

**Chapters 9, 11 & 12**

**Phase Transformation, Microstructure &  
(Mechanical) Properties**

**Dr. Zhe Cheng**

# Strengthening of Metals by Impeding Dislocation Motion

## ➤ Strain hardening - Ch 8 Strain hardening

- Entangled dislocations hamper dislocation motion

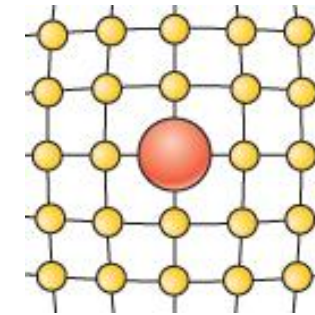
Entangled dislocations



## ➤ Solid solution strengthening - Ch 10 Phase diagram

- Lattice distortion from impurity atoms hampers dislocation motion

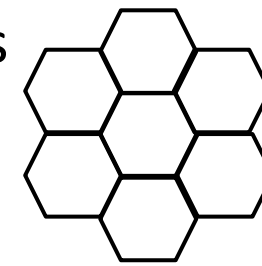
Impurity atom



## ➤ Grain-size strengthening - Ch 9 Solidification

- Grain boundaries (& local distortion) hamper dislocation motion

Grain boundaries

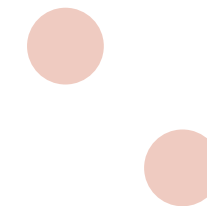


## - Ch 11 & 12 Eutectic transformation & precipitation

### ➤ Secondary-phases or precipitation strengthening

- Hard second phases or precipitates hamper dislocation motion

2nd phases



# Phase Transformation

- **Transformation of phase**, in either structure or composition
  - Also called **phase transition**, or **phase change**
- **Takes time**
  - **Rate & kinetics** matter
- **Types**
  - Short-range, diffusion-dependent, as in solid  $\leftrightarrow$  liquid
    - ✓ Water  $\leftrightarrow$  Ice
    - ✓ Melting/solidification of pure metal
  - Long-range, diffusion-dependent
    - ✓ Solidification of a typical alloy
  - Diffusionless
    - ✓ Extreme fast transformation



<https://www.pinterest.com/pin/265290234275314171/>

# Nucleation & Growth in Phase Transformation

Most phase transformation, not matter which type, involve two parts (or stages):

## Nucleation

Formation of nucleus - very initial part of new phase, often tiny (nanometer) seeds

## Growth

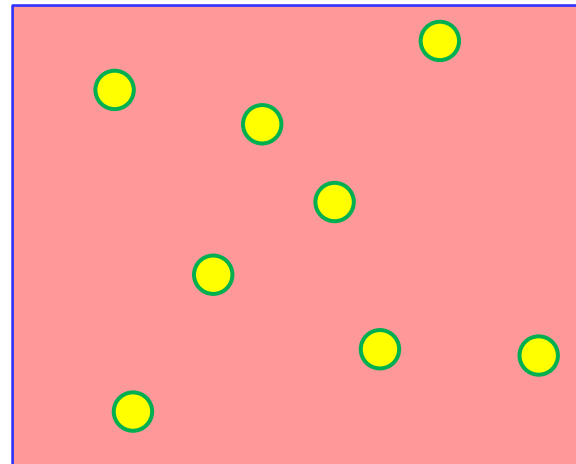
Later part of transformation: continued growth of the formed nucleus

**Initial**



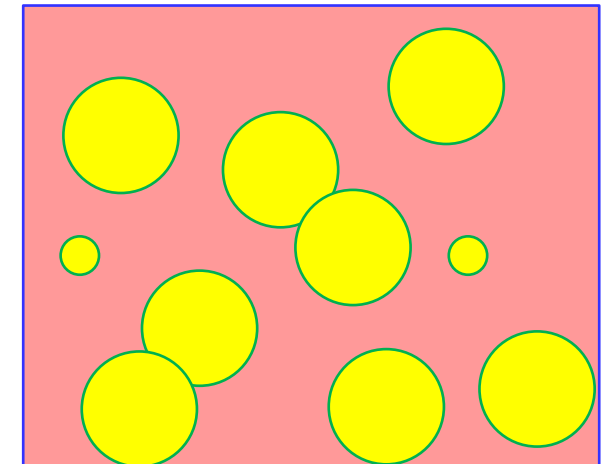
**Nucleation**

of new phase(s)



**Growth**

of new phase(s)



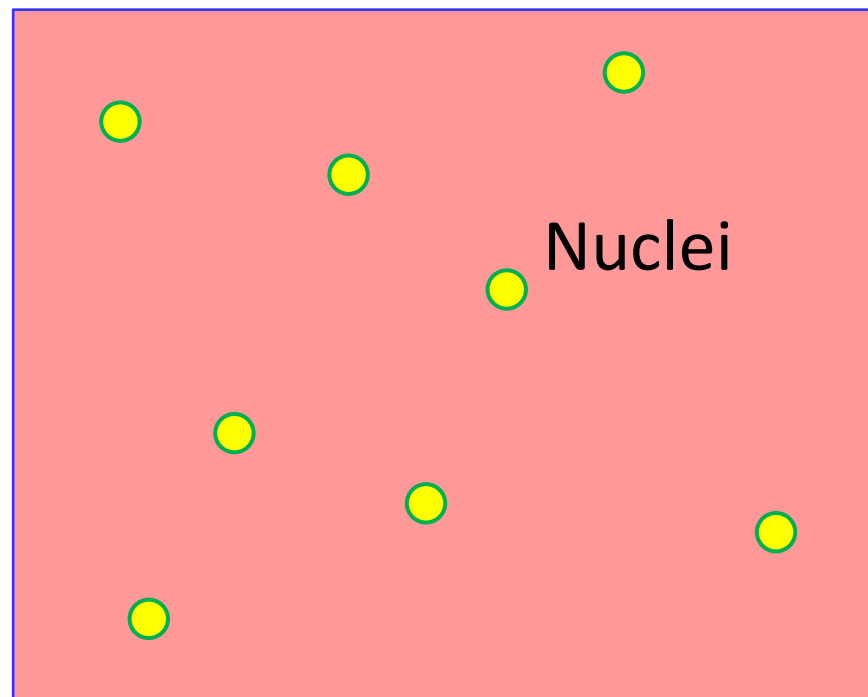
# Nucleation: Homogeneous vs. Heterogeneous

## Nucleation

Formation of nucleus - very initial part of new (phase, often tiny (nm) (crystalline) seeds

