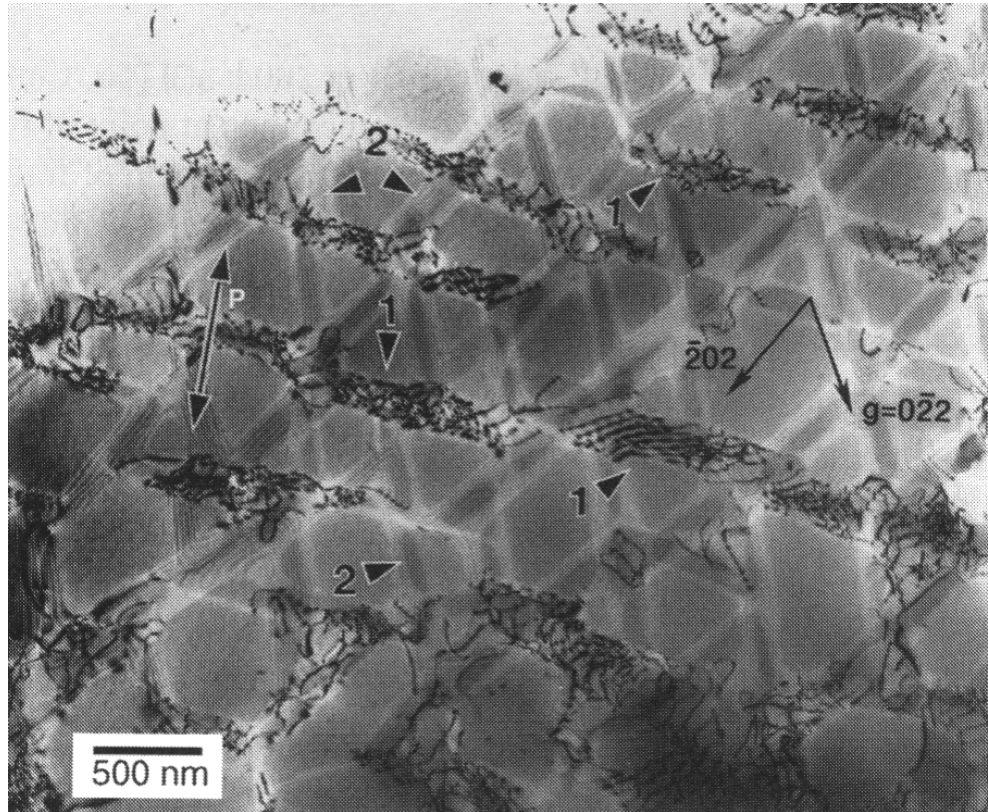


Figure 6-15 Estimate of flow stress of two-phase alloy. (a) Equal strain; (b) equal stress. [Copied from Dieter, p. 209].

Deformation of two-phase aggregates – cont'd

(Ductile + Ductile Phases)

