Precipitation Strengthening

Course: Phase Transformations
Level: 3rd Stage | Semester: 5
Department of Materials Engineering
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Learning Objectives

By the end of this lecture, students will be able to:

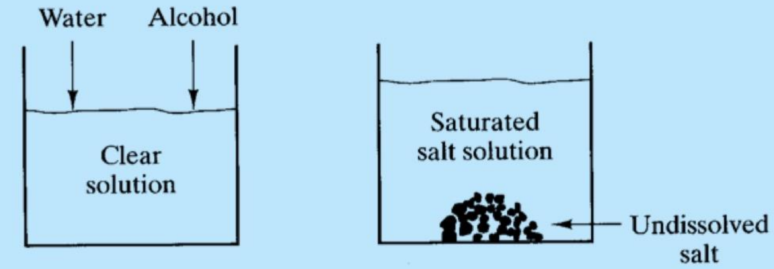
- **Define** the concept of precipitation strengthening and its role in enhancing material strength.
- **Describe** the process of nucleation and growth of precipitates within a metal matrix.
- **Explain** the influence of aging time and temperature on the size, distribution, and effectiveness of precipitates.
- **Differentiate** between under-aged, peak-aged, and over-aged microstructures.
- **Interpret** hardness-aging curves and relate them to microstructural changes.
- **Apply** the principles of precipitation strengthening to real-world alloy systems such as Al-Cu and steels.
- **Identify** factors that control the effectiveness of precipitate strengthening, including coherency, particle spacing, and interaction with dislocations.

Solid Solubility/Solid Solutions

Solid Solution ≡ A solid phase that contains a mixture of more than one element, with the elements combining to give a uniform composition everywhere

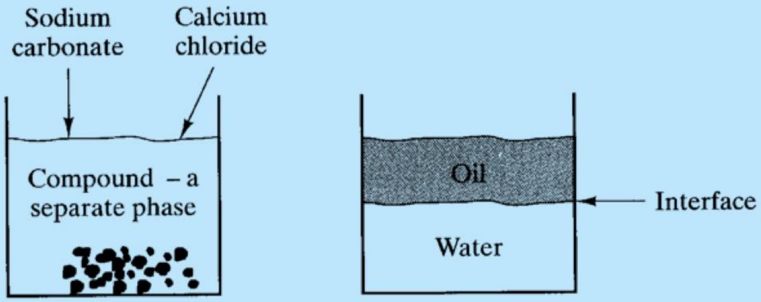
Solid Solubility ≡ Extent to which one phase (**solvent**) can accommodate the addition of a solute without creating (**precipitating**) a new phase

Three extreme forms of solid solubility



(a) Complete solubility
(one liquid phase)

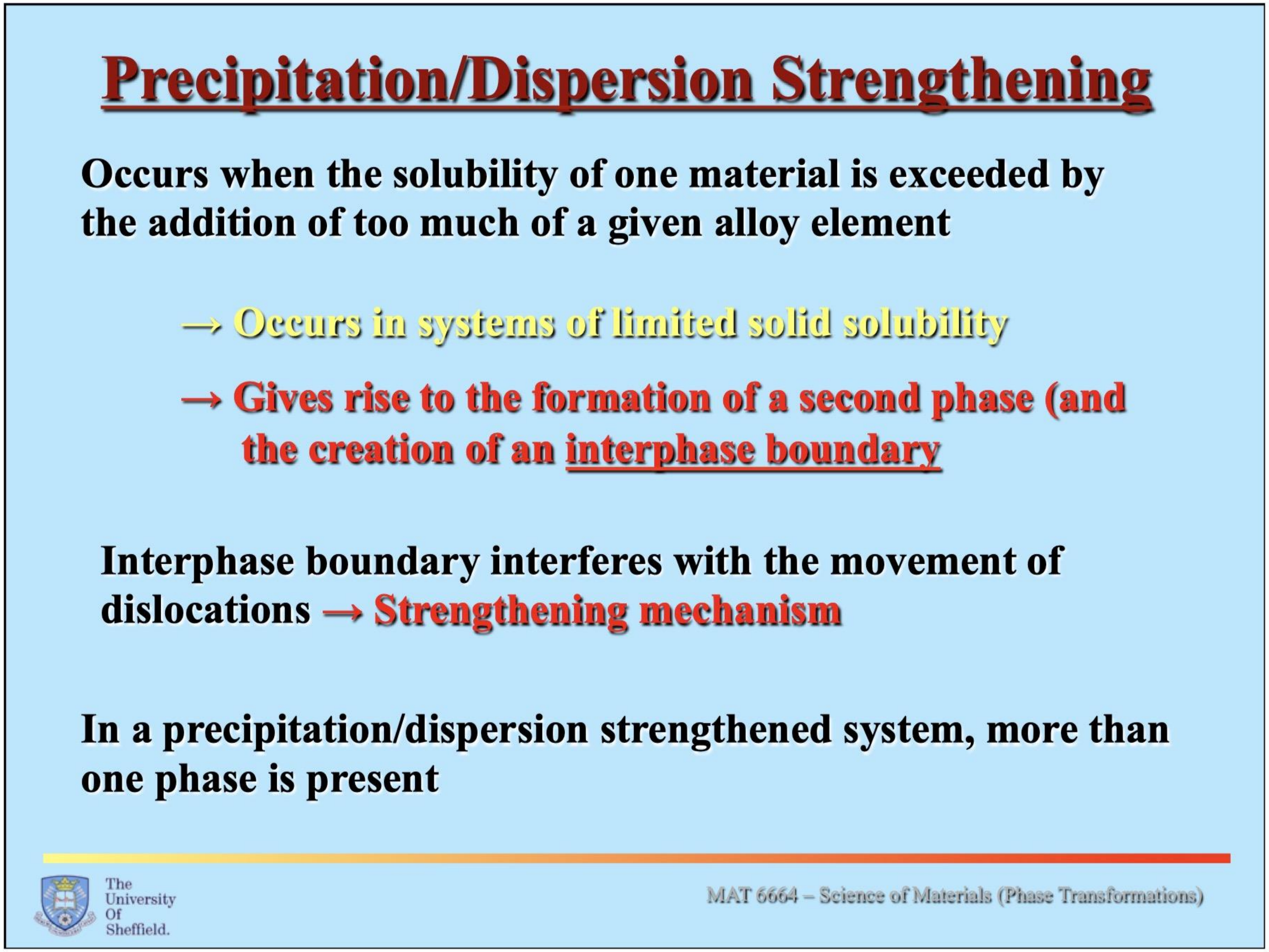
(b) Partial solubility
(two phases – liquid + solid)



(c) Compound formation
(two phases –
liquid + solid)

(d) Two insoluble phases
(two liquid phases)

Fig. 5-3 Cases in the liquid state: (a) complete solubility, (b) partial solubility, (c) compound formation, (d) insolubility of phases.