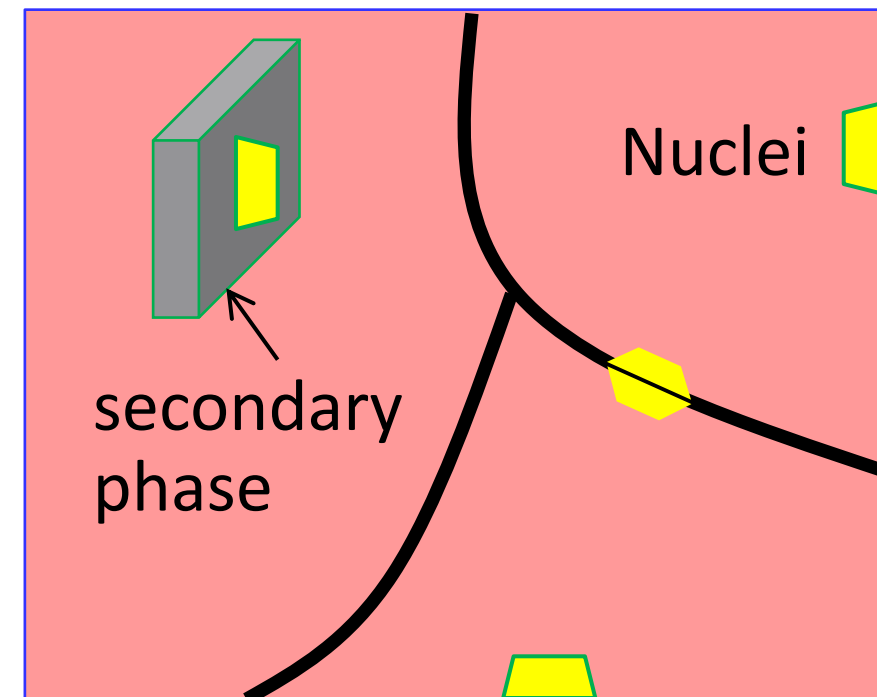
## Location of nucleation

### Homogeneous nucleation



- Every place possible w/ equal probability
- Randomly occurring

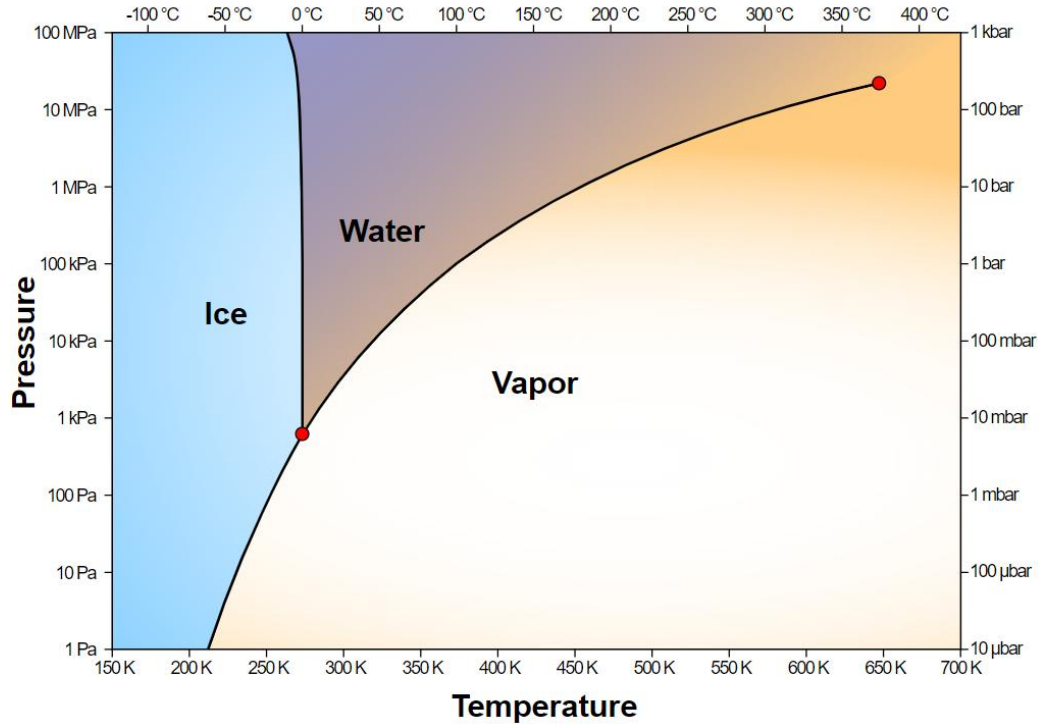
### Heterogeneous nucleation



- Only at specific locations:
  - ✓ Side walls
  - ✓ Interface w/ secondary phases
  - ✓ grain boundaries ...

# Nucleus Phase vs. Host/Matrix Phase

- Different structure, same composition  
Solidification of pure element/compound

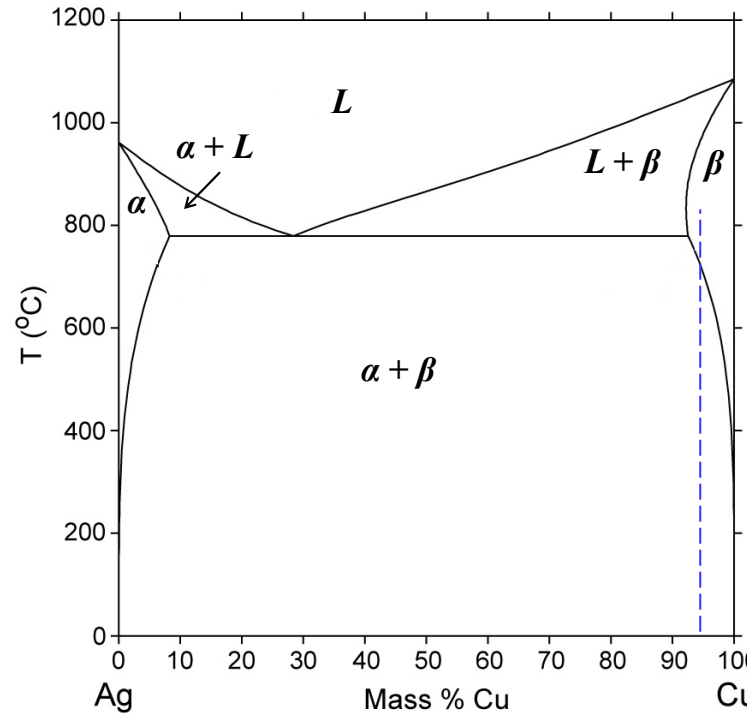


Ice crystals

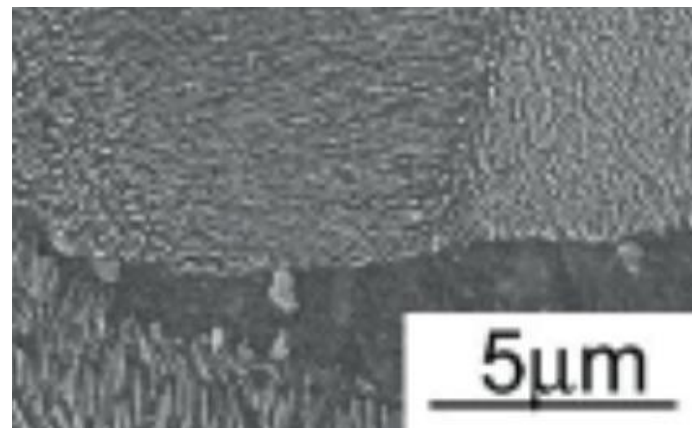
Ice dendrites



- Different composition, same crystal structure  
Ag precipitation from Cu solid solution w/ Ag

