Strengthening from second phase

Many commercial alloys are composed of two or more metallurgical phases which provide strengthening effects:

- **Two phase aggregates**
- **Second phase/intermetallic particles**
- **Precipitation hardening**
- **Fibering structure**

Note: 1-These are heterogeneous on a microscopic scale or may be homogeneous on a macroscopic scale.

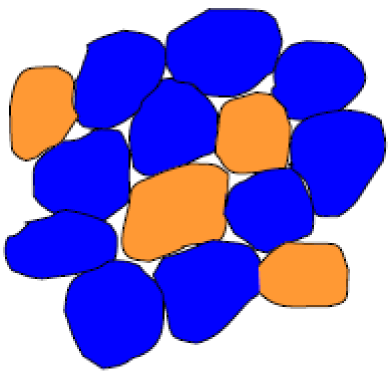
2- Strengthening from second phases is normally additive to the solid solution strengthening produced in the matrix.

Strengthening by two-phase aggregates

The size of the second phase particles are of similar size to that of the matrix.

Examples;

- **Beta brass particles in an alpha brass matrix**
- **Pearlite colonies in the ferrite matrix in annealed steels.**



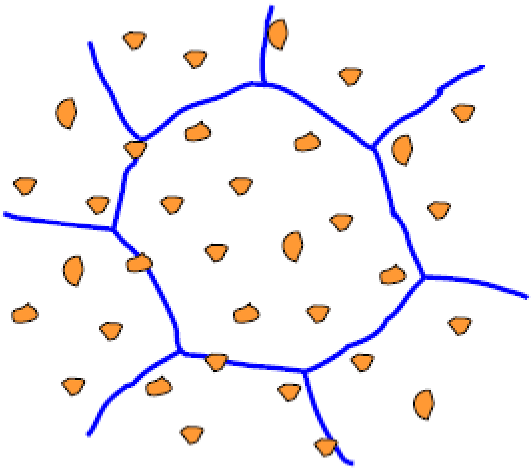
Two-phase aggregates

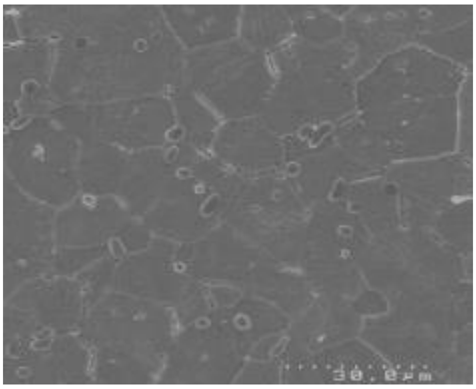
Strengthening by second phase particles

• **The second phase or intermetallic particles are much finer (down to submicroscopic dimensions) than the grain size of the matrix.**

• **The second phase particles produce localised internal stresses which**

alter the plastic properties of the matrix.





Dispersed second-phase particles in the matrix

Factors influencing second-phase particle Strengthening

1-<u>Particle size</u>

2-<u>Particle shape</u>

3-<u>Number (V_f)</u>

4-Distribution

5-<u>Interparticle spacing</u>

If the contributions of each phase are independent, the properties of the multiple phase alloy is the summation of a weighted average of individual phases.

Stress: $\sigma_{avg} = V_1\sigma_1 + V_2\sigma_2 + ...V_n\sigma_n$

Strain: $$\varepsilon_{avg} = V_1\varepsilon_1 + V_2\varepsilon_2 + \dots V_n\varepsilon_n$$