Precipitation/Dispersion Strengthening

Occurs when the solubility of one material is exceeded by the addition of too much of a given alloy element

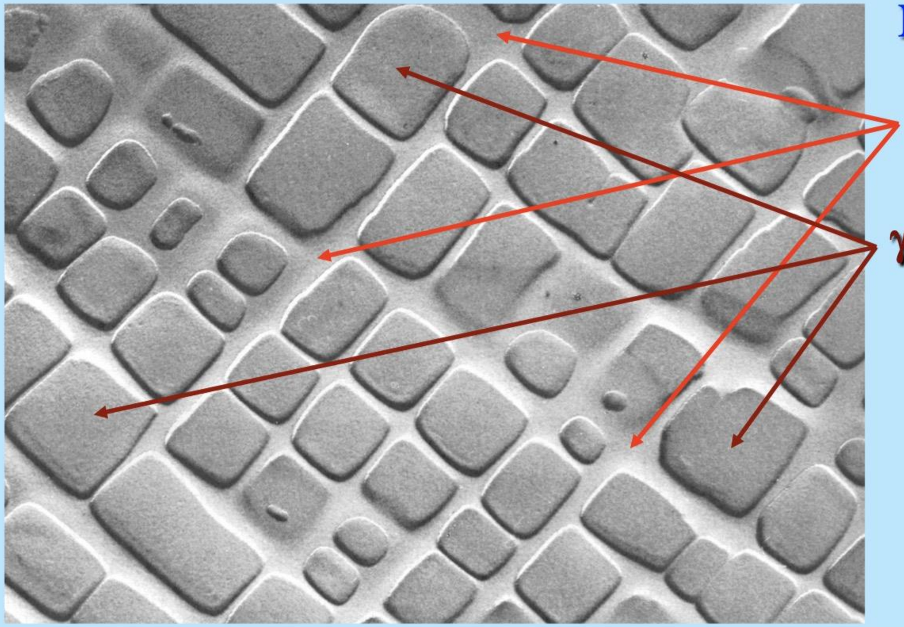
- **→ Occurs in systems of limited solid solubility**
- **→ Gives rise to the formation of a second phase (and the creation of an interphase boundary**

Interphase boundary interferes with the movement of dislocations → Strengthening mechanism

In a precipitation/dispersion strengthened system, more than one phase is present

Matrix Phase: Continuous phase which is usually present in larger amounts

Precipitate: Second phase, usually in smaller amounts

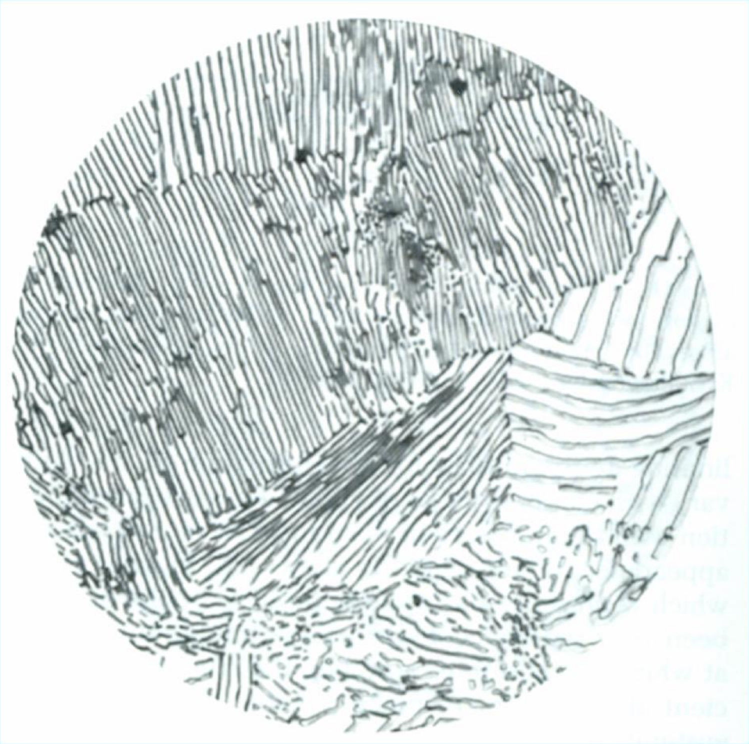


Ni_3Al

γ-phase (matrix)

