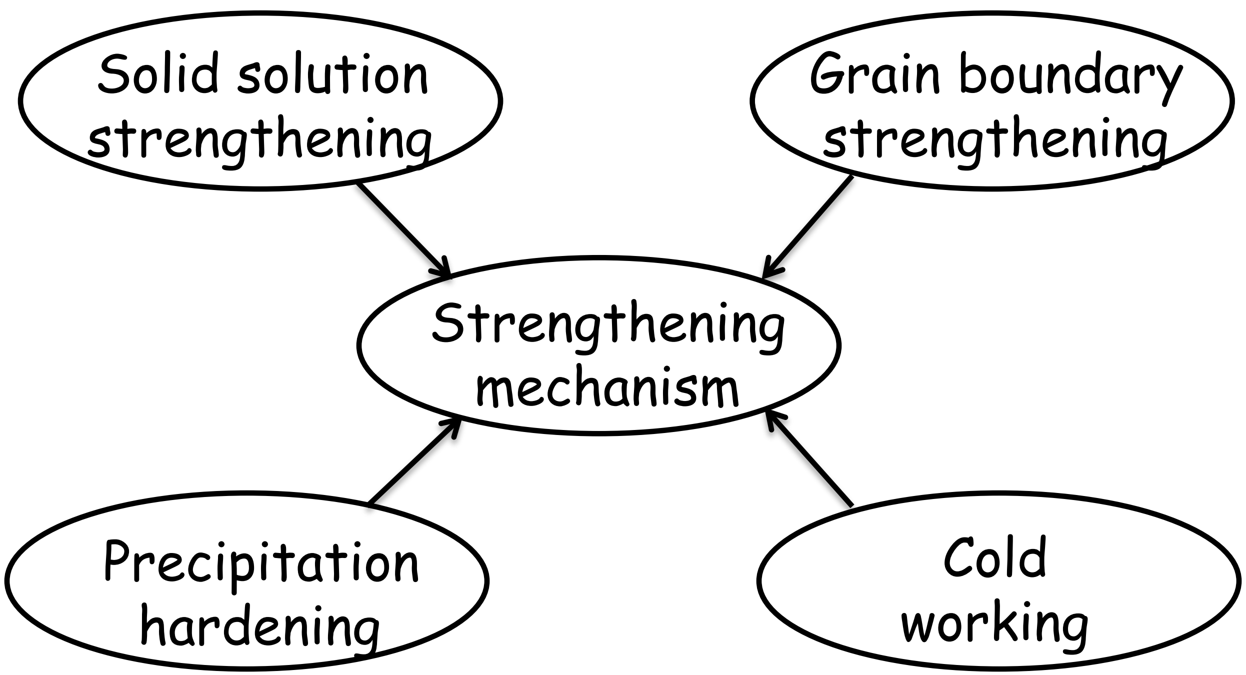
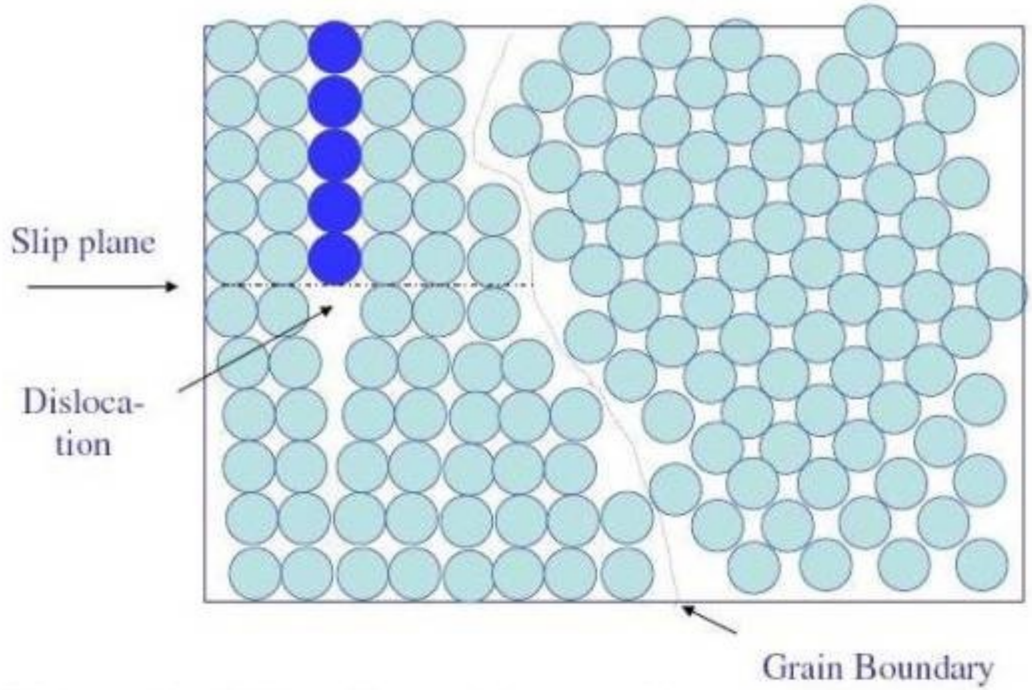
Strengthening Mechanisms

The ability of a metal/ alloy to plastically deform depends on the ability of dislocations to move. ⇒ Strengthening techniques rely on restricting dislocation motion to render a harder and stronger material.



Grain Boundary Strengthening



Motion of a dislocation as it encounters a grain boundary

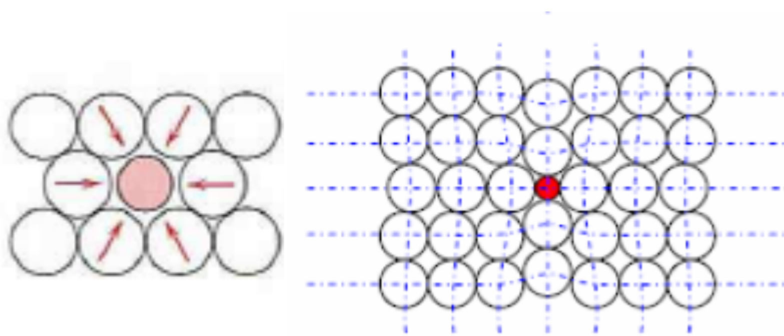
Smaller grain size:
more barriers to slip,
higher strength.

Hall-Petch Equation:

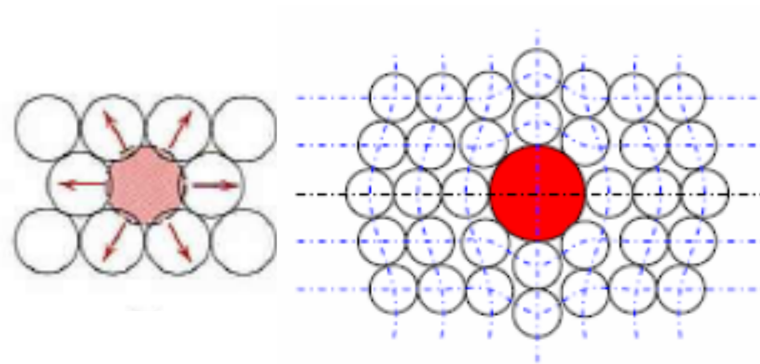
$$\sigma_y = \sigma_i + \frac{k}{\sqrt{D}}$$

Solid Solution Strengthening

- The presence of solute atoms produces lattice strain, either tensile or compressive, depending on the relative size of the solute atom.
- Solute atom generates local shear that opposes dislocation motion.



Smaller substitutional atom creates tensile lattice strain to the host atom.



Bigger substitutional atom creates compressive lattice strain to the host atom.