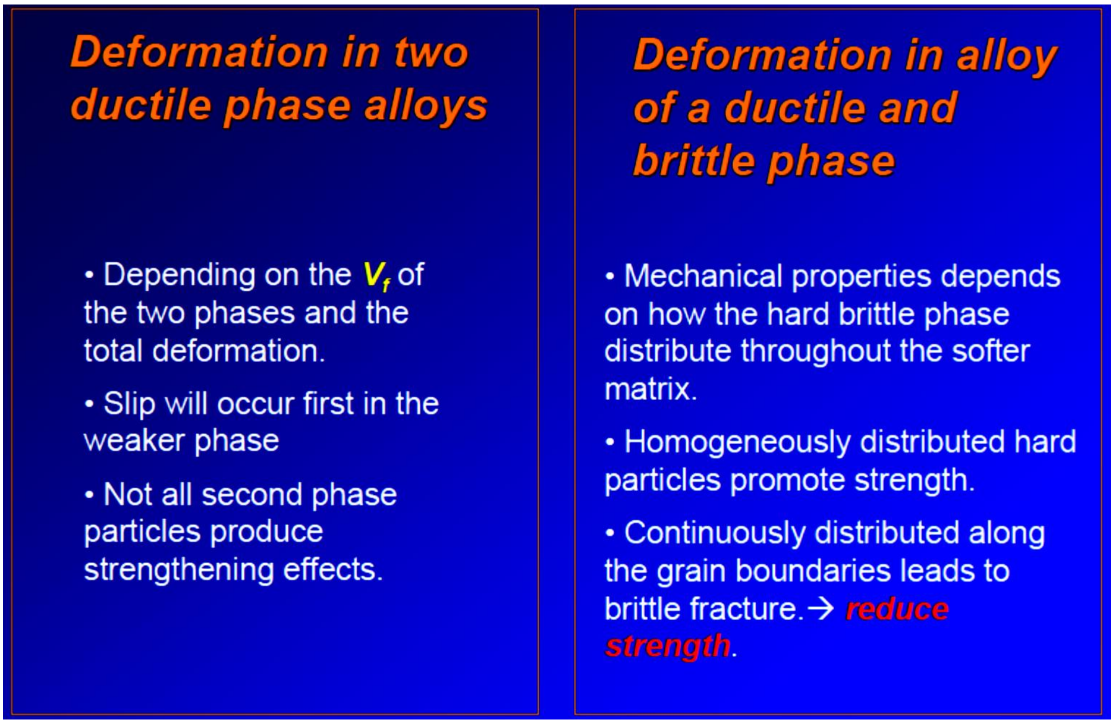
Where the volume fraction V

$$V1 + V2 + - - - - - - - - Vn = 1$$

• The average property in the two-phase alloy will increase with the volume fraction Vf of the strong phase.

• It is more often that the second phase is stronger than the matrix but not all second-phase particles produce strengthening effects.

• The strong bonding between particles and matrix is required to be able to produce strengthening effects.



1- Precipitation hardening (Age hardening)

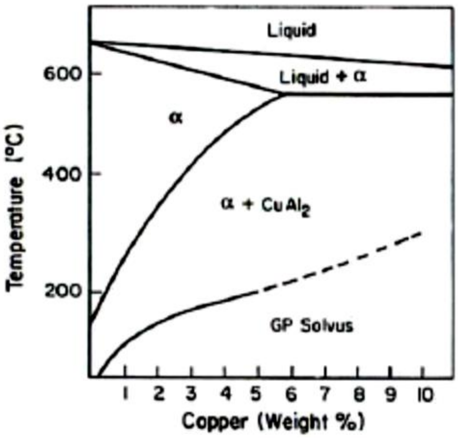
Precipitation hardening or age hardening requires the second phase which is soluble at high temperature but has a limited solubility at lower temperatures.

1-Solution treating at high temperature, then quenching

(Second phase is in solid solution)

2-Ageing at low temperature Precipitation of the second phase, (giving strengthening effect)

Example: Age hardening aluminium alloys Copper-beryllium alloys



Note: In precipitate-hardened system, there is coherency between the second-phase particle and the matrix. But in dispersion-hardened system, there is no coherency.

The formation of coherency precipitate

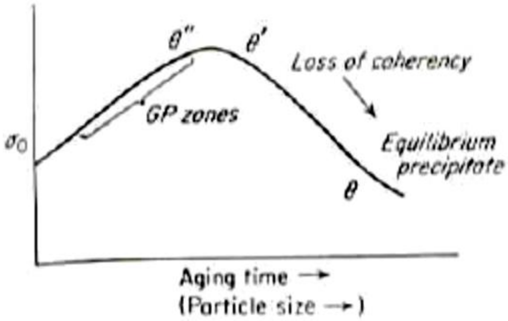
A number of steps occurs during precipitation hardening.