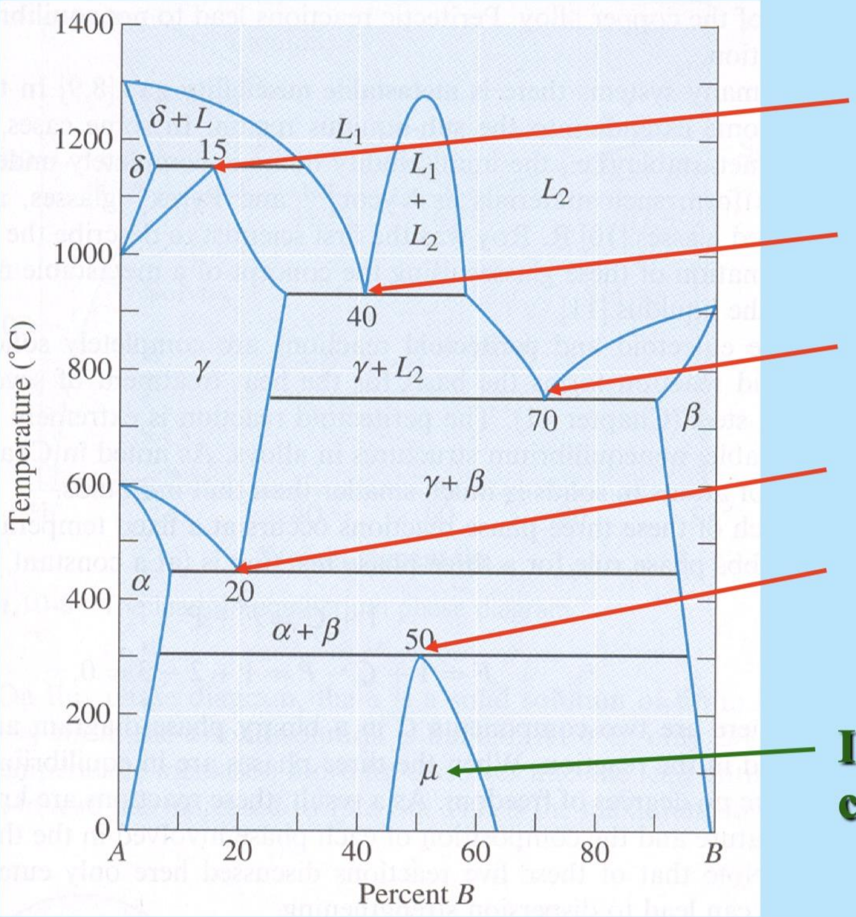
γ'-phase (precipitate)

In some cases, both phases form concurrently with one another, such that they exist in nearly equal proportions



→ microconstituent

Pearlite ($\alpha + Fe_3C$) in steels



Peritectic

Monotectic

Eutectic

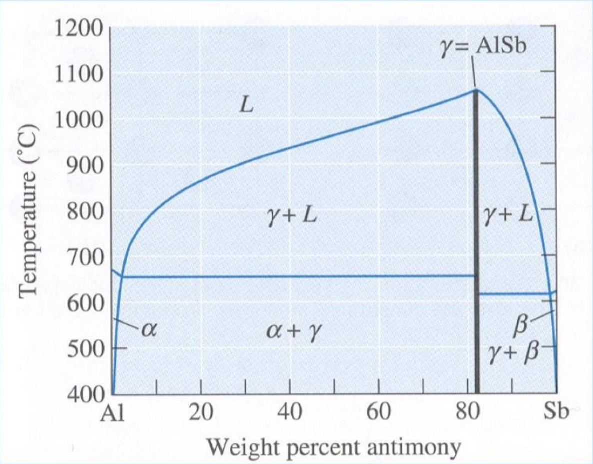
Eutectoid

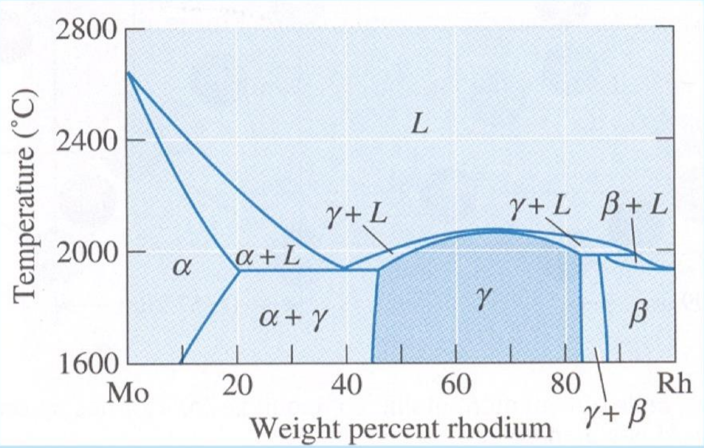
Peritectoid

Intermetallic compound

Intermetallic Compound

- Comprised of two or more elements and produces a new phase (exhibiting its own composition, crystal structure and properties)
- Composition can be stoichiometric (fixed) or non-stoichiometric (variable)





Nucleation in the Solid State

- **Similar to nucleation of solidification**
- **Additional term, however, is introduced to account for strain energy produced during the transformation of a new solid phase in a rigid solid matrix**

$$\Delta G_{total} = -\frac{4}{3}\pi r^3\left(\Delta G_v - \Delta G_\varepsilon\right) + 4\pi r^2 \gamma$$

$\Delta G_\varepsilon \equiv$ strain energy

Effect of strain energy is to reduce the effective driving force for the transformation!!

$$r^* = \frac{2\gamma}{\Delta G_v - \Delta G_\varepsilon} \qquad \Delta G^* = \frac{16\pi\gamma^3}{3\left(\Delta G_v - \Delta G_\varepsilon\right)^2}$$

The strain energy contribution effectively makes both r^* and ΔG^* large!

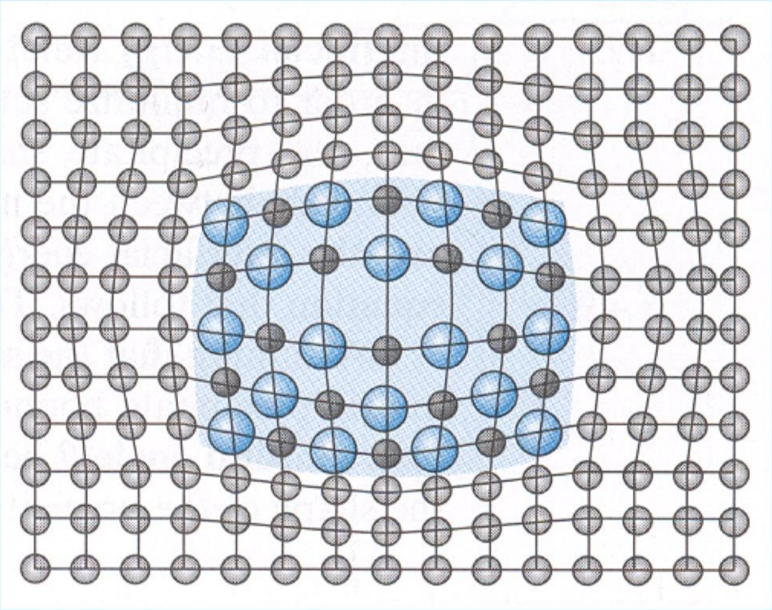
It is clear from the above expressions that ΔG^* will be lowered by having a low γ and a low ΔG_ε