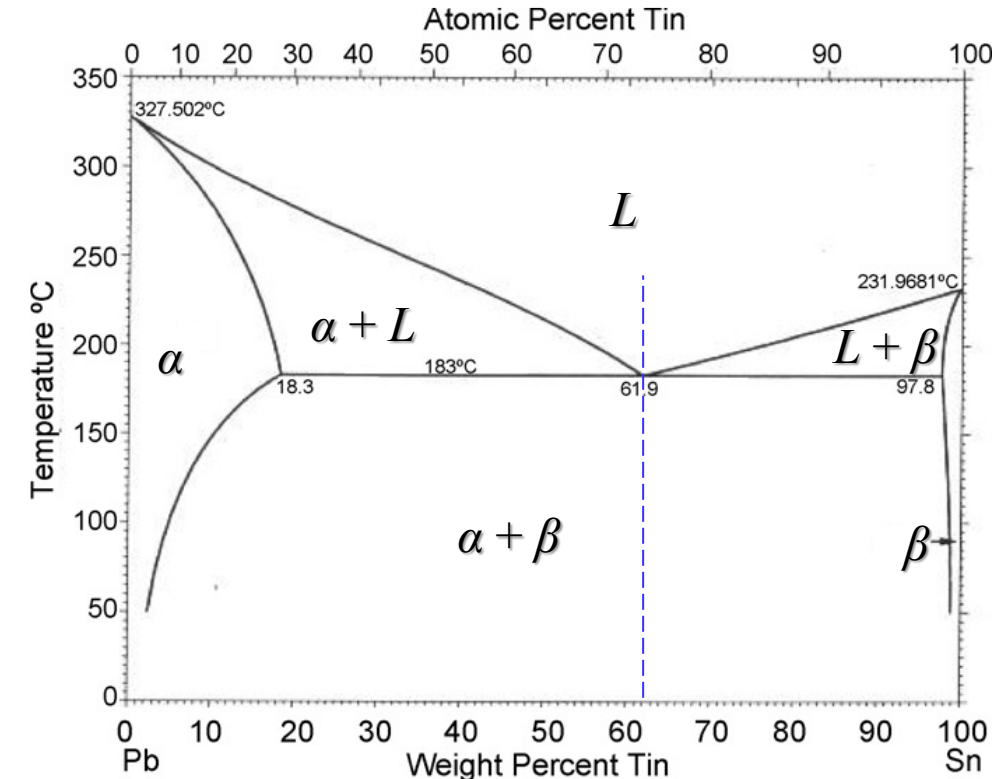


Ag precipitates from 6 wt.% Ag in Cu

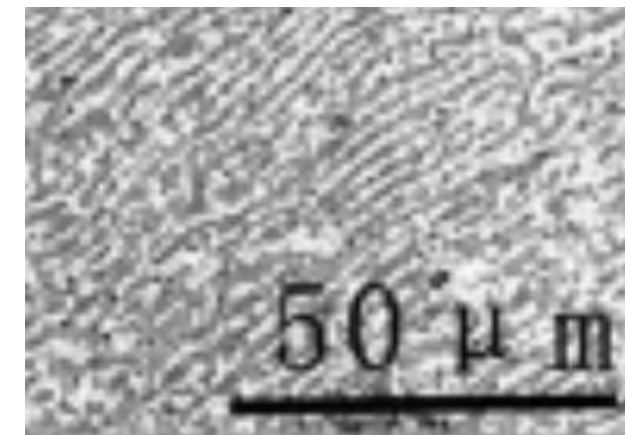


Bao et al,  
Mater Res Lett (2016)  
v4(1), p37

- Different composition, different structure  
Pb/Sn eutectic structure



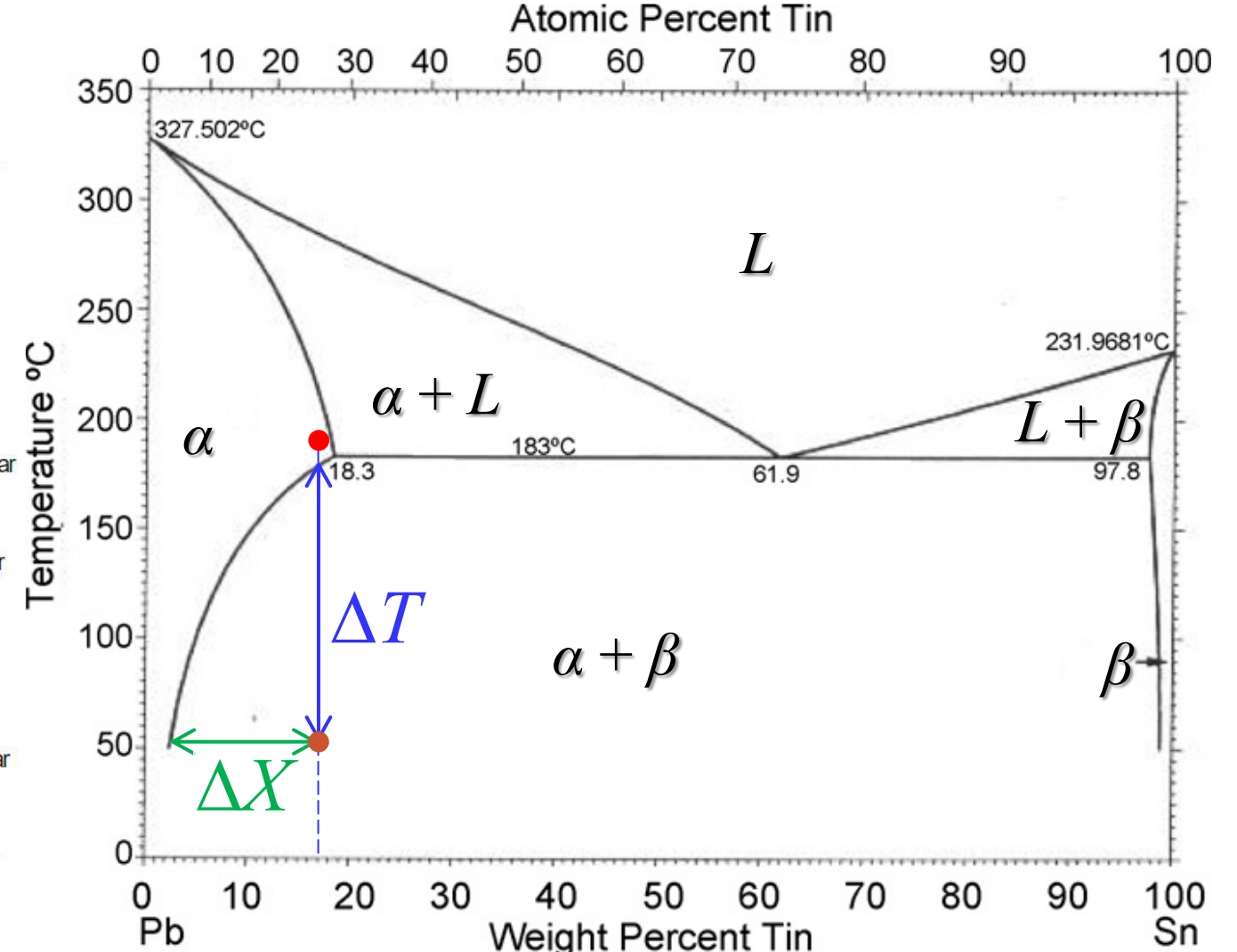
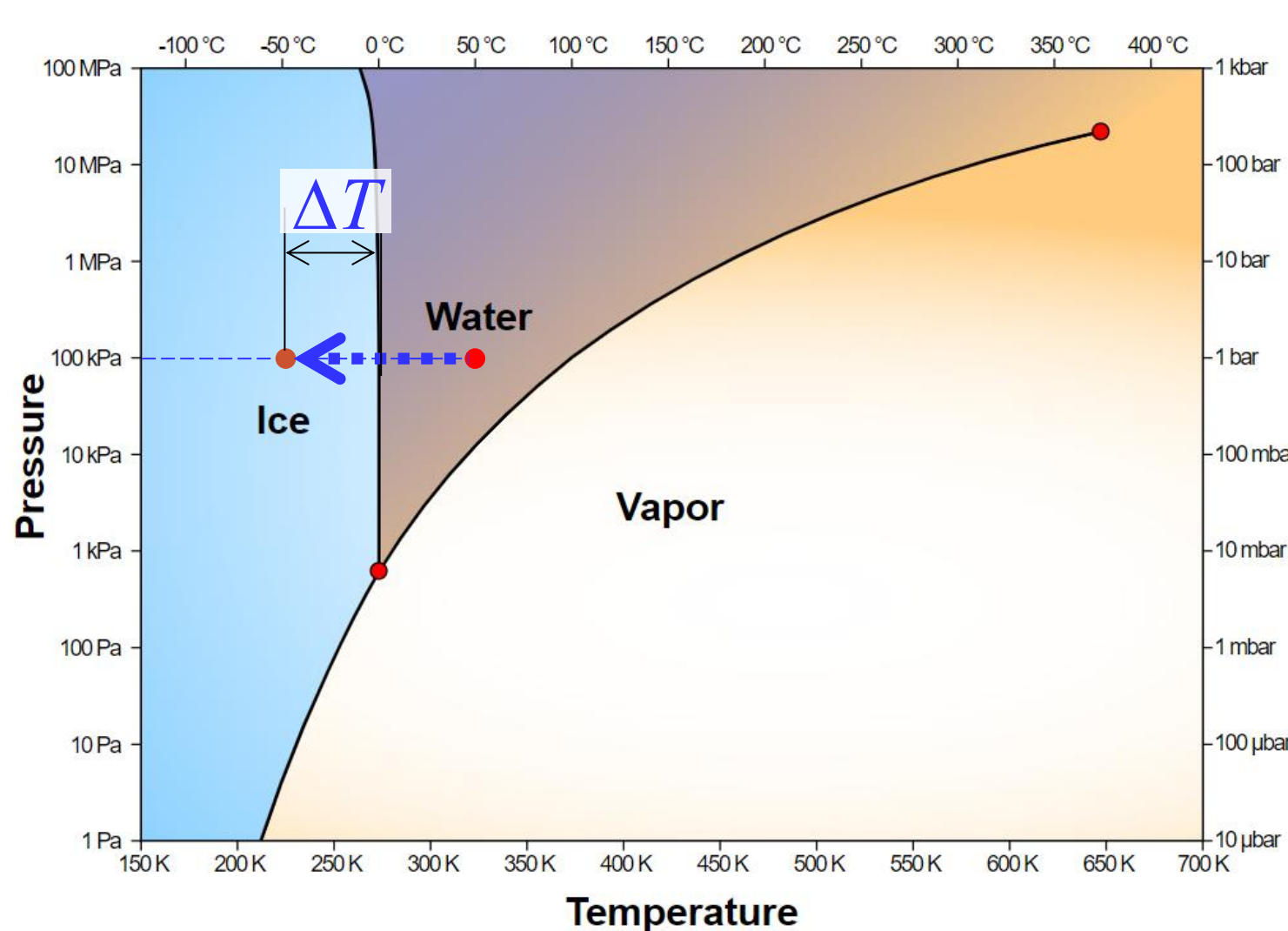
Pb-Sn eutectic structure



Zhang et al,  
J Mater Eng Perform (2019) v28,  
p3714

# Nucleation Rate

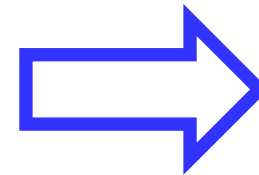
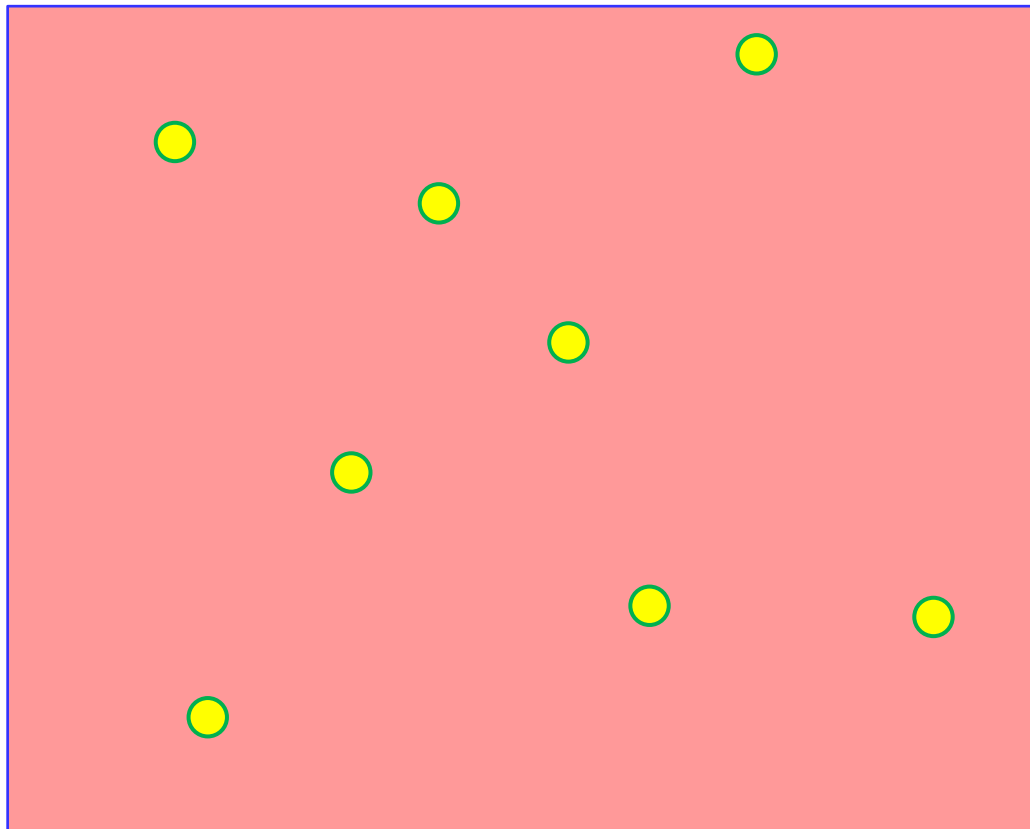
- Temperature, especially **under-cooling**  $\Delta T$ : Larger  $\Delta T \rightarrow$  faster nucleation (but NOT too large due to slower diffusion)
- **Over-saturation** (often related to  $\Delta T$ )  $\Delta X$ : Larger  $\Delta X \rightarrow$  faster nucleation
- **Special sites density** (for heterogeneous nucleation): container wall, free surface, grain boundary, secondary phase(s): More sites  $\rightarrow$  faster nucleation