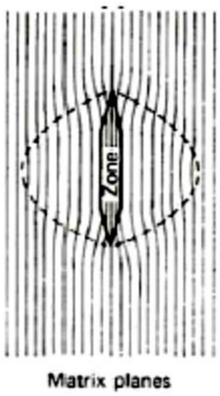
• After quenching from solid solution the alloy contains areas of solute segregation or clustering.→ GP zone.

This clustering is GP[1] produces local strain giving higher hardness than the matrix.
• The hardness of the GP zone increases with ageing time, developing GP[2] or θ ''.

• Precipitate θ ' is coherent with the matrix. →further increase in hardness.

• Further ageing produces θ, (not coherent with the matrix). → lowering the hardness.



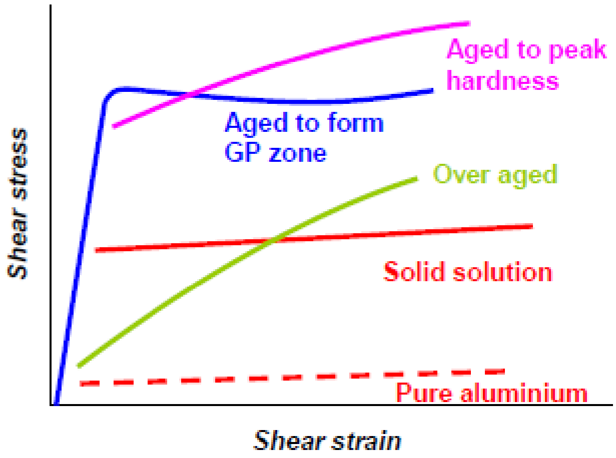


Deformation of alloys with fine particle strengthening

(Case study in deformation of Al-4.5%Cu single crystal)

After solution treated and quenched, copper is in supersaturated solid solution, giving higher yield stress than pure aluminium.

• The yield stress increases when the crystal is aged to form **coherent GP zone**. Yield drop and low strain hardening suggest that dislocations cut through the zone once the stress reaches a high enough value.



Strain hardening significantly increase when the crystal is aged to peak hardness. Dislocations are short and move around particles.

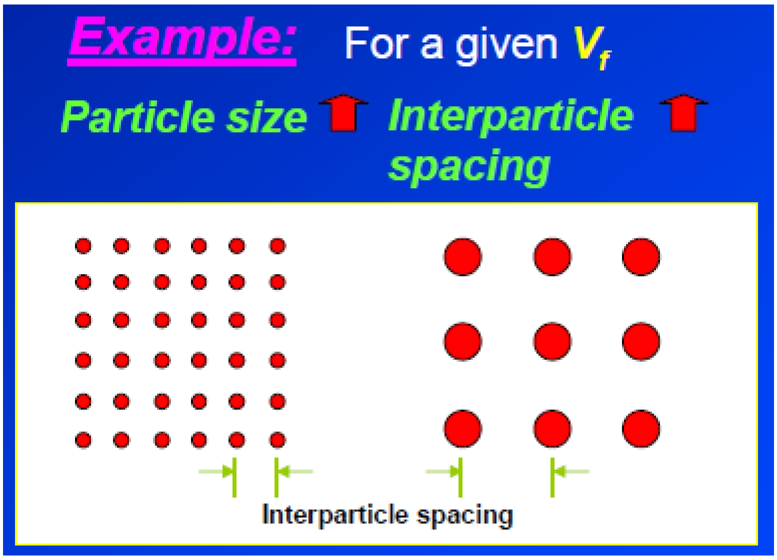
• **Over-aged** condition produces coarse non coherent particles, giving low yield stress, high strain hardening.

Factors affecting precipitation hardening

Particle size, shape, volume fraction and distribution are key factors in improving precipitation hardening (cannot vary independently).

• High strength alloys seem to consist of fine strong particles well distributed in deformed matrix.

• Fine hard particles increase strength by cutting dislocations → dislocation tangles → increasing strain hardening.



Interparticle spacing λ

$$\lambda = \frac{4(1-V_f)r}{3V_f}$$

Where V_f is the volume fraction of spherical particles of radius r.

• Deformed matrix bares the load which makes fracture more difficult.

2- Properties affecting strengthening mechanisms by particles

Coherency strain

• Misfit between particles and matrix produces strain field → improving strength.