→ Nature of interface will be very important

Three Possible Interphase Interfaces

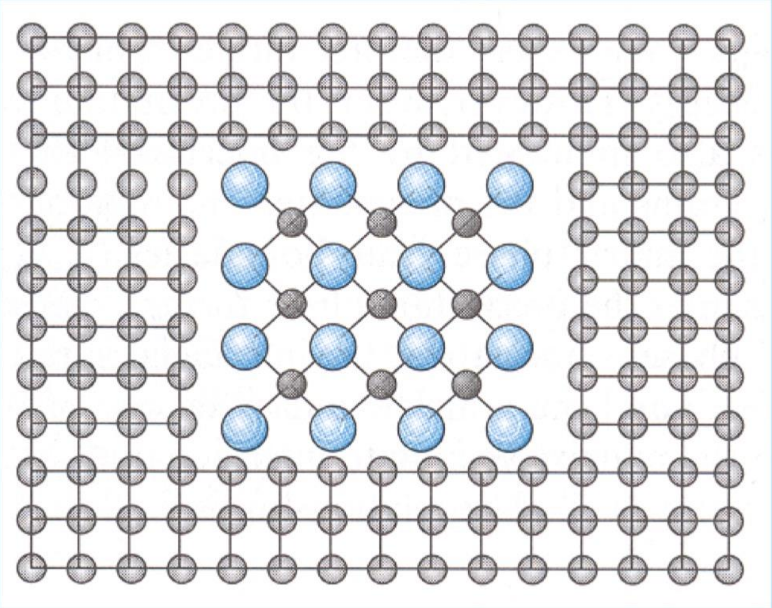
1. Coherent

- **One-to-one lattice matching across interface**
- **Gives rise to a high strain energy (ΔG_ε) and a low interfacial energy (γ)**



2. Incoherent

- No lattice matching across interface
- Gives rise to a low strain energy (ΔG_ε) and a high interfacial energy (γ)



3. Semi-coherent

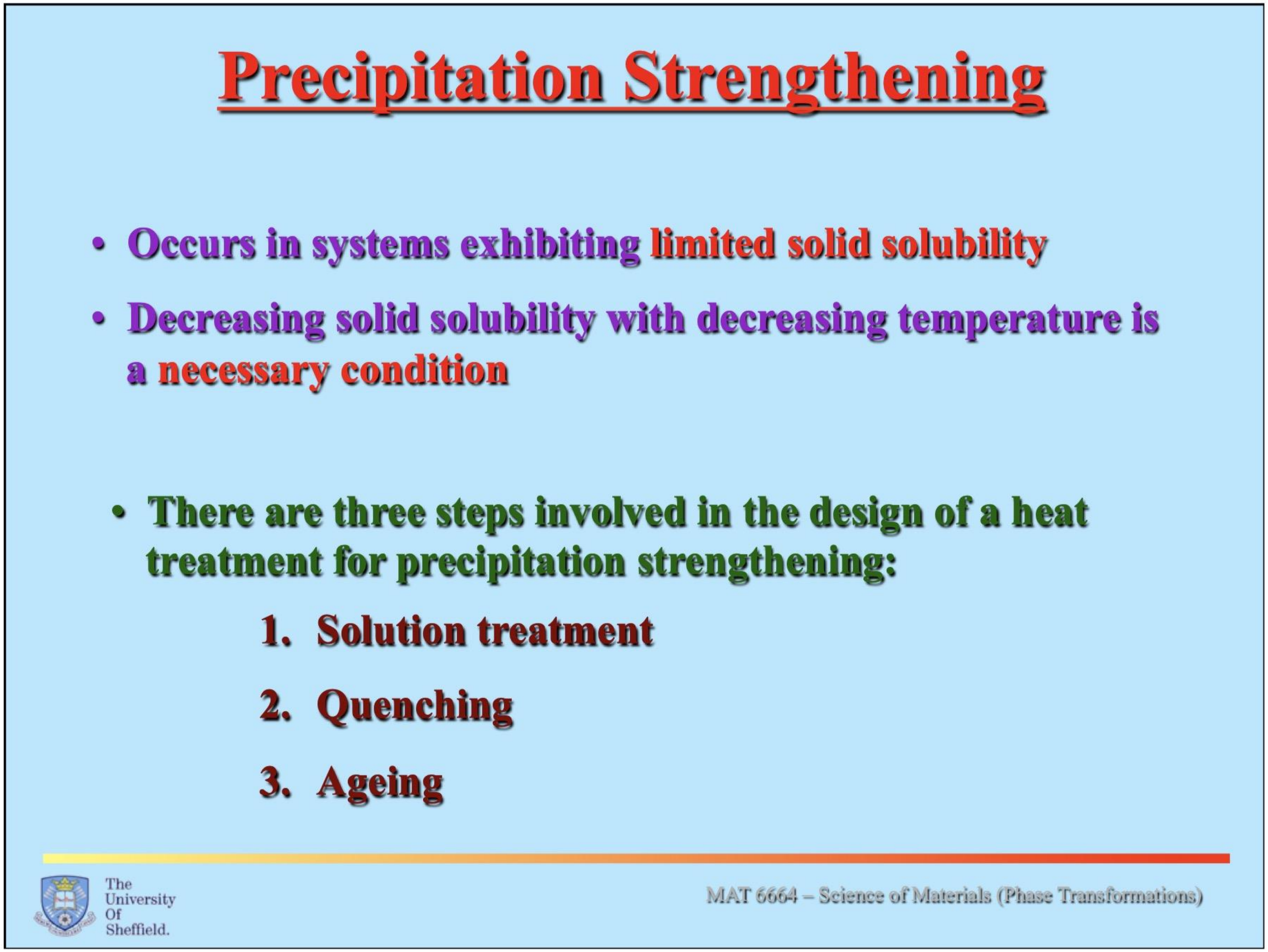
- Some lattice matching

ΔG_ε versus γ

(which term is more important?)