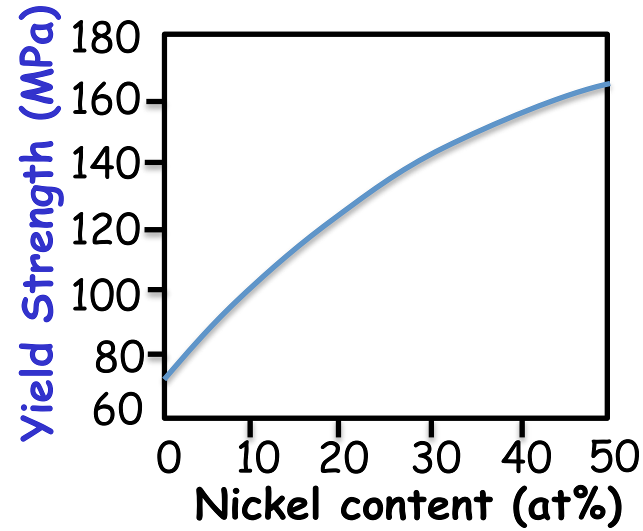
Solid Solution Strengthening

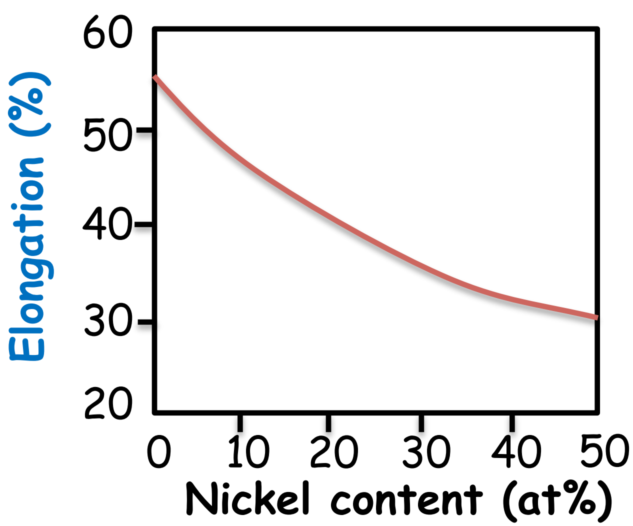
Impurity atom content increase:

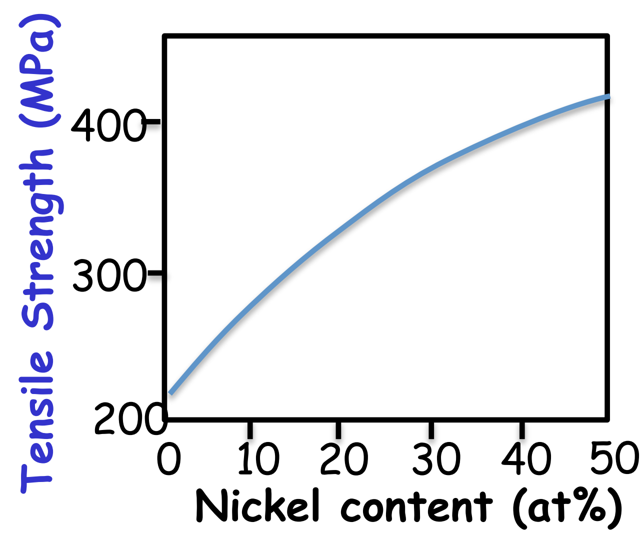
Tensile and yield strength ⬆

Ductility ⬇

Example: Cu-Ni Alloy





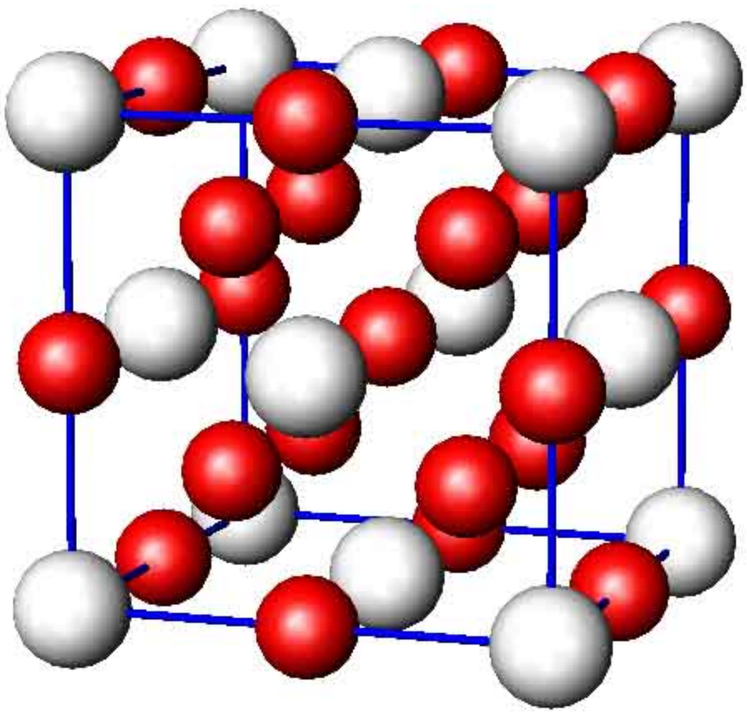


Solid Solution Strengthening

In ordered condition:

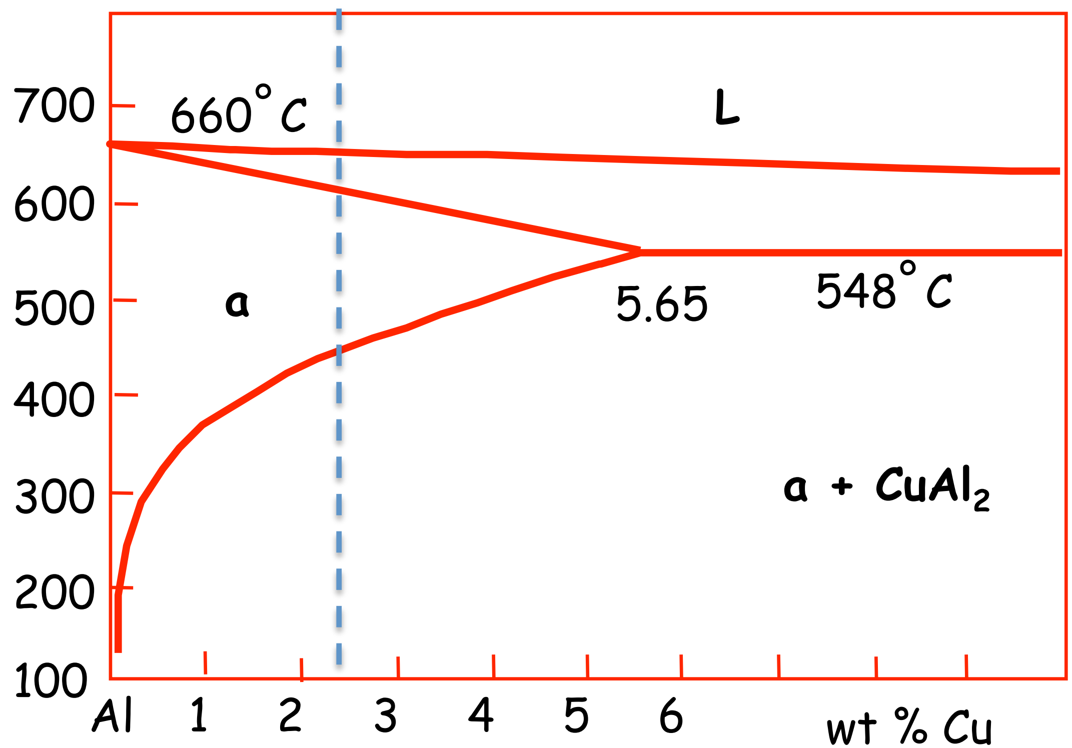
burgers vector is large

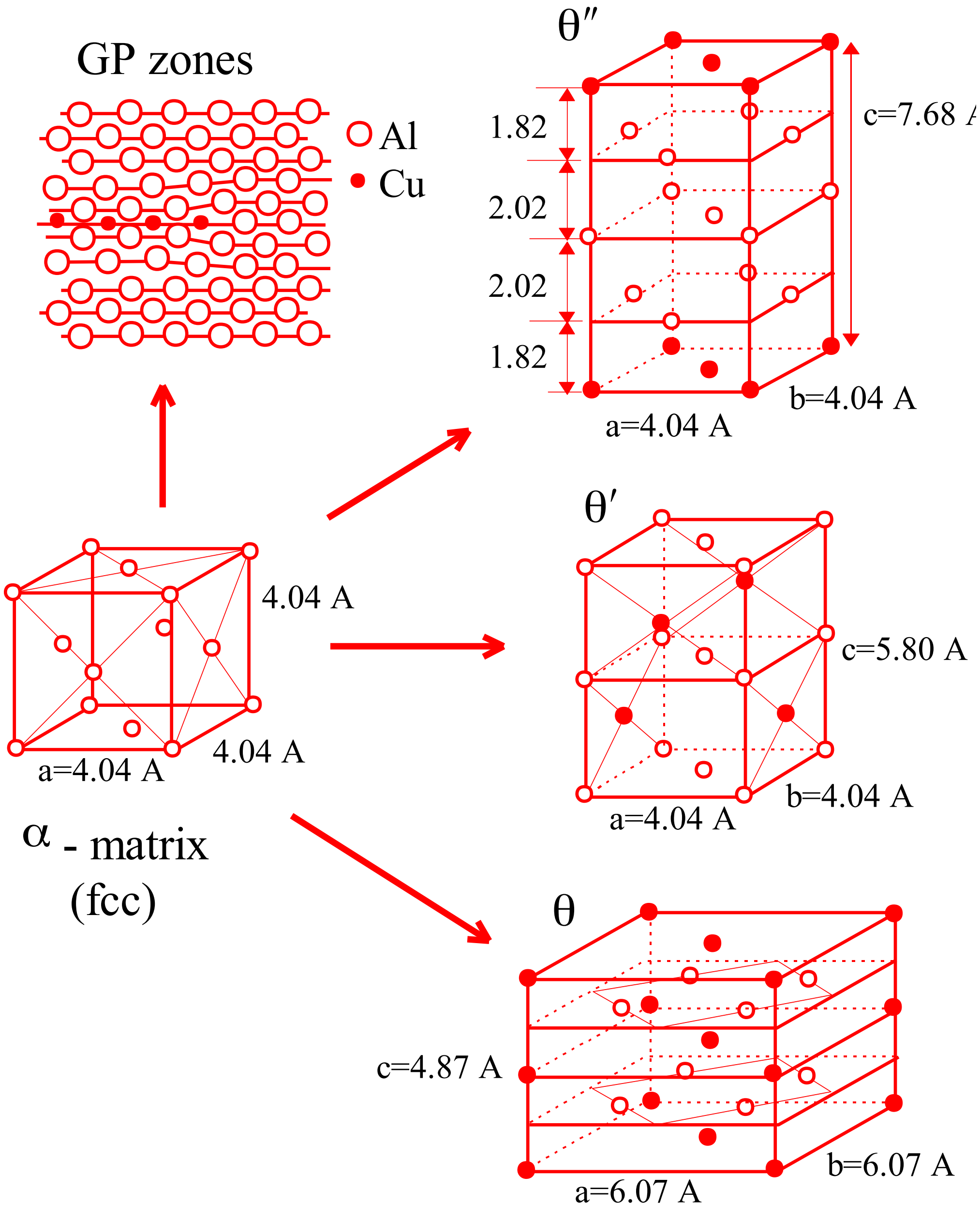
➔strain hardening rate is higher

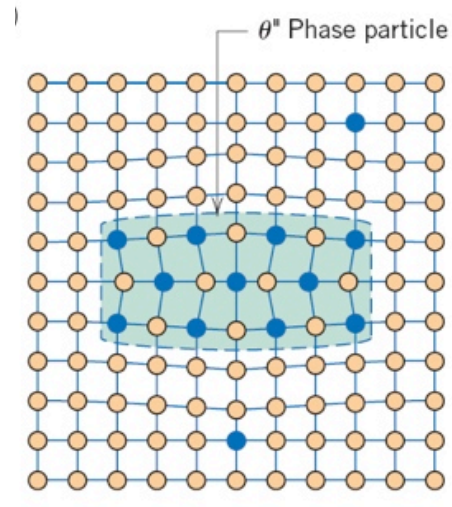


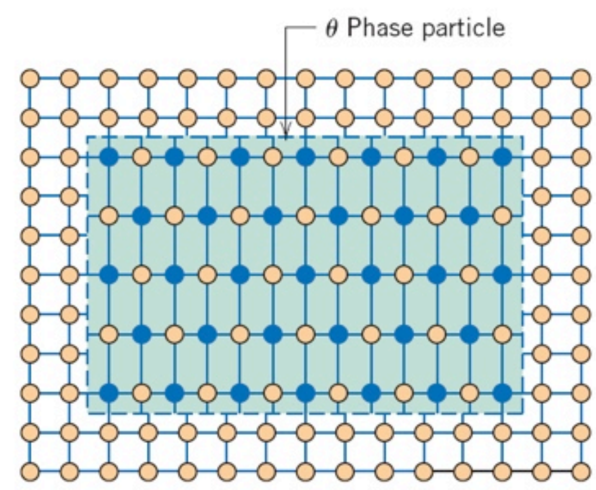
Precipitation Hardening

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



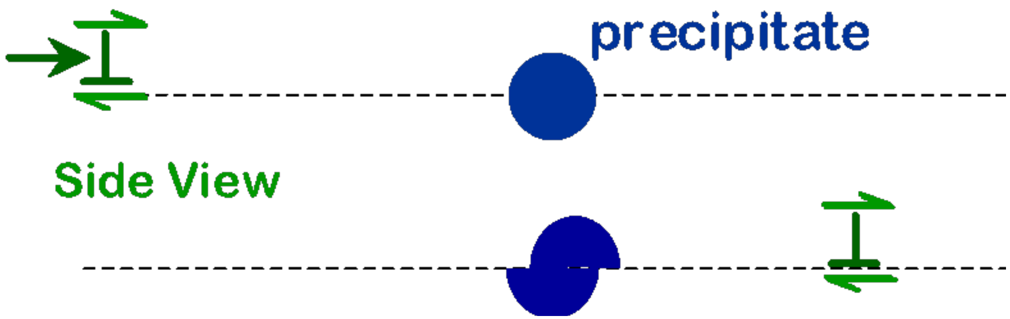

GP zones
Al
Cu
θ″
1.82
2.02
2.02
1.82
c=7.68
a=4.04 A
b=4.04 A
θ′
c=5.80 A
a=4.04 A
b=4.04 A
θ
c=4.87 A
a=6.07 A
b=6.07 A
4.04 A
4.04 A
a=4.04 A
α - matrix
(fcc)