Modulus effect

• Modulus difference between the matrix and the particles produces strength but it is not the case in most alloys.

Stacking-fault energy

• Yield stress increases with the difference in stacking fault energy between the particle and the matrix.

Interfacial energy and morphology

• High particle-matrix surface energy leads to higher strength. (rely on surface-to-volume ratio or morphology)

Ordered structure

• introduce anti-phase boundaries.

• good high temperature strength.

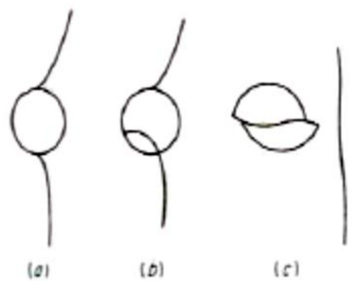
Lattice friction stress

• Peierls stress in particle and matrix produce strengthening effect.

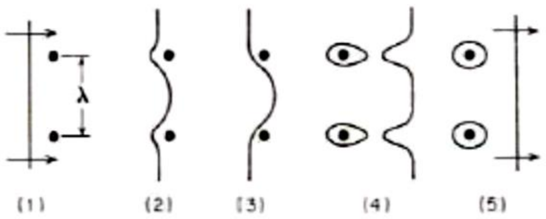
Interaction between fine particles and dislocations

Second phase
particles act in two distinct ways to retard the motion of dislocations.

1-**Particles maybe cut by dislocation**



2- **Particles allow dislocation to bypass/bow around them.**



[Orawan’s mechanism of dispersion hardening.]

• In over aged noncoherent precipitates. Bowing of dislocations around particles leaving dislocation loops behind.

(**Stress required to force** dislocation between particles; of dispersion hardening.)

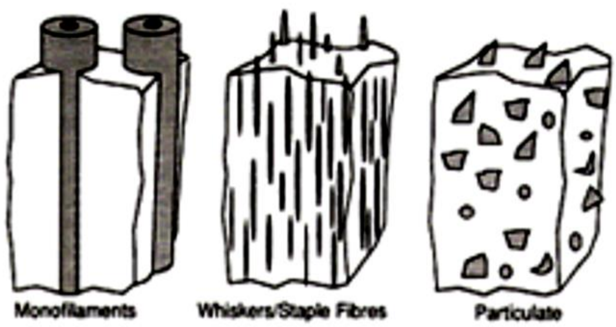
$$\tau_o = \frac{Gb}{\lambda}$$

3- Fiber strengthening

Ductile metals can be reinforced using relatively **stronger** fibers.

• Very high strength whiskers of Al_2O_3, or SiC fibers have been used for this purpose.

• Fiber-reinforced materials (metal or polymer as matrix) are also known as **composite materials.**



The matrix transmits the load to the fibers.