$$\Delta G^* = \frac{16\pi\gamma^3}{3\left(\Delta G_v - \Delta G_\varepsilon\right)^2}$$

- **Nucleation in the solid state is dominated by the γ term (as opposed to the ΔG_ε term)**
- **In keeping ΔG^* to a minimum, it is more important to keep γ low than it is to keep ΔG_ε low**
- **This explains why the first precipitates often have coherent interfaces**



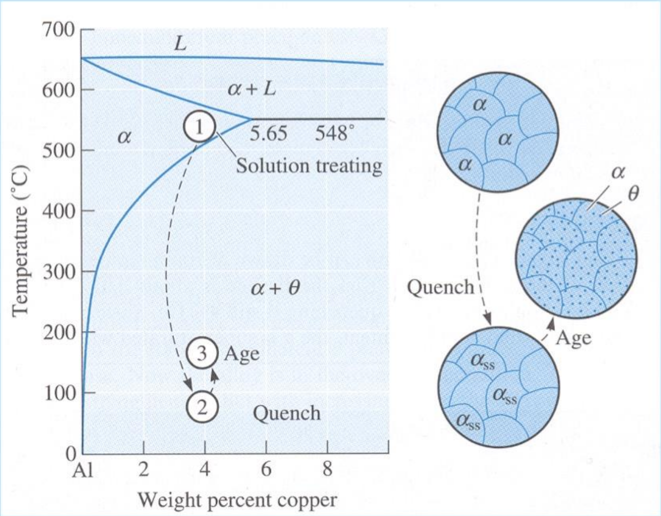
Precipitation Strengthening

- Occurs in systems exhibiting limited solid solubility
- Decreasing solid solubility with decreasing temperature is a necessary condition

- There are three steps involved in the design of a heat treatment for precipitation strengthening:
  1. Solution treatment
  2. Quenching
  3. Ageing

1. Solution Treatment

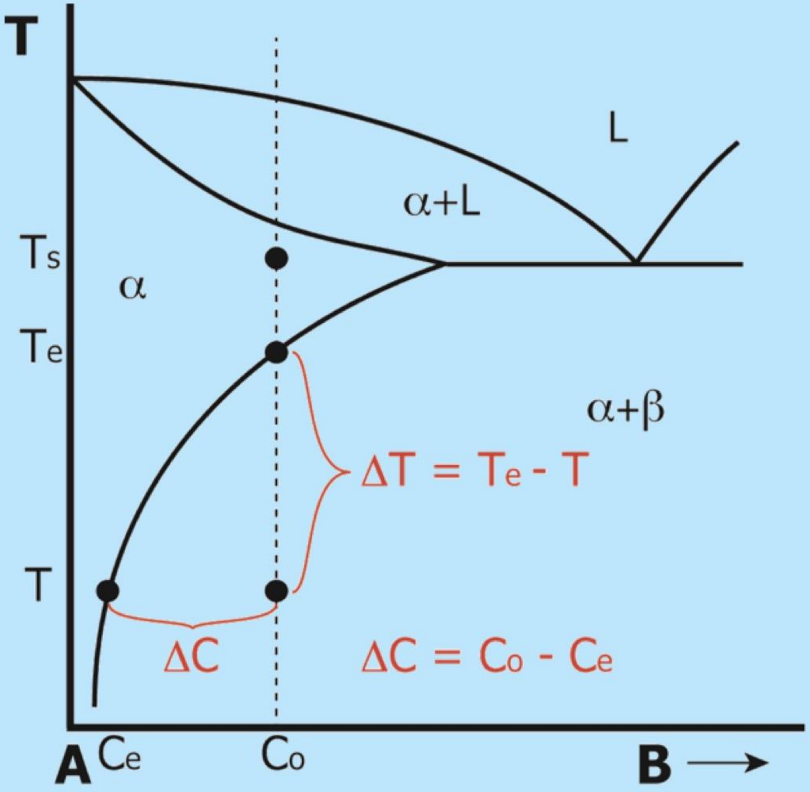
- Alloy heated above solvus temperature and held until a **homogeneous solid solution** (single phase) is produced
- This step ensures that all alloy elements are in solution



2. Quench

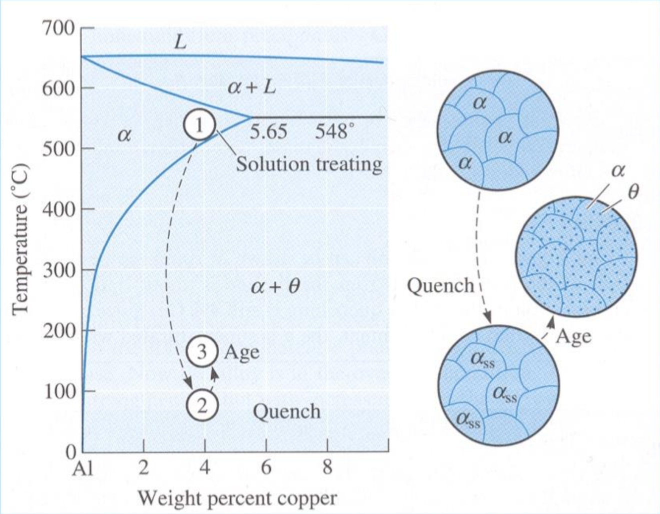
- Little (if any) time for diffusion, resulting in a **supersaturated solid solution**
- Represents a condition of unstable equilibrium

- **Degree of supersaturation increases as the quenching temperature decreases**



3. Age

- **Process where supersaturated solid solution is heated to (and held at) a given temperature below the solvus**