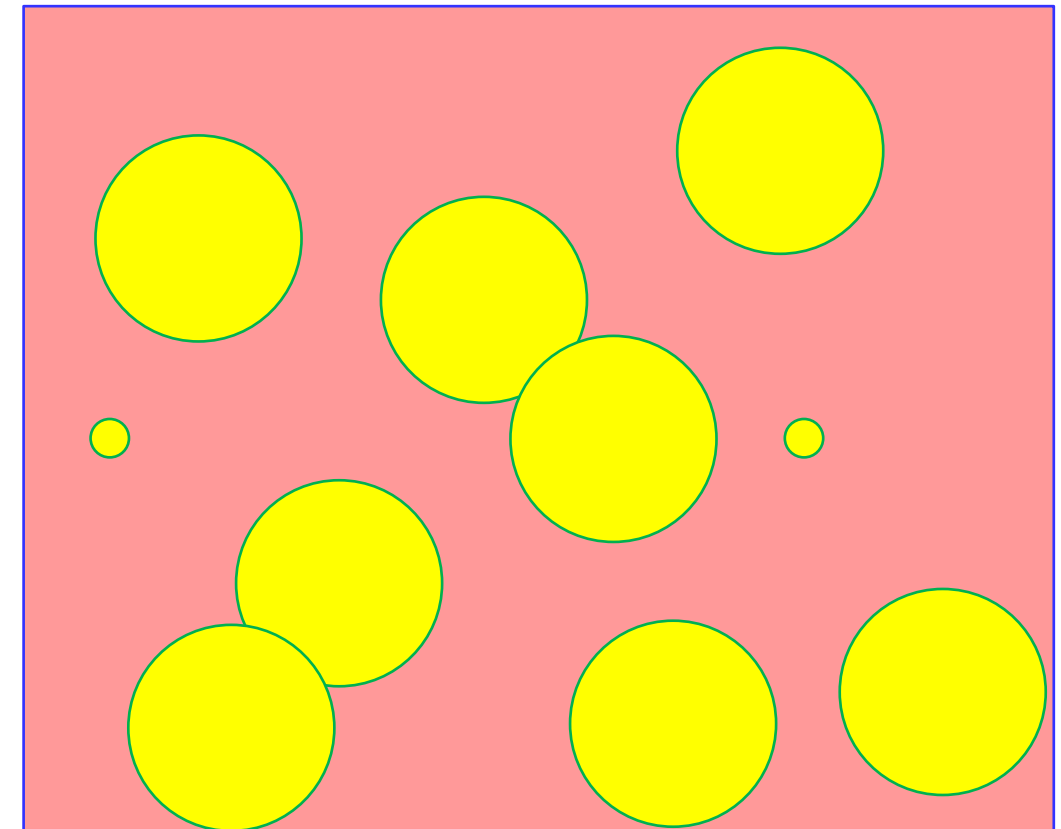
# Growth (of Nucleus)

- In phase transformation, newly formed nuclei (or small crystal “seeds”) will grow over time to achieve the transformation from the original phase(s) to the final one(s)
- During growth of existing nuclei, new nuclei may continue to be formed