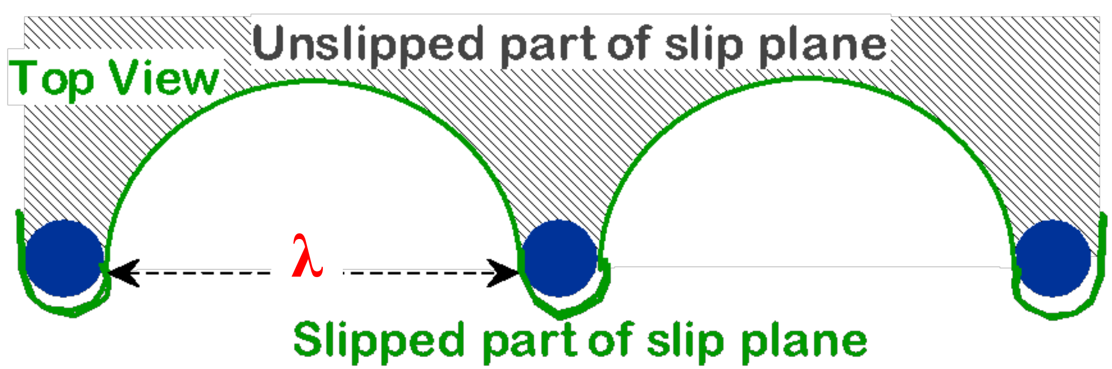

θ" Phase particle


θ Phase particle

Interaction of Dislocations with Precipitates

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

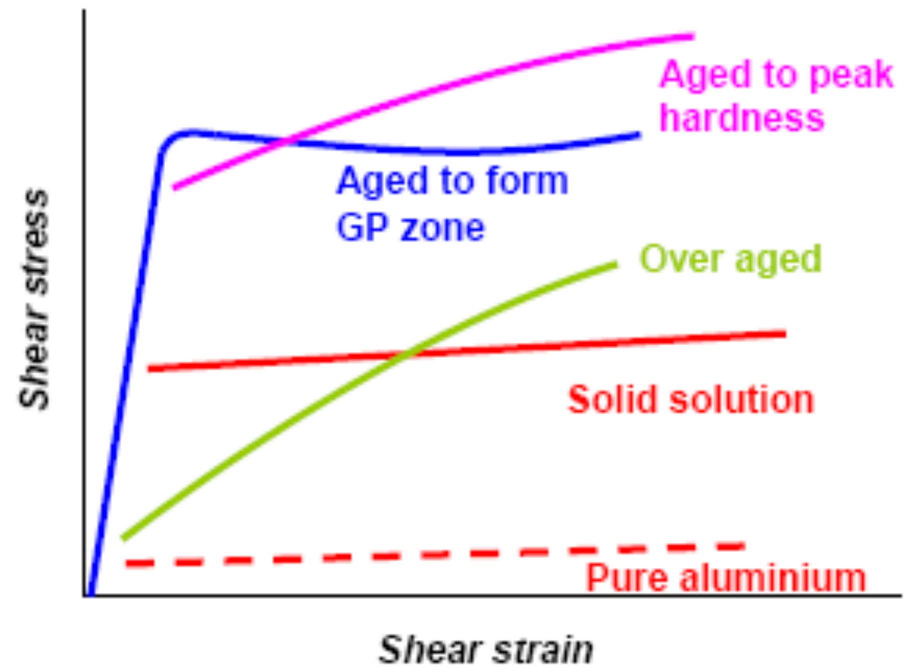




Stress required to force dislocation between particles: $\tau = \dfrac{Gb}{\lambda}$

Precipitation Hardening

- 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 incoherent particles, giving low yield stress, high strain hardening.

Precipitation vs. Dispersion Hardening

- In dispersion hardening, hard particles are mixed with matrix powder and processed by powder metallurgy techniques.

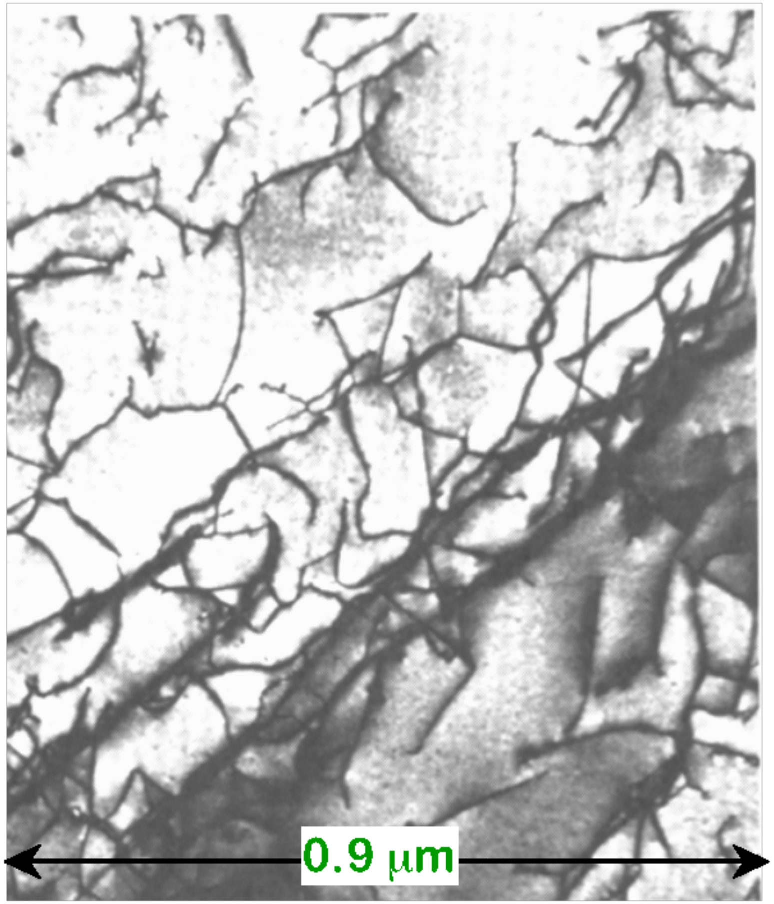
- In dispersion hardening, there is no coherency between second phase and matrix.

- In dispersion-hardening, the second phase has very little solubility in the matrix, even at elevated temperatures.

- Dispersion hardening systems have more temperature stability.

Cold Working

- Cold-work structure occurs when plastic deformation is applied in a temperature region such that the strain hardening is not relieved (0.3 - 0.5 T_m).



- Cold worked structure contains dislocation ~10^8-10^{10} mm^{-2}, while annealed structure possesses ~10^3-10^4 mm^{-2}.
- Dislocations entangle with one another during cold work. Hence dislocation motion becomes more difficult.

As T ↓, strain rate ↑
stored energy ↑

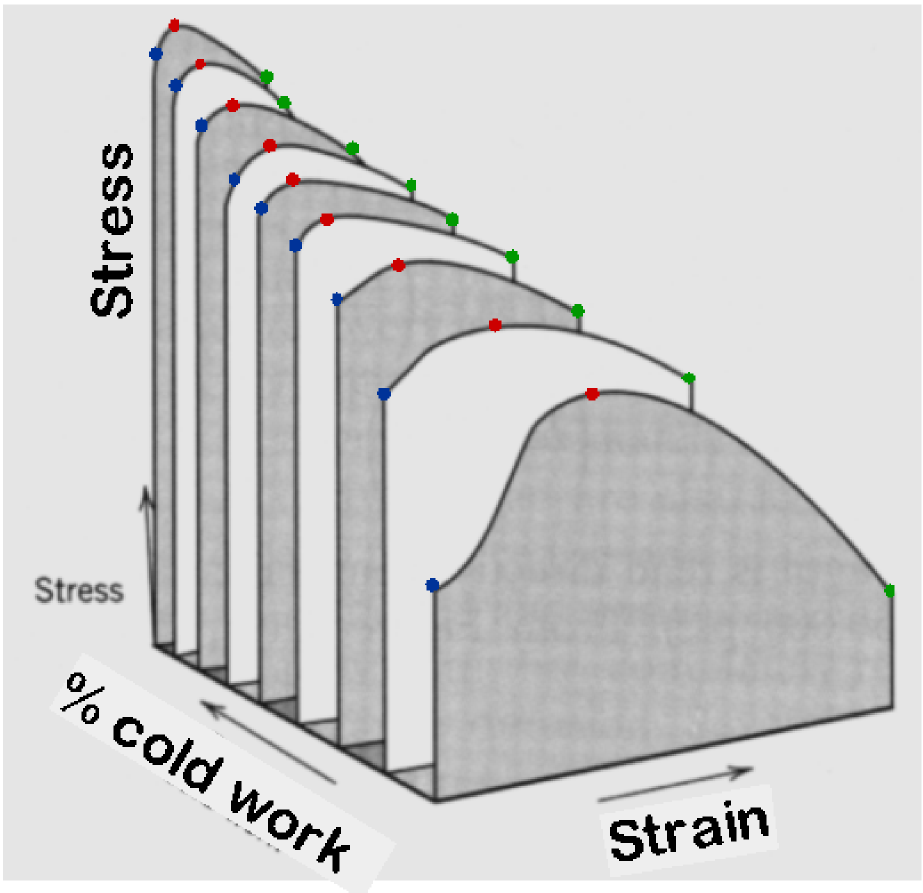
Strain Hardening

- Strain hardening or cold working is esp. used to harden alloys that do not respond to heat treatment.
- The rate of strain hardening is lower in HCP than in cubic metals.