Natural ageing: Hold at RT

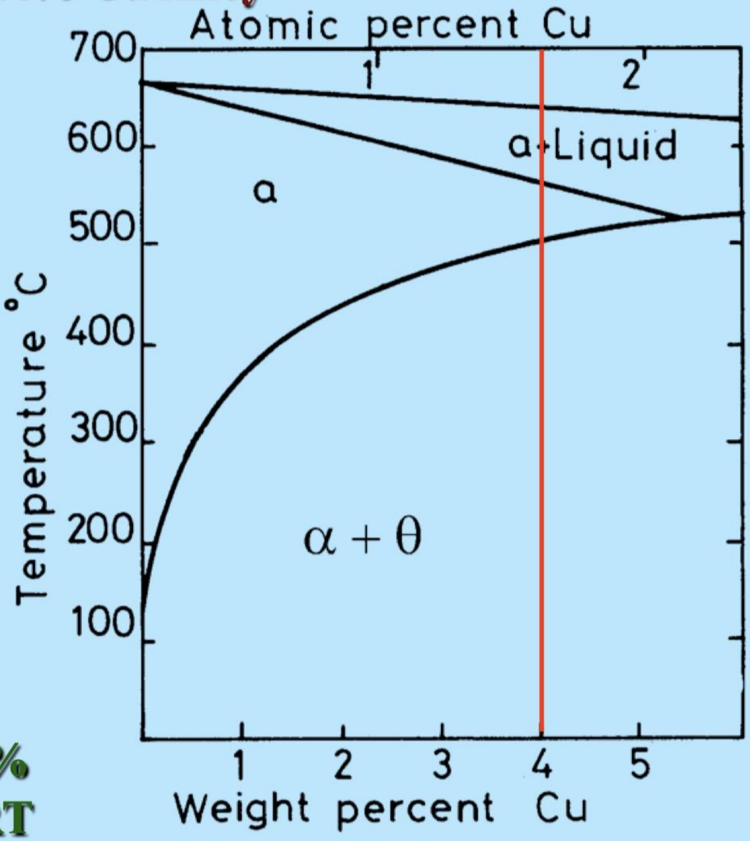
Artificial Ageing: Hold at some T>RT but less than the solvus temperature

- **Supersaturated microstructure is unstable and decomposes (e.g., precipitates) as a new phase**
- **Precipitates initially nucleate at defects, and often nucleate with coherent interfaces (low γ)**

Example

Al – 4 wt% Cu Alloy

1. Solution treatment
   - 500-548°C
   - Solid solution in α
2. Quench to RT
   - Supersaturated solid solution α



Has 4wt% Cu in solid solution whereas phase diagram predicts ~0 wt% Cu in solid solution at RT

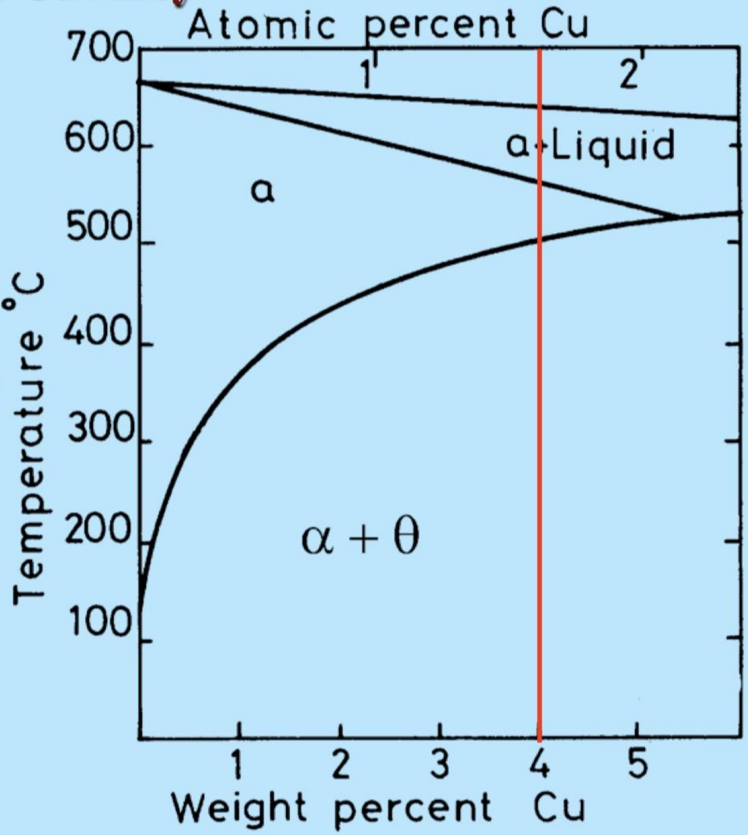
Example

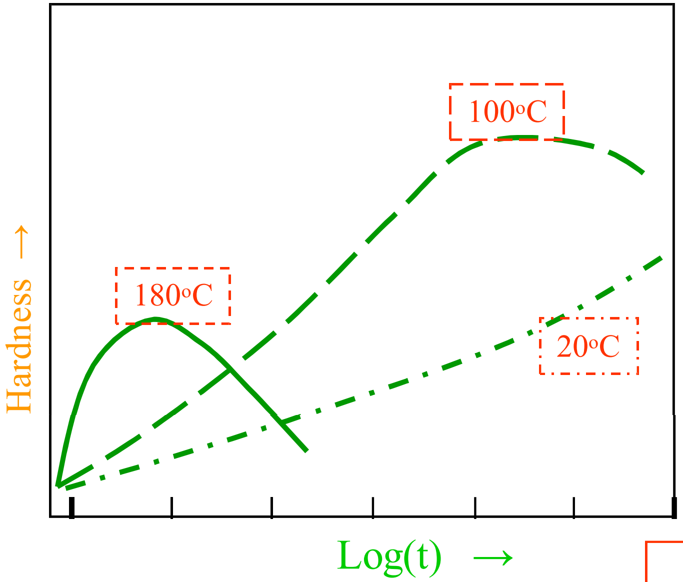
Al – 4 wt% Cu Alloy

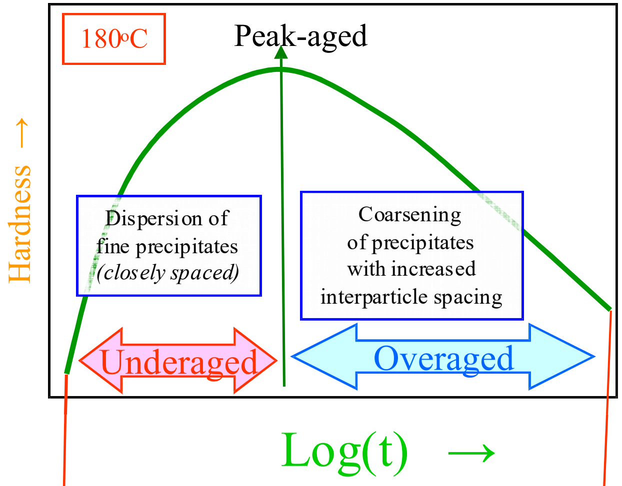
3. Age

- **Hold at some temperature between RT and 500°C (below solvus)**
- **After a long enough time, precipitation of equilibrium θ phase**