**Nucleation**  
of new phase(s)



**Growth**  
of new phase(s)



# Ch09 Solidification

# Nucleation & Growth in Solidification

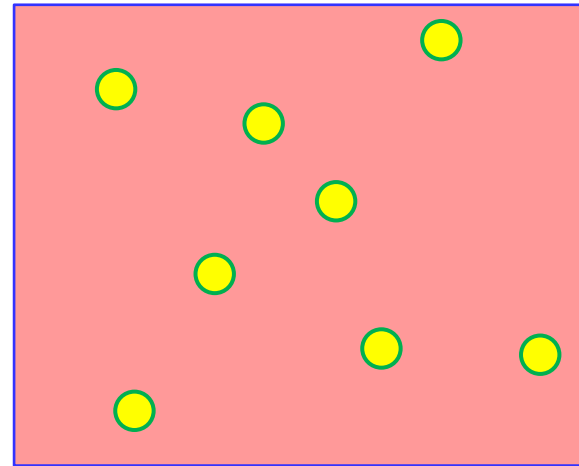
## Solidification

- Phase transformation from liquid to solid - simplest & best understood

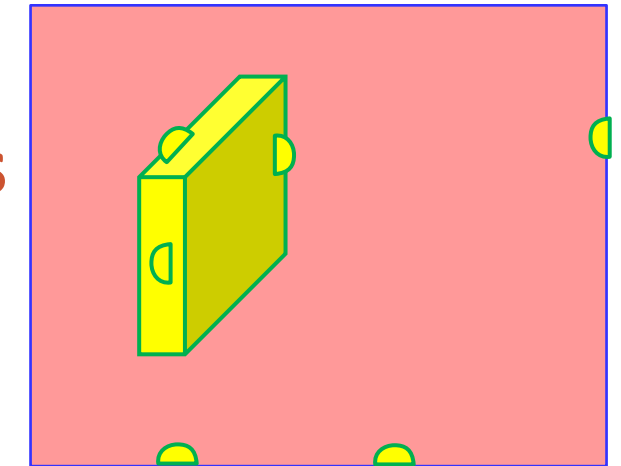
## Nucleation in solidification

- Spherical nuclei

**Homogenous nucleation**

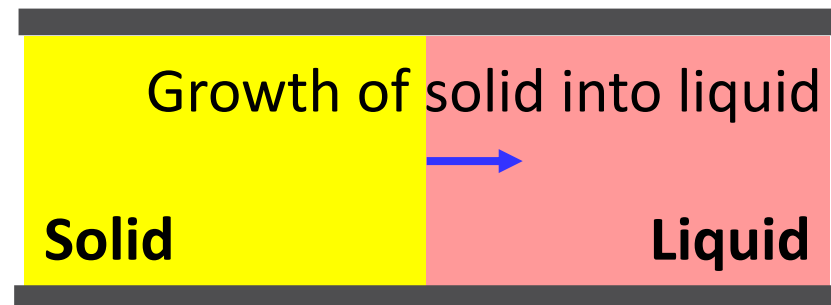


**Heterogeneous nucleation**

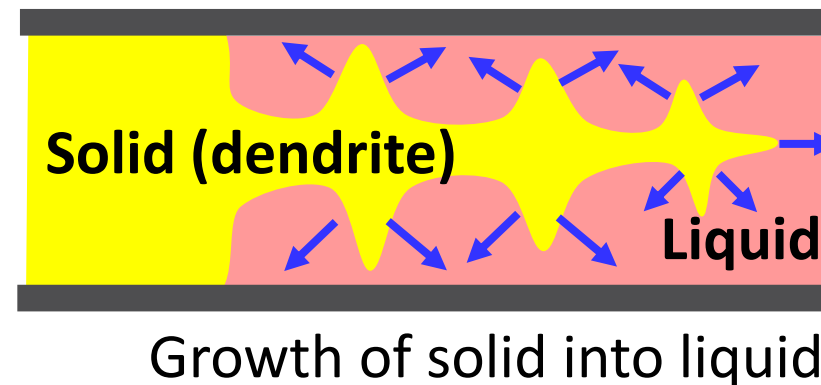


## Growth of nuclei/crystal during solidification

**Planar Growth**



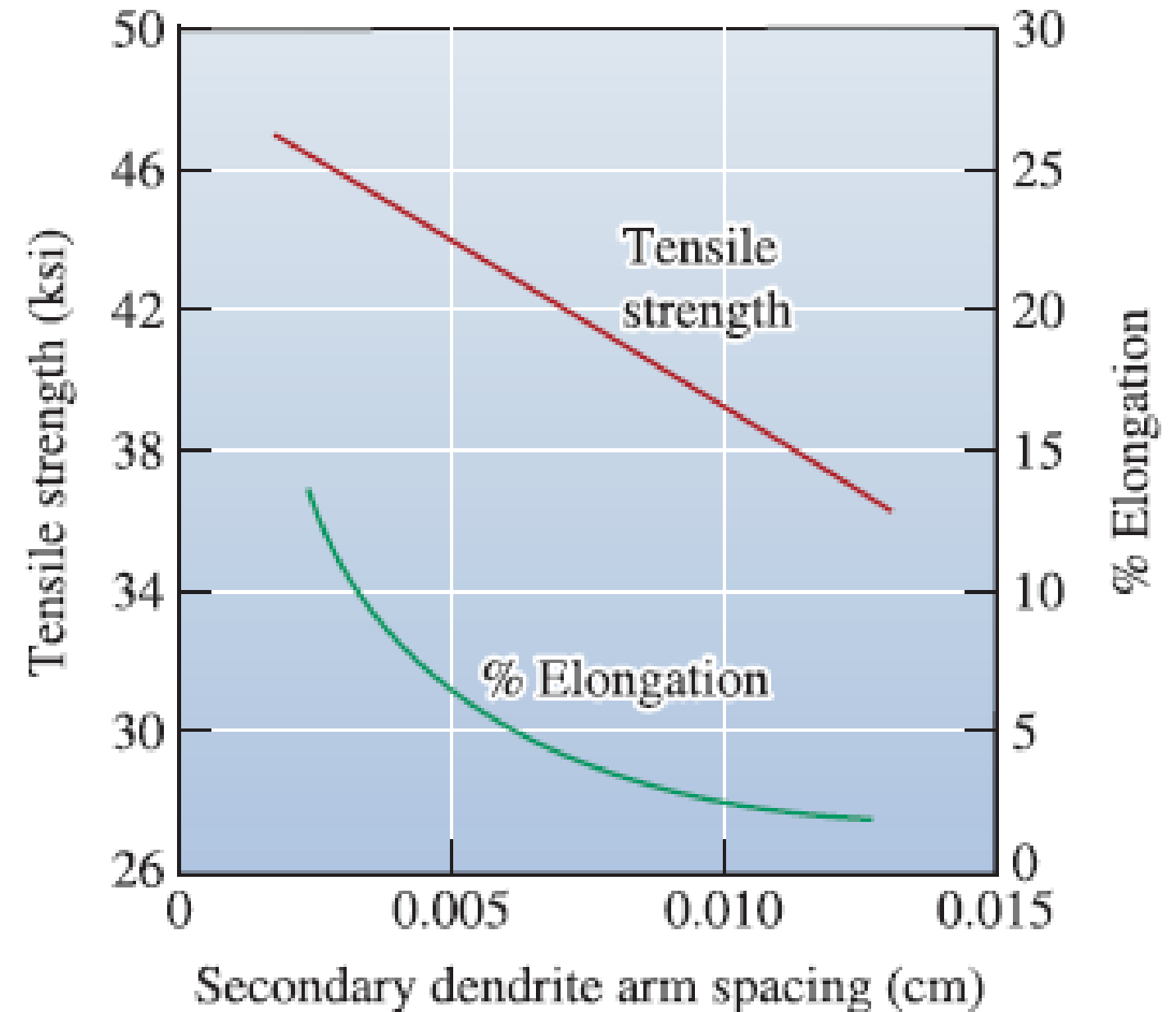
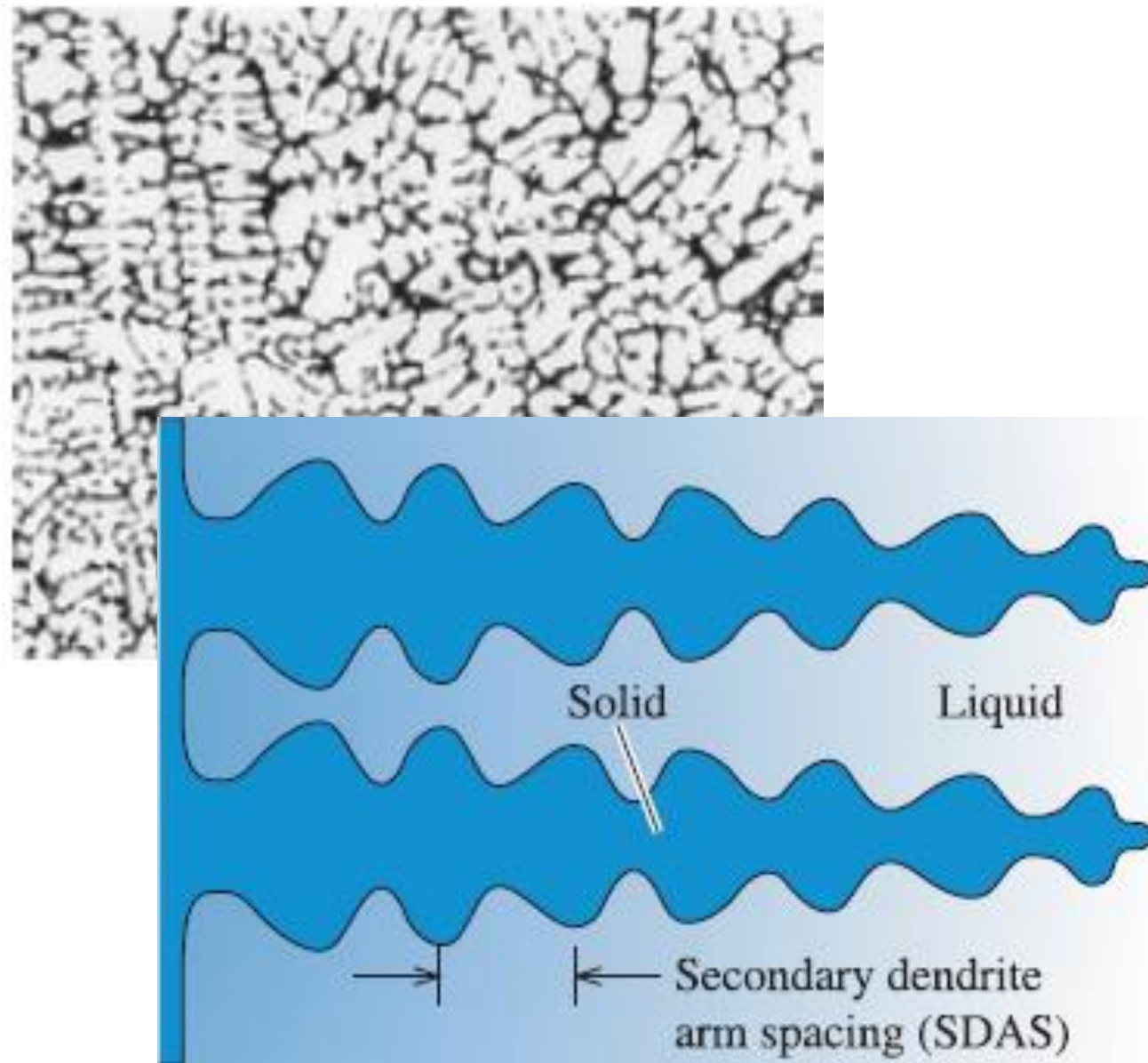
**Non-planar/Dendritic Growth**



Dendritic/Tree-like silver

# Dendritic Structure on Mechanical Properties

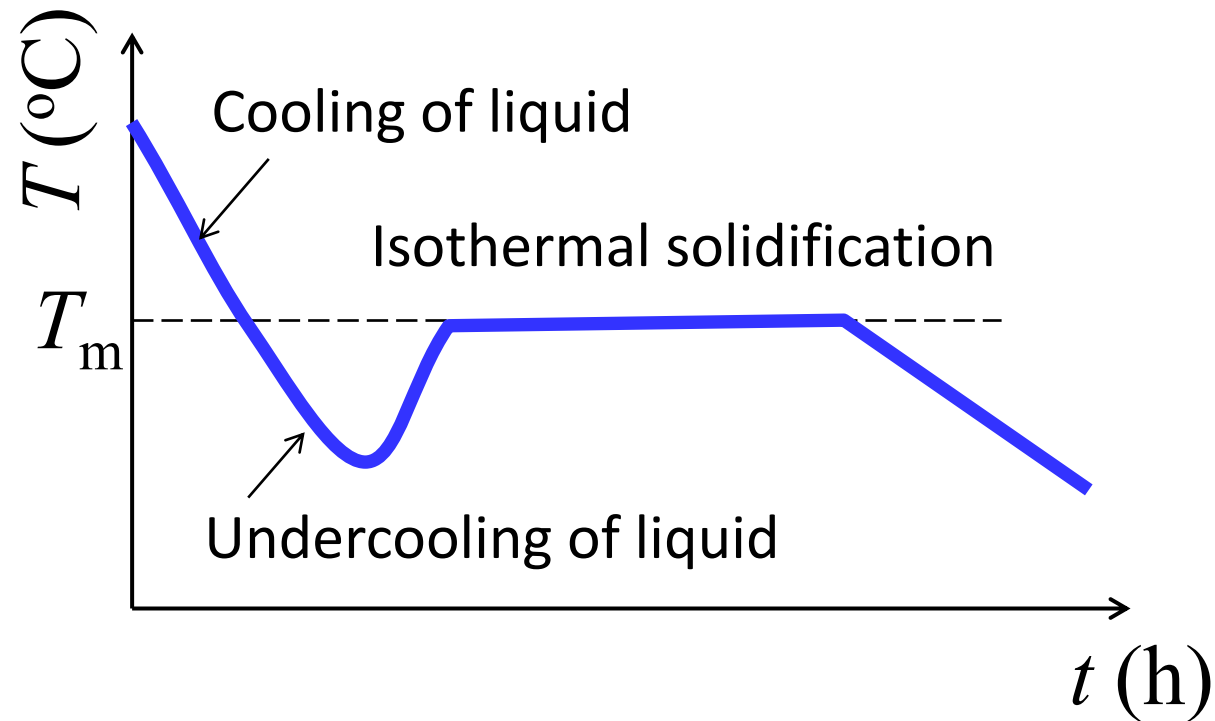
- Large solidification dendritic structure detrimental to metal's mechanical properties