Cold work ⇧

Strength ⇧

Ductility ⇩



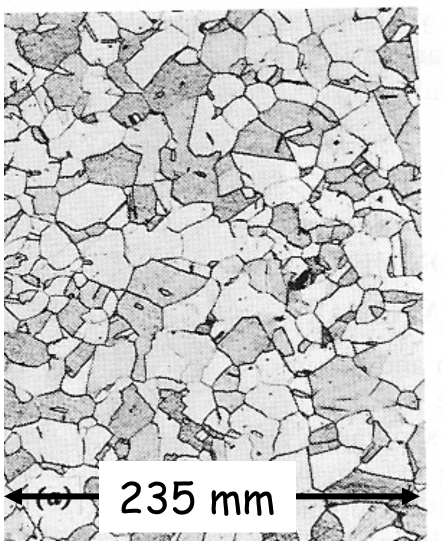
Texture Formation

- Severe deformation produces a reorientation of the grains into a preferred orientation. Certain crystallographic planes tend to orient themselves in a preferred manner with respect to the maximum strain direction.
- The preferred orientation resulting from plastic deformation is strongly dependent on the available slip and twining systems, but not affected by processing variable such as die angle, roll diameter, roll speed, etc.

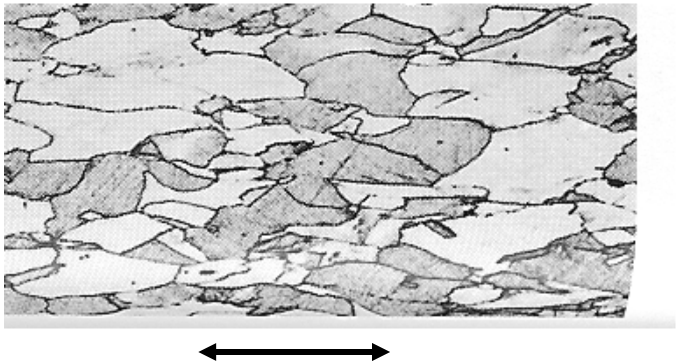
Anisotropy in σ_{yield}

Can be induced by rolling a polycrystalline metal

-before rolling



-after rolling



rolling direction

isotropic

since grains are approx. spherical & randomly oriented.

anisotropic

since rolling affects grain orientation and shape.

Importance of Anisotropy

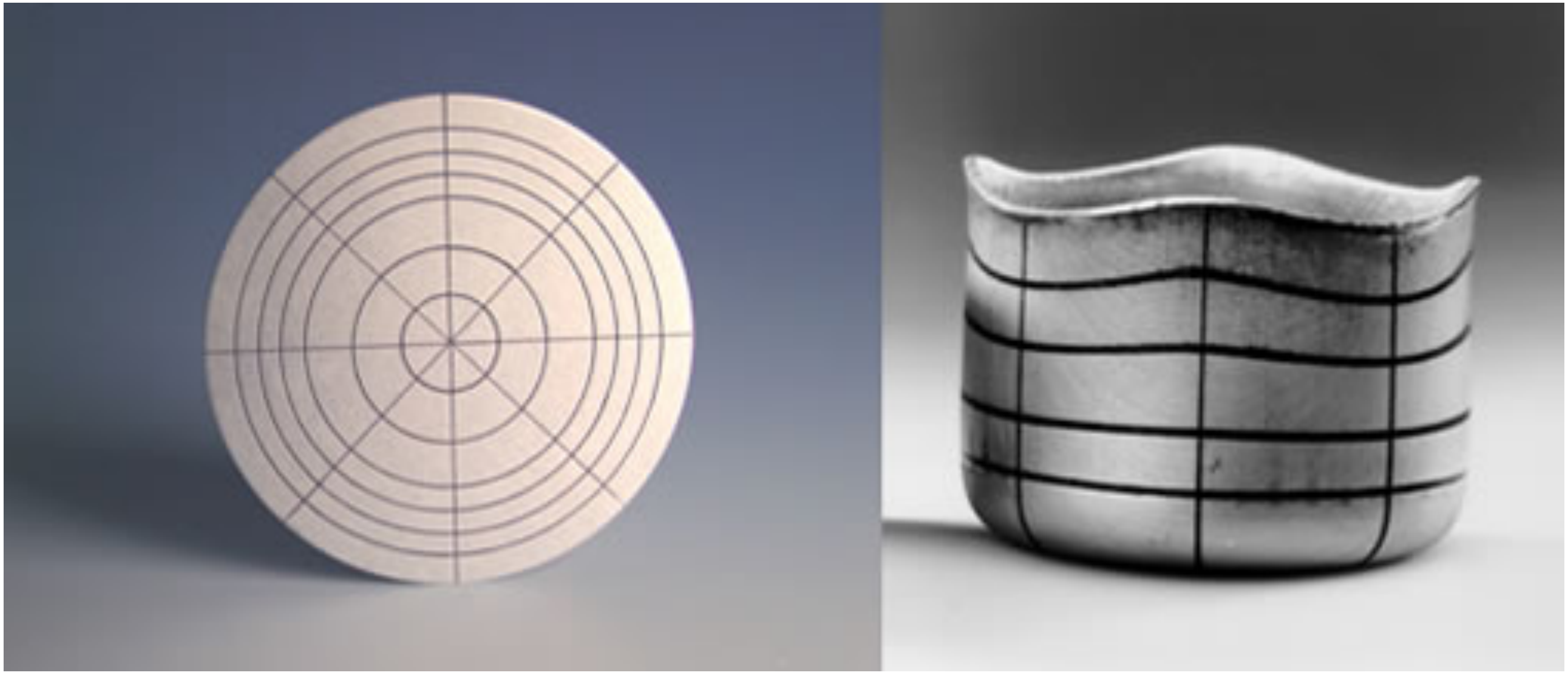
- Normal Anisotropy, R:

$$R = \frac{\varepsilon_w}{\varepsilon_t}$$

- Planar Anisotropy, ΔR:

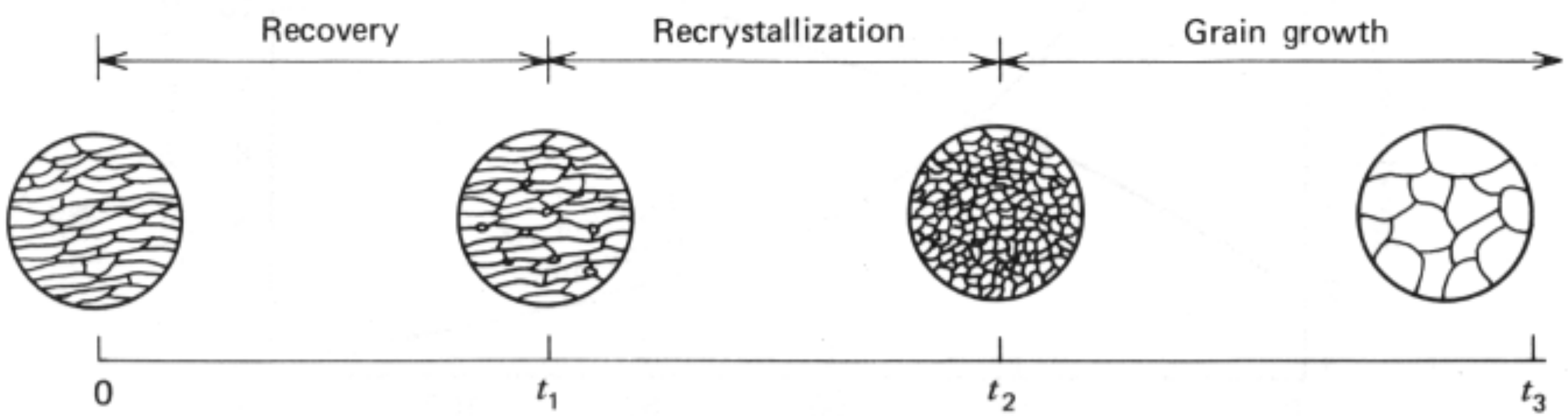
$$\Delta R = \frac{R_0 + R_{90} - 2R_{45}}{2}$$