This in not quite the complete story however







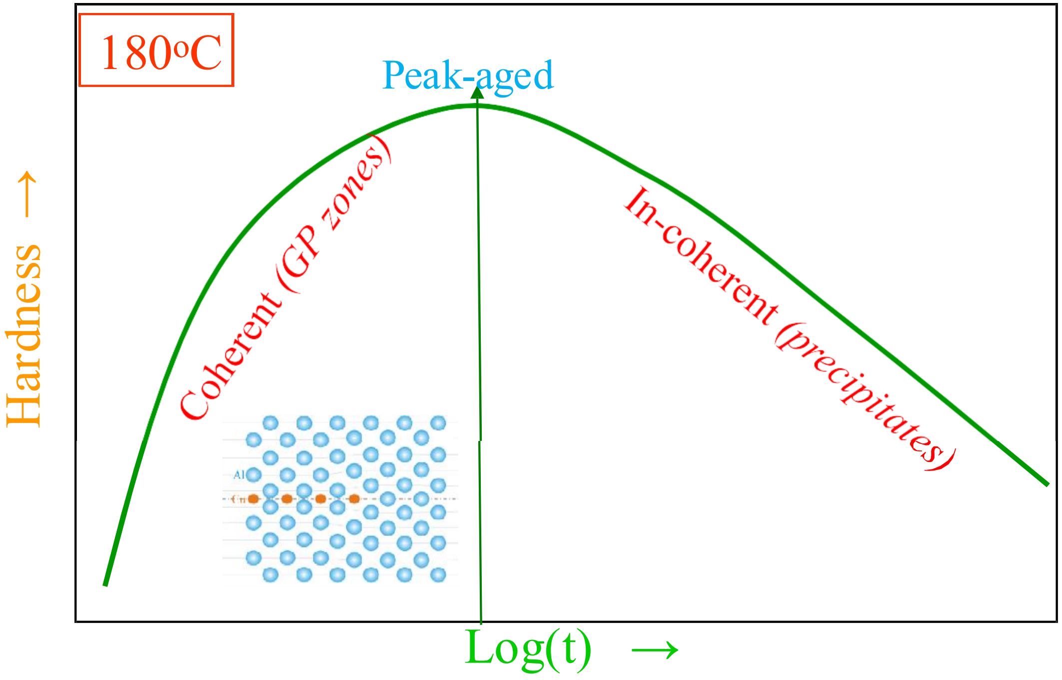
Region of solid solution strengthening *(no precipitation hardening)*

Region of precipitation hardening *(but little/some solid solution strengthening)*

- ❑ Higher temperature ⇒ less time of aging to obtain peak hardness
- ❑ Lower temperature ⇒ increased peak hardness

⇒ optimization between time and hardness required

A complex set of events are happening parallely/sequentially during the aging process → These are shown schematically in the figure ⇒



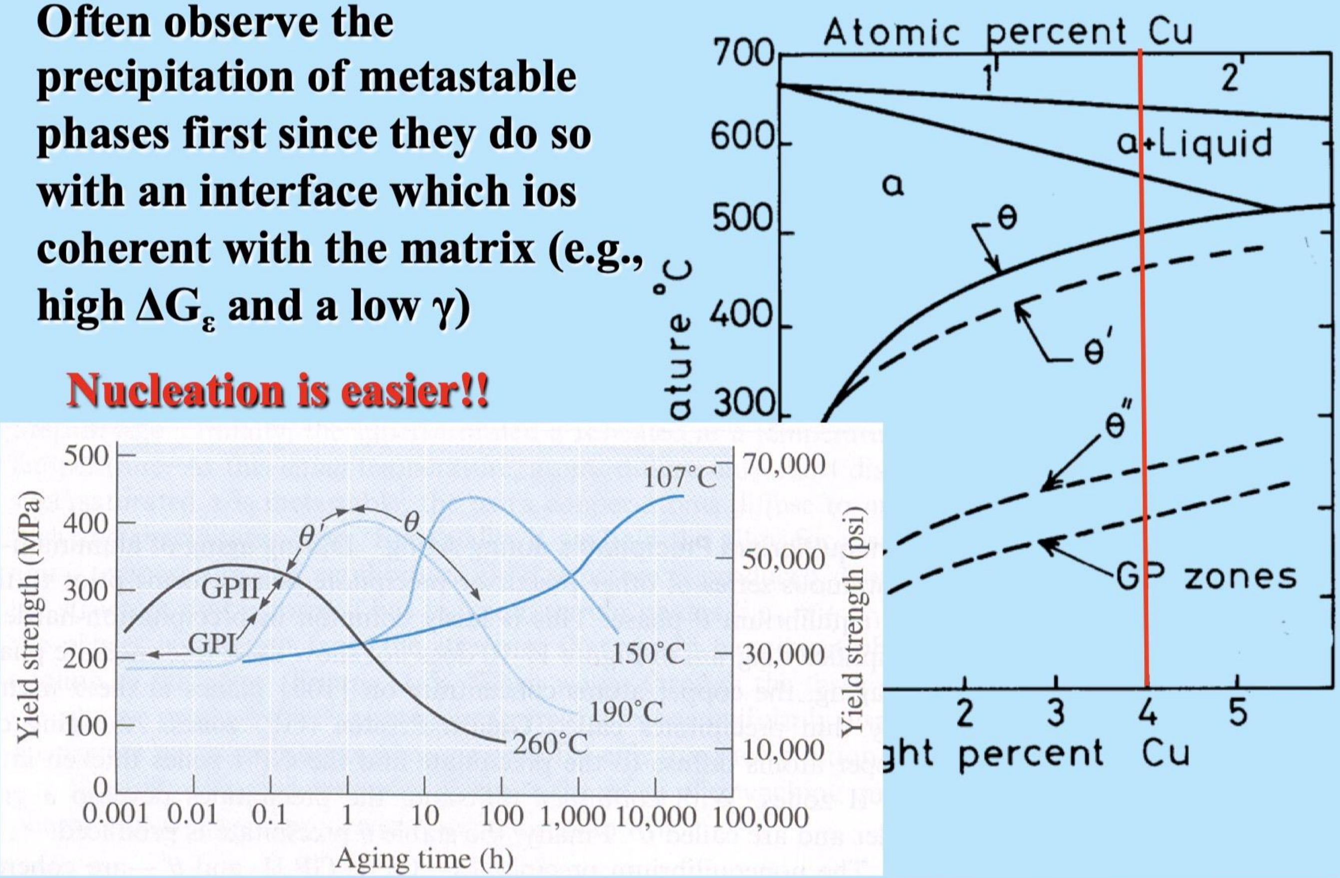
Increasing size of precipitates with increasing interparticle (inter-precipitate) spacing