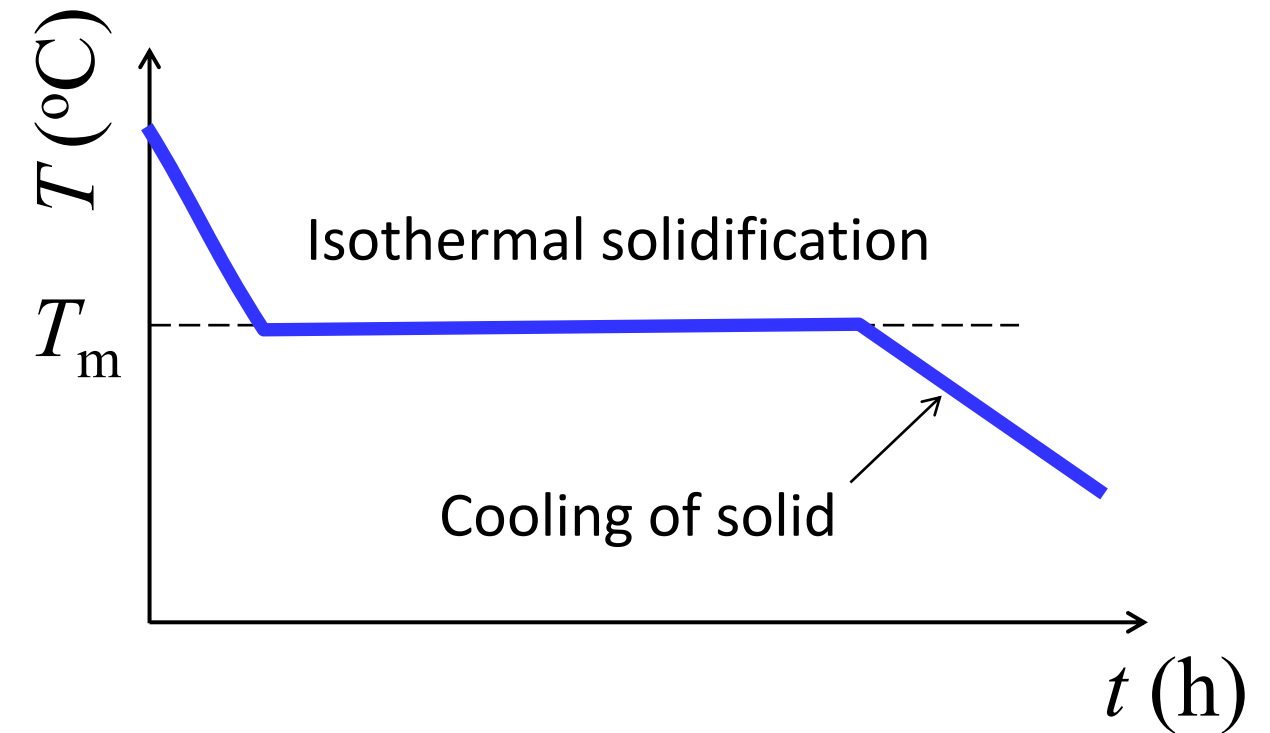
- Dendrites form due to **large undercooling** – liquid cooling to well below melting point
- Inhibit dendrite formation by proper “seeding” to promote nucleation