Earing

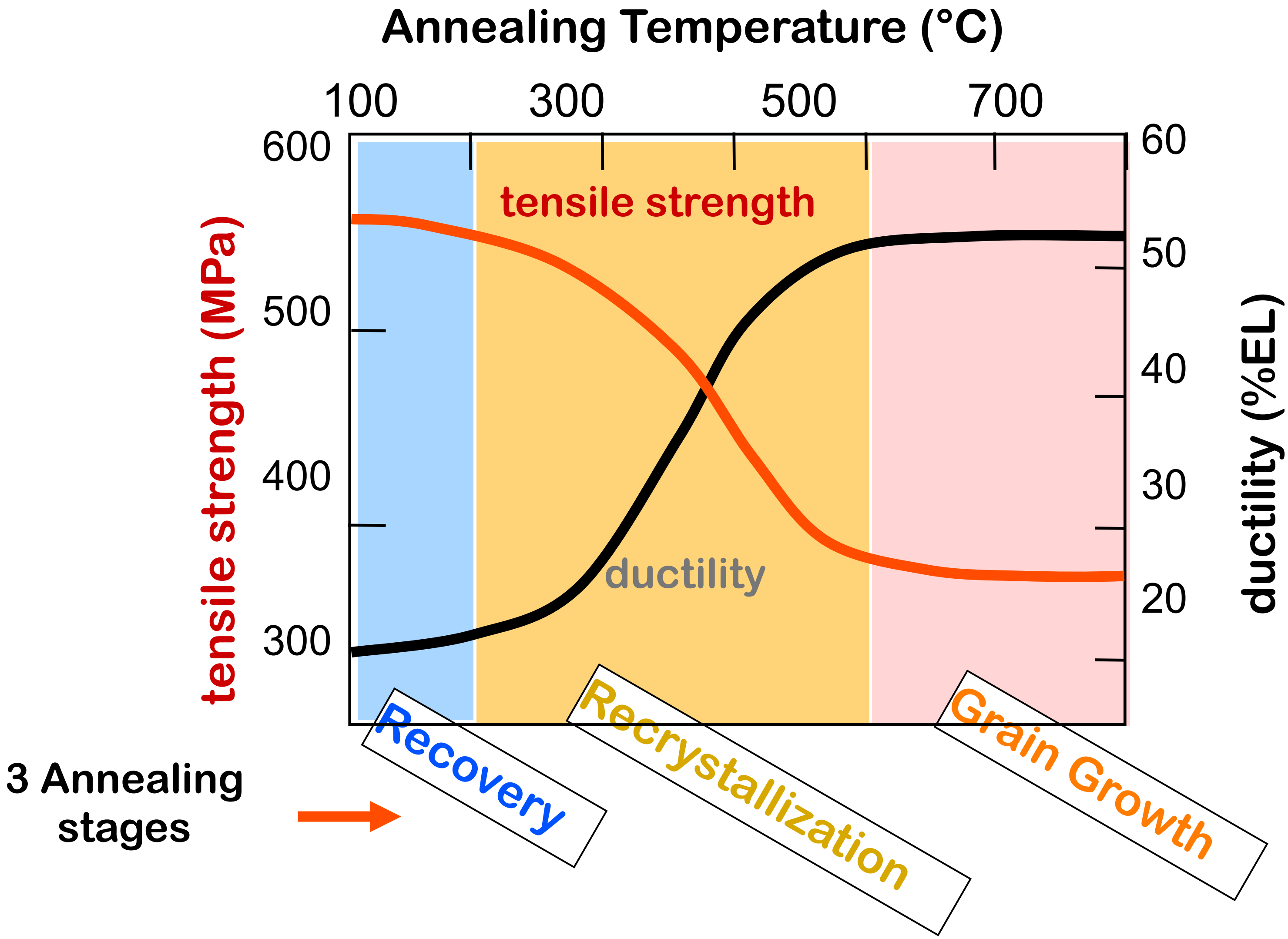


Annealing of Cold-Worked Metal

- Annealing of the cold worked structure at high temperature softens the metal and reverts to a strain-free condition.
- The transformations that take place during annealing are recovery, recrystallization and grain growth, respectively.
- The driving force for recovery and recrystallization is the energy of the defects introduced during cold working (stored energy of the deformed matrix).
- The driving force for grain growth is the boundary curvature.



Annealing of Cold-Worked Metal



Effect of 1 hour heating on mechanical properties

Recovery

Recrystallization
nucleation and growth of strain free grains

Grain growth

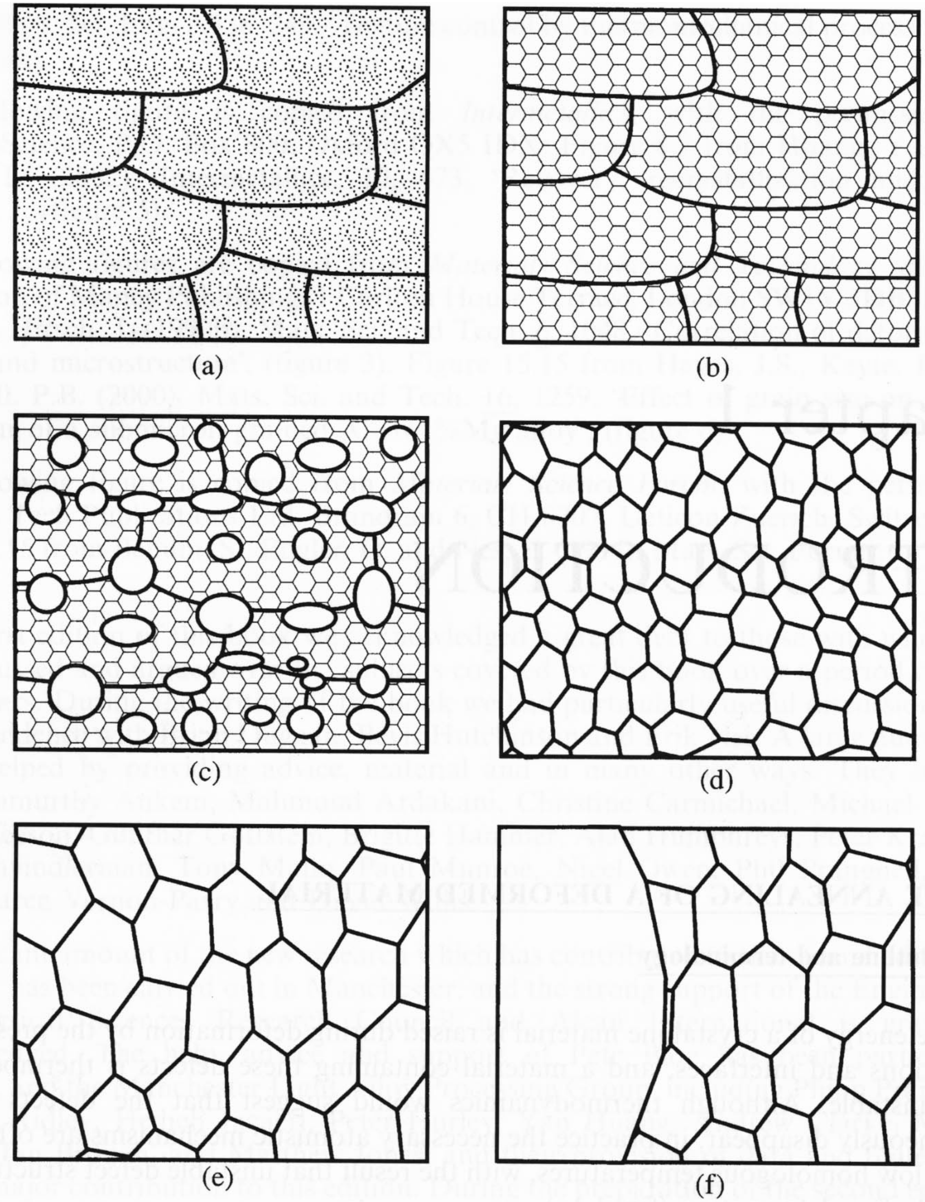
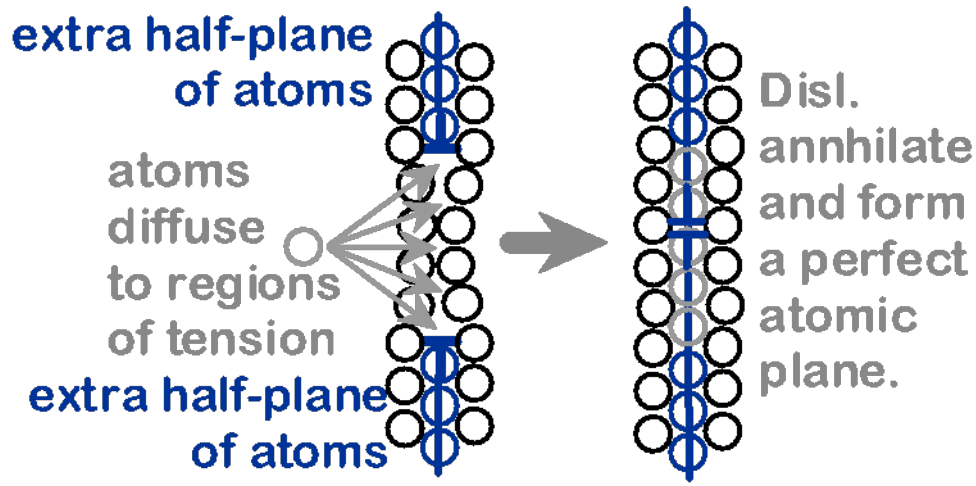