Interface goes from coherent to semi-coherent to incoherent

Precipitate goes from GP zone → θ'' → θ' → θ

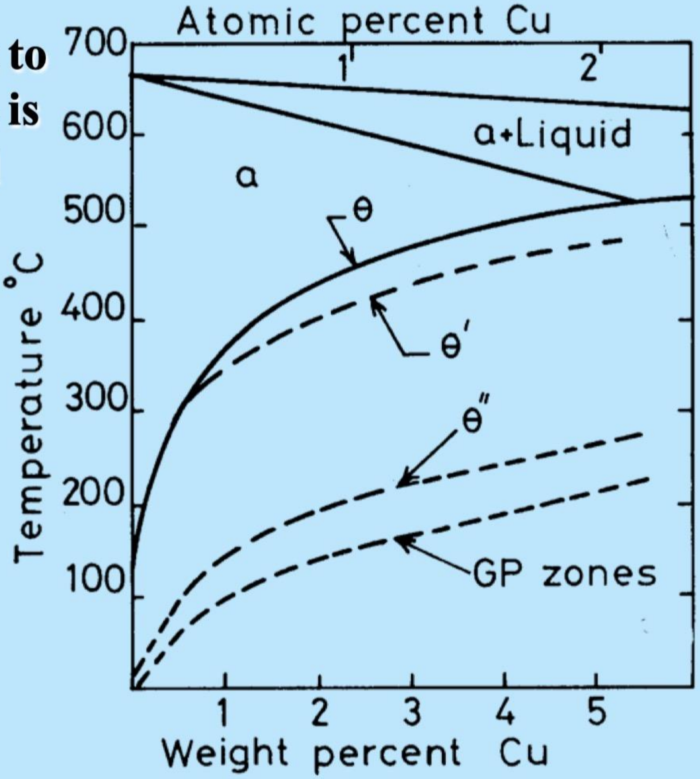
Often observe the precipitation of metastable phases first since they do so with an interface which ios coherent with the matrix (e.g., high ΔG_ε and a low γ)

Nucleation is easier!!



Equilibrium phase is the last to precipitate since its interface is incoherent (e.g., low ΔG_ε and high γ)

→ Nucleation is difficult



Often observe a precipitation sequence where metastable (non-equilibrium) phases (e.g., GP zones → θ” → θ’) form first followed by the equilibrium phase (θ)

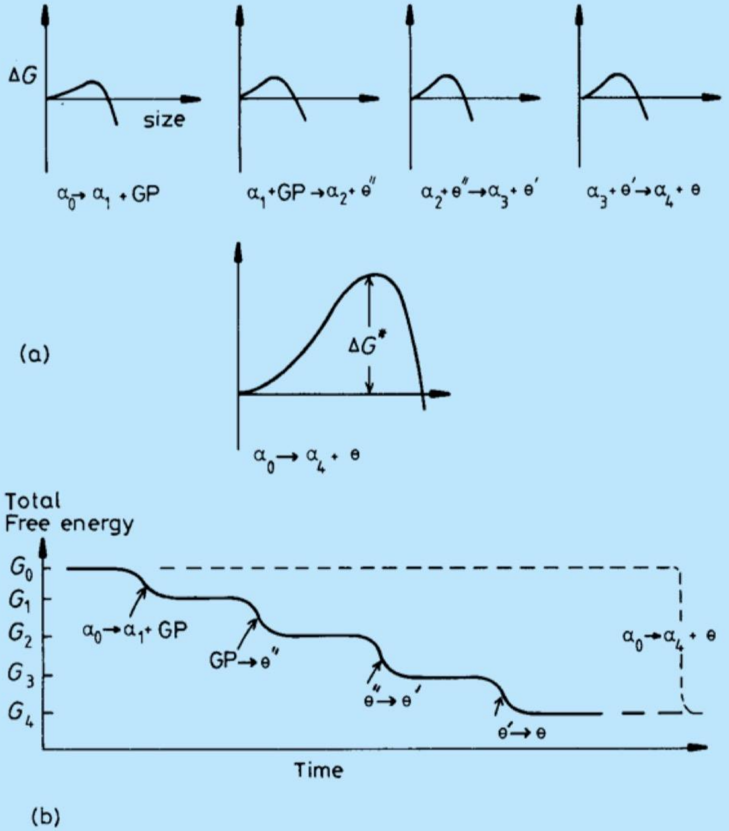


Fig. 5.28 (a) The activation energy barrier to the formation of each transition phase is very small in comparison to the barrier against the direct precipitation of the equilibrium phase. (b) Schematic diagram showing the total free energy of the alloy v. time.