# Cooling Curves for Solidification (Pure Metal or Ceramics)

Cooling curve for “**not well-seeded**” **pure metal** showing undercooling



Cooling curve for “**well-seeded**” **pure metal** showing **NO** undercooling

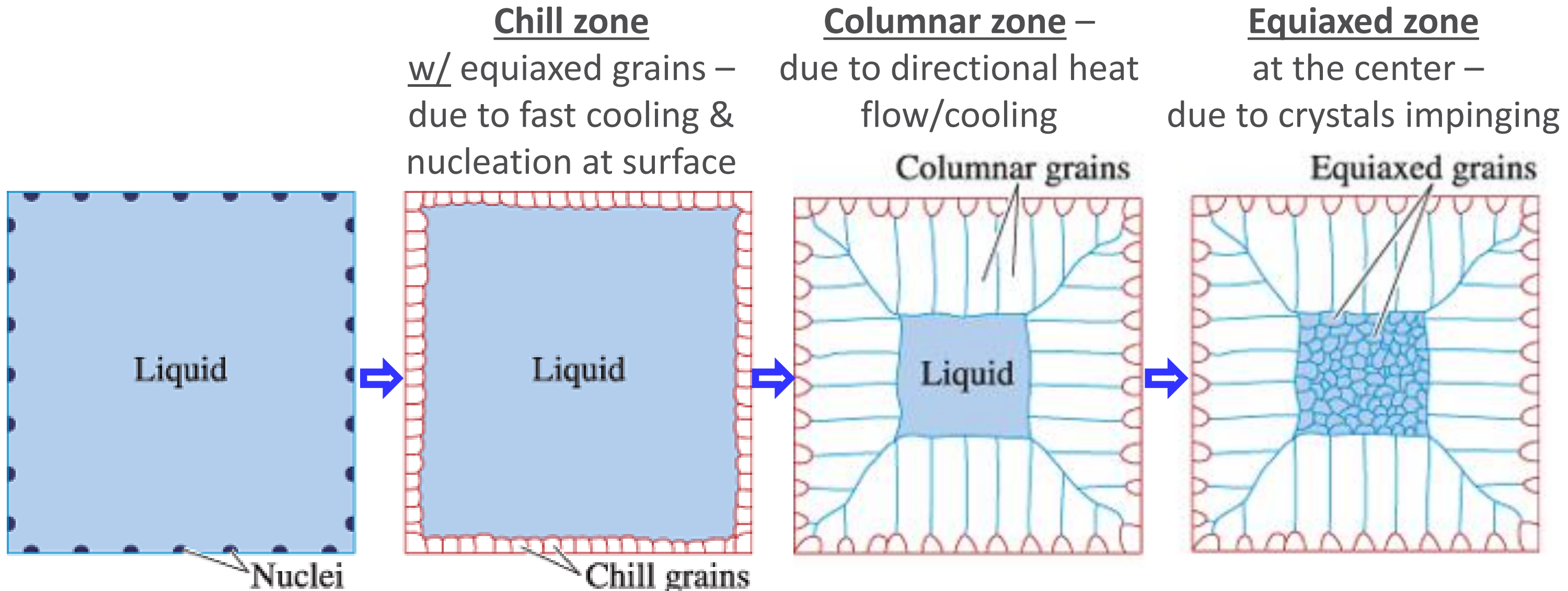


# Structural Features Formed in Casting/Solidification

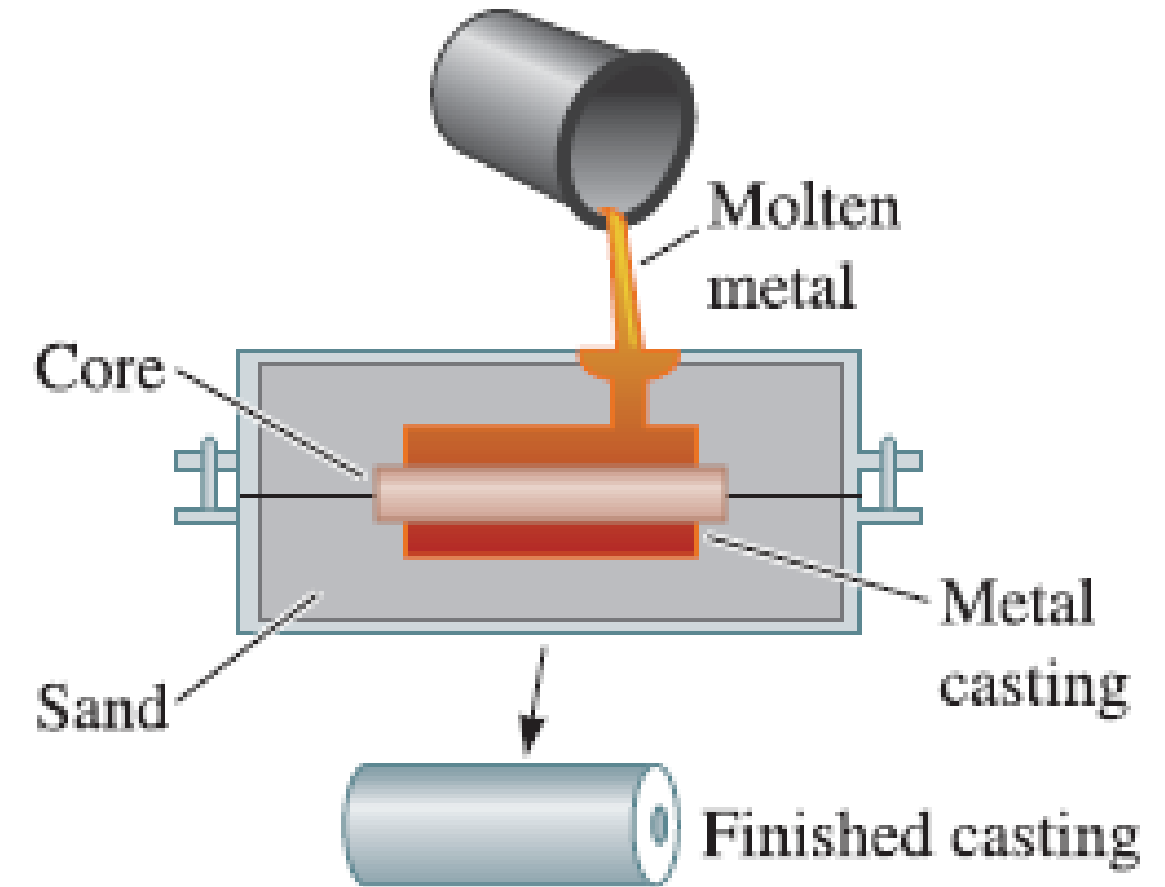
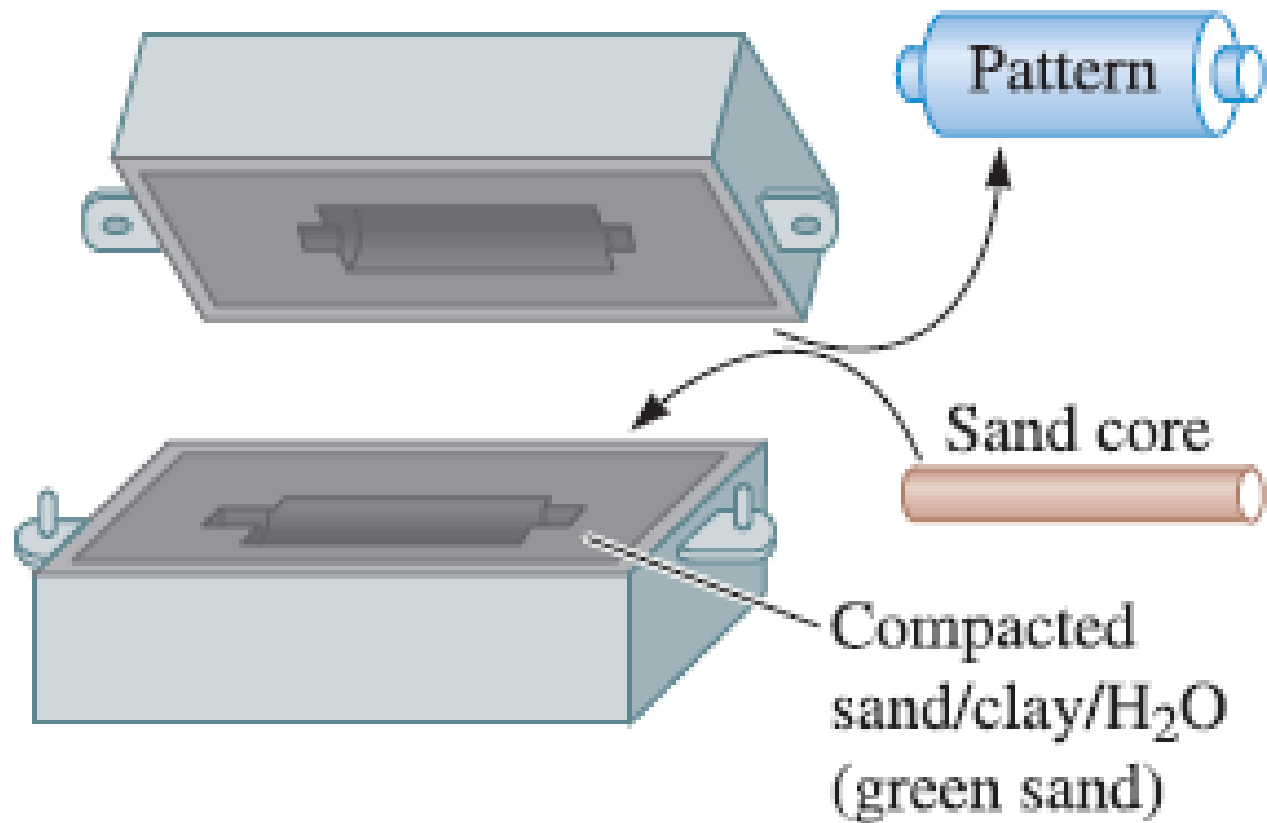
## ➤ Casting:

Forming structure through solidification of liquid metal, typically metals.