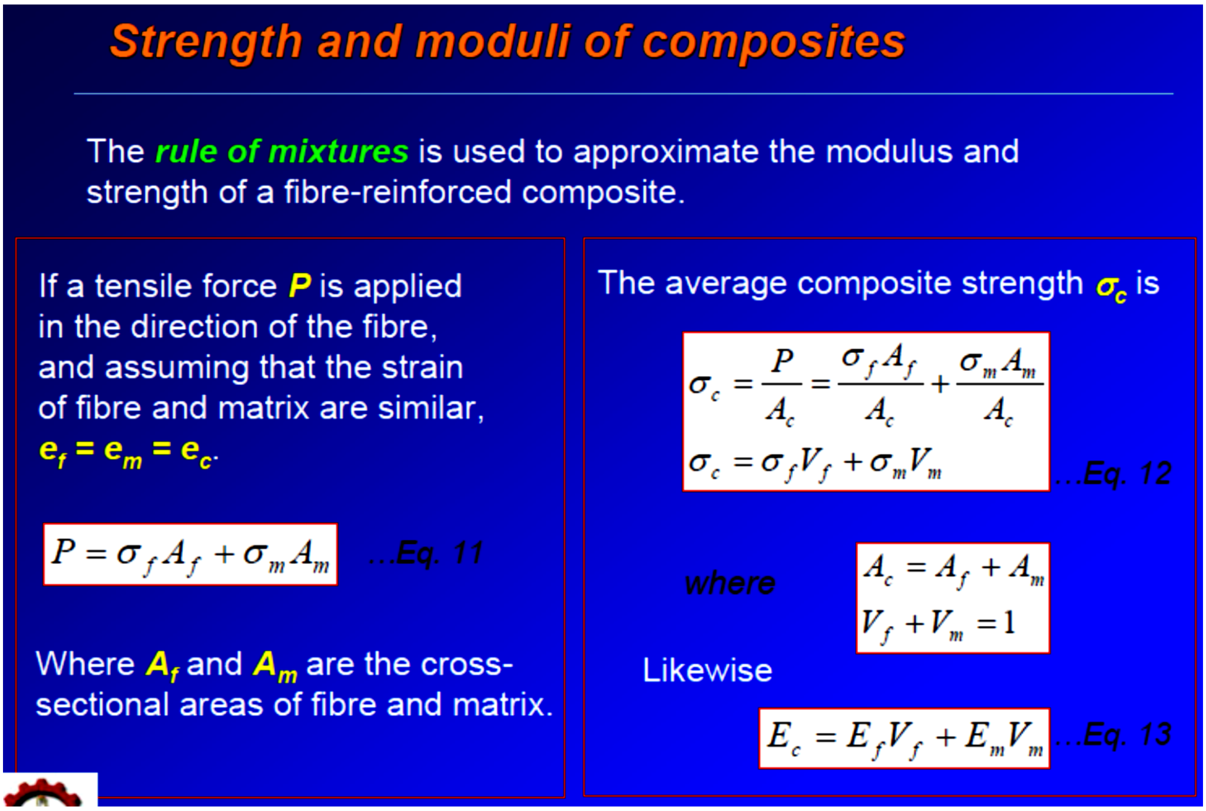
protect fibers from surface damage.

separate individual fibers and blunt crack from fiber breakage.

• High modulus fibers in Fiber-reinforced metals carry more load than dispersion-reinforced metals.

• Fiber-reinforced materials are highly anisotropic.

Note: Variation of stress between fibers and matrix is complex.



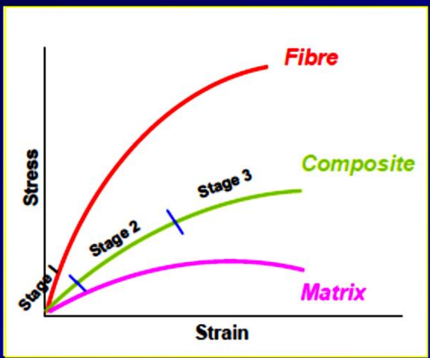
Example: *Boron fibre, E_f = 380 GPa, are made into a unidirectional composite with an aluminium matrix, E_m = 60 GPa. What is the modulus parallel to the fibres for 10 and 60 volume%.*

$$E_c = E_f V_f - (1 - V_f) E_m$$

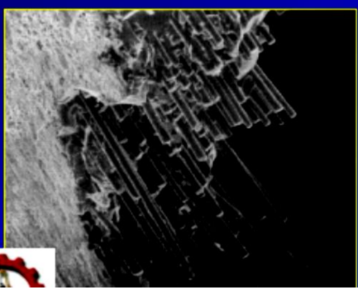
$$V_f = 0.10 \ , E_c = 380(0.10) + 0.9(60) = 92 \ \ GPa$$

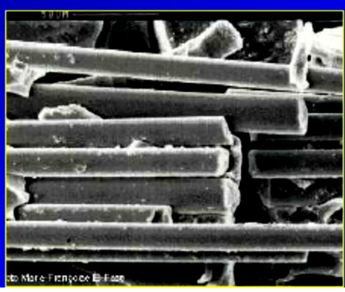
$$V_f = 0.60 \ , E_c = 380(0.60) + 0.4(60) = 252 \ \ GPa$$

Stress-strain curves of the fibre, matrix and fibre-reinforced composite



- ***Stage 1 :*** Both fibres and matrix undergo elastic deformation.
- ***Stage 2 :*** Matrix deforms plastically but fibres deform elastically.
- ***Stage 3 :*** Both matrix and fibres undergo plastic deformation.





- The load is transferred from ductile matrix to strong fibres.
- Breakage or pull-out of fibres increase the strength.