Fig. 1.1. Schematic diagram of the main annealing processes; (a) Deformed state, (b) Recovered, (c) Partially recrystallized, (d) Fully recrystallized, (e) Grain growth and (f) Abnormal grain growth.

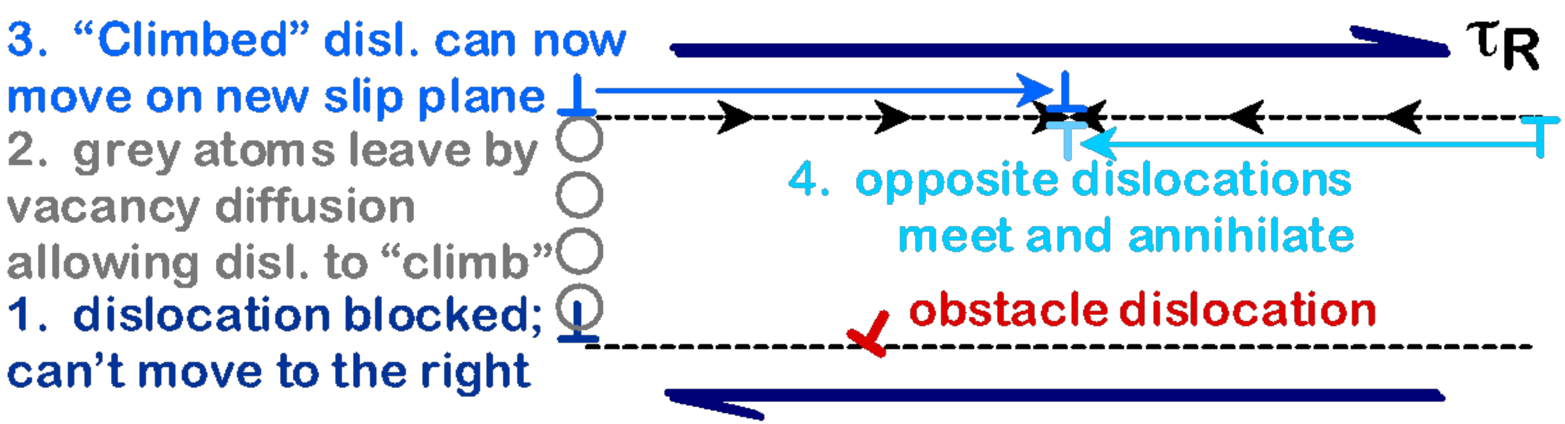
Recovery

Annihilation reduces dislocation density.