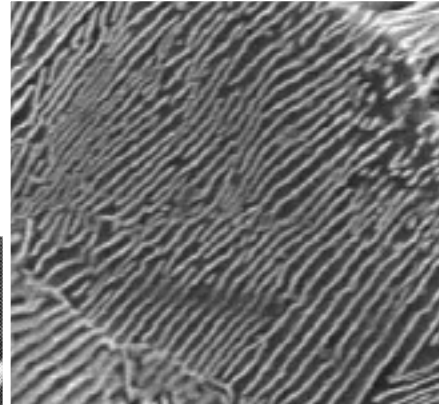
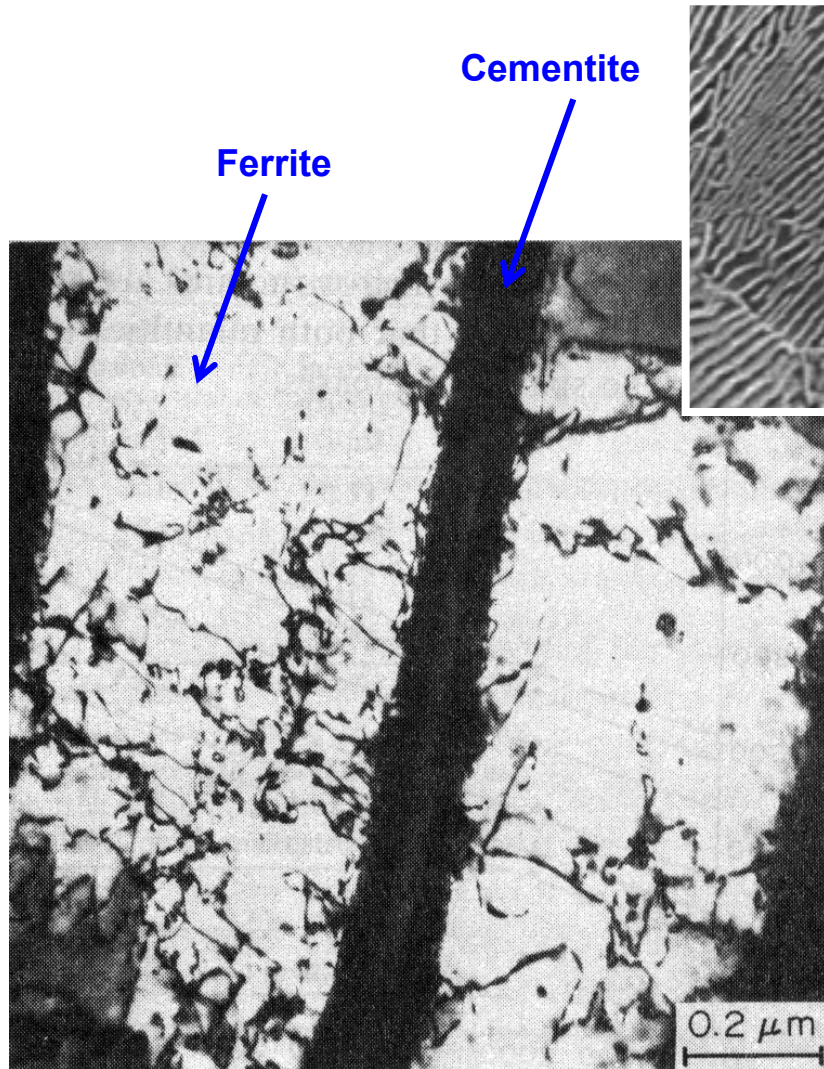
- Deformation mode depends upon the volume fractions of both and the total deformation.
- There must be a strong particle-matrix bond for strengthening to occur.
- Slip occurs first in the weaker phase. Most deformation will be localized there.
- Ni-base superalloys and pearlite demonstrate this behavior quite nicely.



Ni-Base Superalloy

Ni-base superalloys consist of two phases, gamma (γ) and gamma prime (γ'). The volume fraction of second phase can be as high as 70%. Gamma prime is stronger. At high volumes of γ' , dislocations are constrained to the γ channels between precipitates.

The scanned figure shows the dislocation microstructure in a Ni-base superalloy deformed at 950°C demonstrating flow localization into gamma channels between the gamma prime phase particles. This figure was adapted from R. Reed, The Superalloys: Fundamentals and Applications, (Cambridge University Press, Cambridge, 2008) p.188.



PEARLITE

In pearlite, deformation is initially localized in the ferrite phase.

The scanned figure shows the dislocations in pearlite deformed 0.71% in tension. This figure was adapted from M. Dollar, I.M. Bernstein and A.W. Thompson, *Acta Metallurgica*, v. 36 (1988) pp. 311-320.

Deformation of two-phase aggregates – cont'd

- When the volume fraction of the harder phase exceeds 30 vol.%, the soft phase is no longer continuous. Then the two phases deform with equal strains.
- Above 70 vol.% of the harder phase, deformation is controlled by the properties of the harder phase.

Deformation of two-phase aggregates – cont'd

(Ductile + Brittle Phases)

- Deformation depends on distribution of brittle phase.
 - Segregated in form of GB envelope (i.e., “skeleton” structure), alloy is brittle. Hypereutectoid steels are a good example.
 - In form of discontinuous particles at grain boundaries, brittleness is reduced.
 - In form of a fine uniformly distributed dispersion in a soft matrix, optimal strength and ductility is obtained.
 - Tempered martensite is an example.
 - Pearlite is also a very good example of this principle at work.