Scenario 1



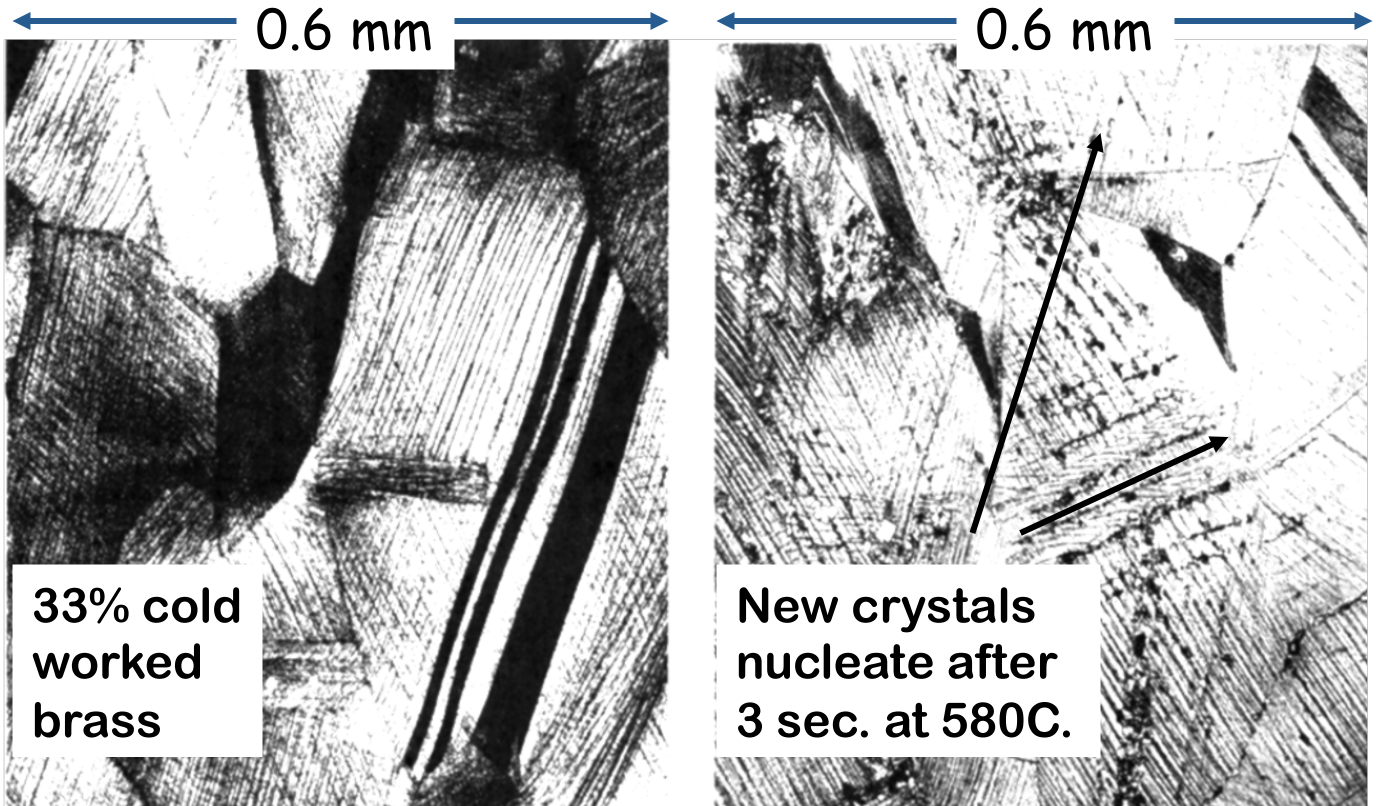
Scenario 2



Recrystallization

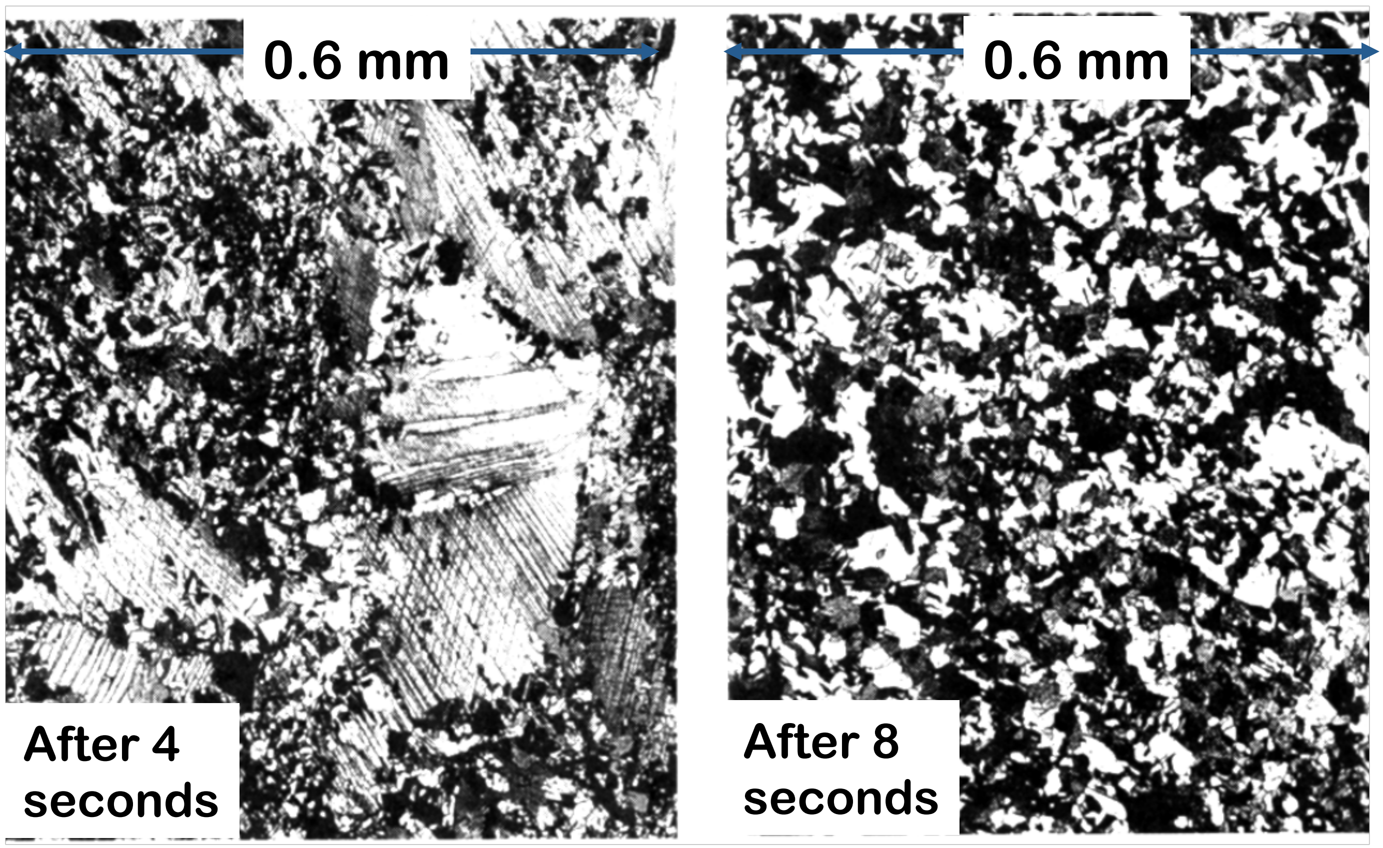
New crystals are formed that:

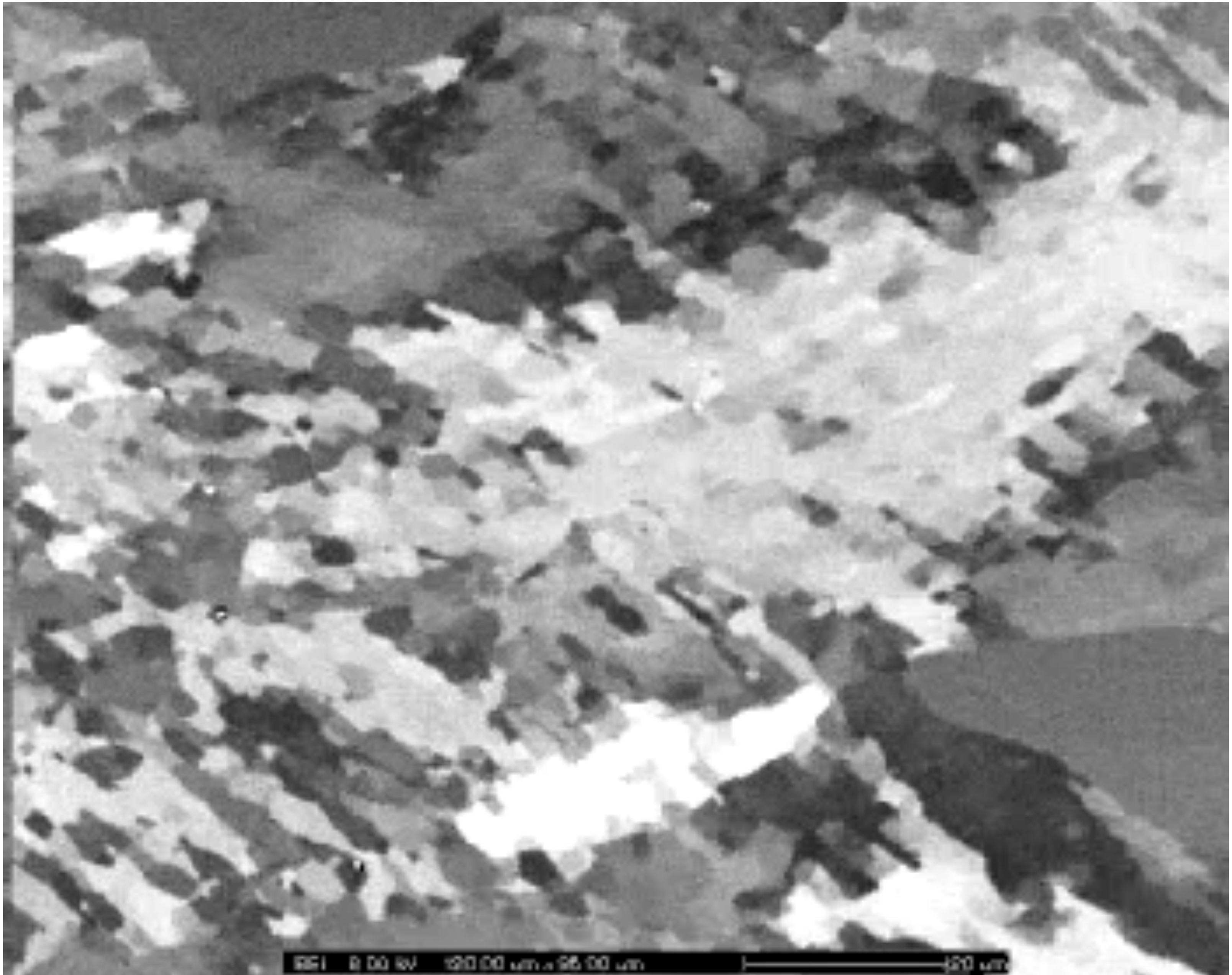
- have a small dislocation density
- are small
- consume cold-worked crystals.



Further Recrystallization

All cold-worked crystals are consumed.





Variables Affecting Recrystallization

1) The amount of prior deformation
2) Temperature
3) Time
4) Initial grain size
5) Composition
6) Amount of recovery prior to start the recrystallisation.

Recrystallization temperature can be defined as the temperature at which a given alloy in a highly cold-worked state completely recrystallizes in 1 h.

Degree of Deformation ⇧ T_{recrys} ⇩ T_{anneal} ⇩ GS_{recrys} ⇩

Impurity ⇧ T_{recrys} ⇧

Grain Growth

- At longer times, larger grains consume smaller ones.
- Grain boundary area (and therefore energy) is reduced.