## ➤ Three zones in typical cast structure:

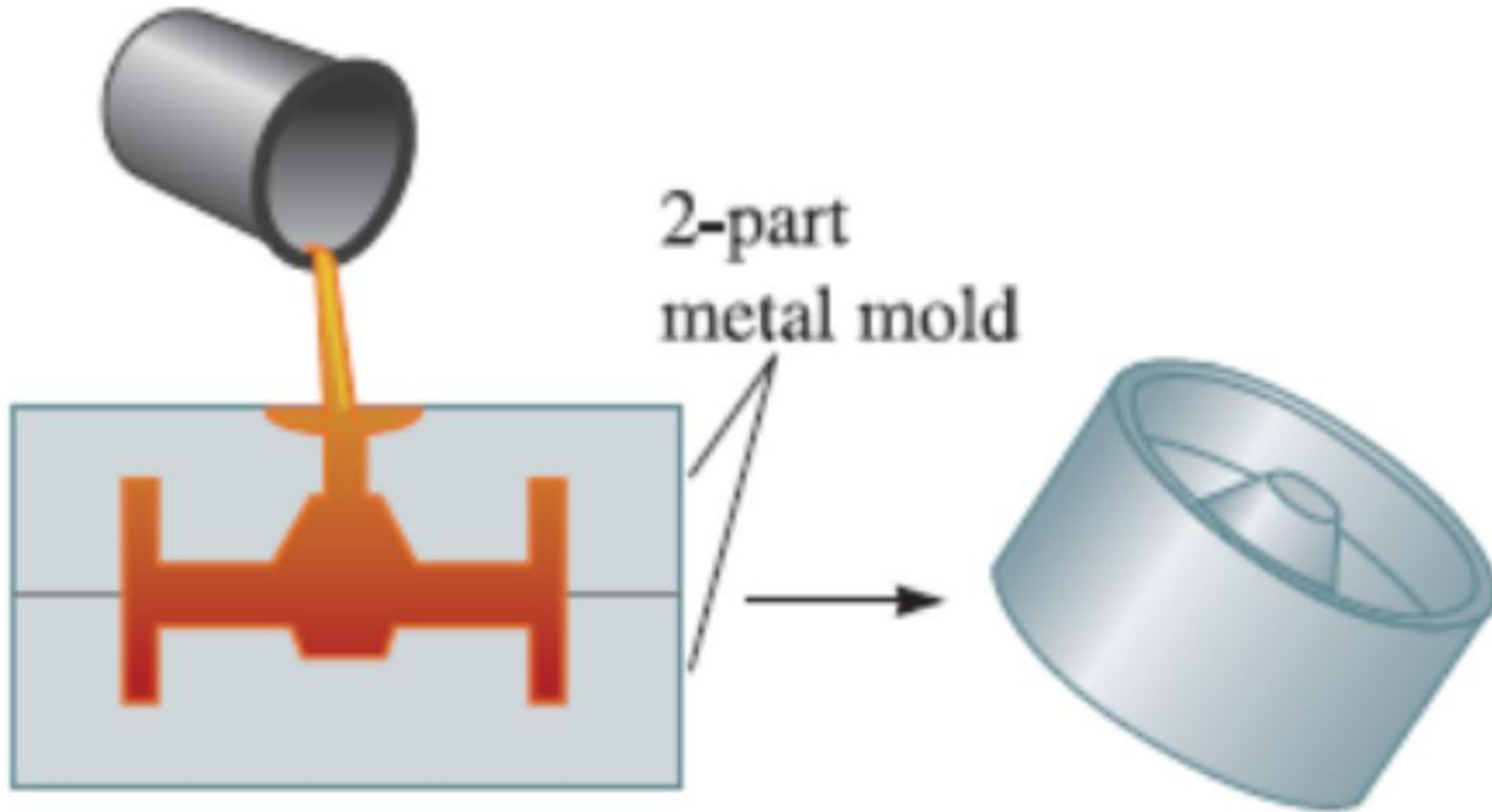


# Casting Techniques (1) – Sand Molding



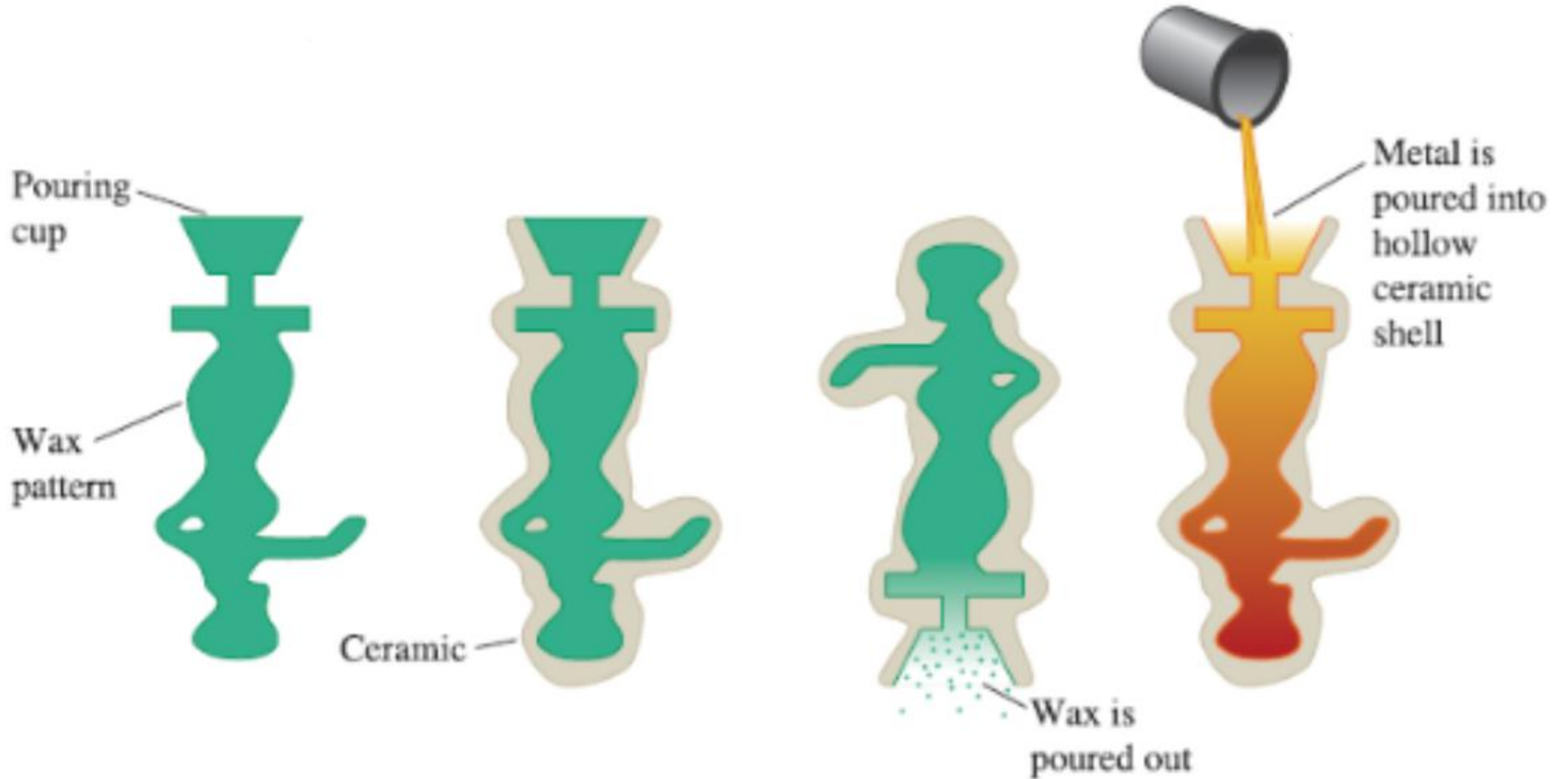
Casting liquid metal into sand mold

# Casting Techniques (2) – (Permanent) Die Casting



Casting liquid metal into permanent (often metal) mold

# Casting Techniques (3) – Investment Casting



Wax pattern → Ceramic "shell" → Cast parts

# Examples of Casting Defects

## Cracks



From fast, uneven shrinkage

## Porosity/Holes

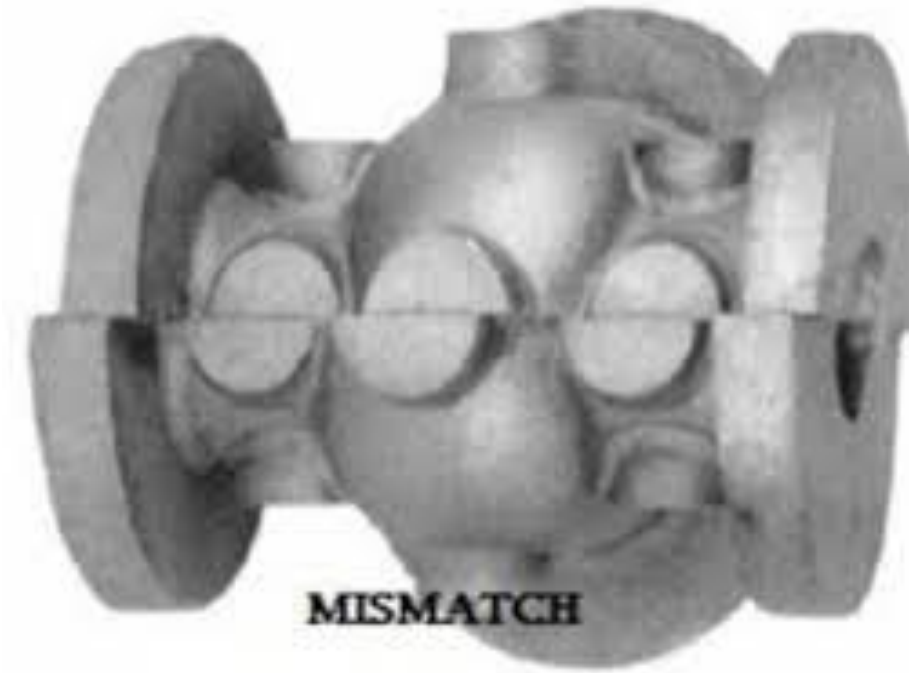


From uncompensated shrinkage or gas release



From incomplete filling of mold

**Misrun (missing)**



From improper alignment of mold parts

**Shifts/Mismatch**

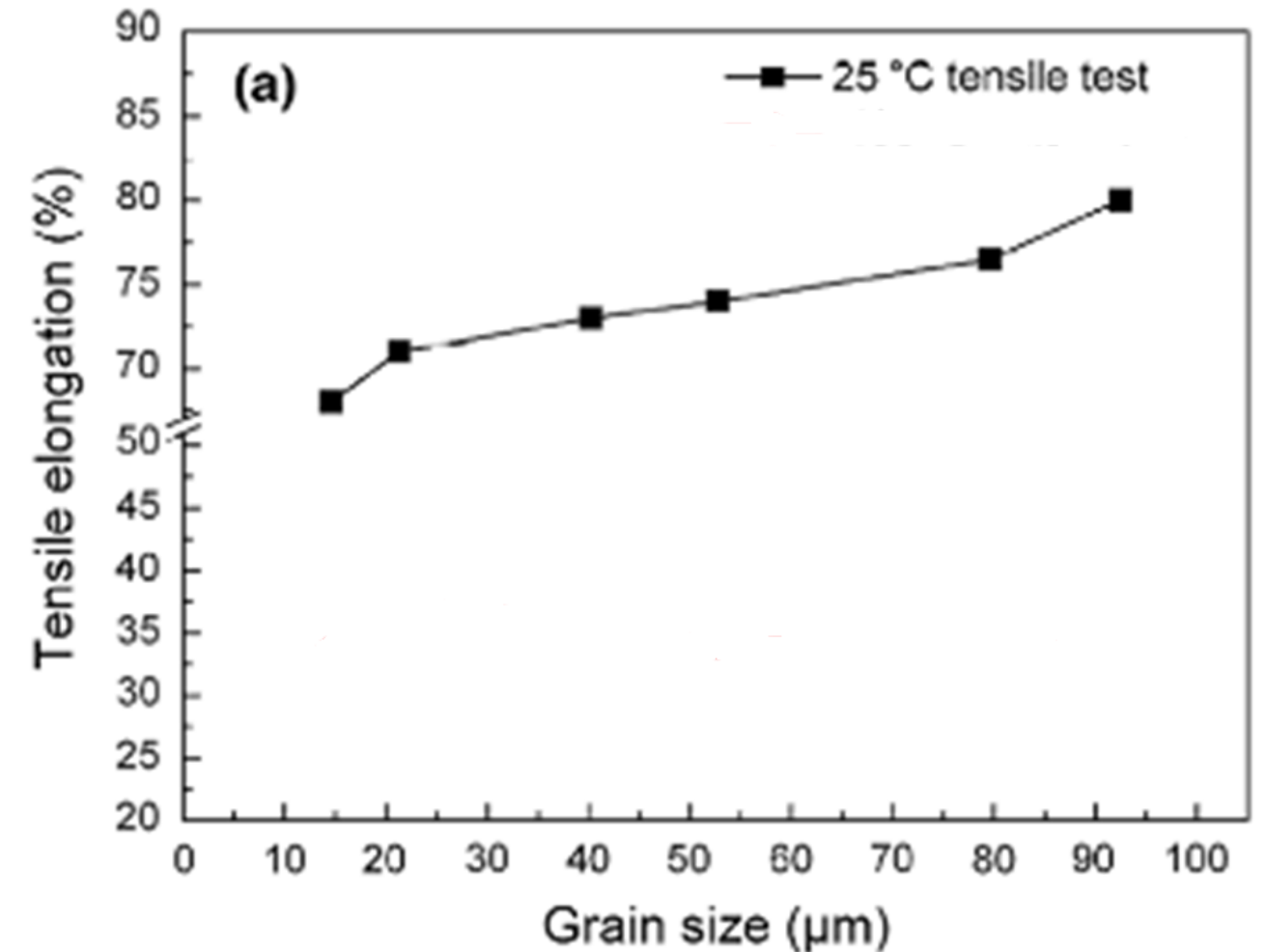
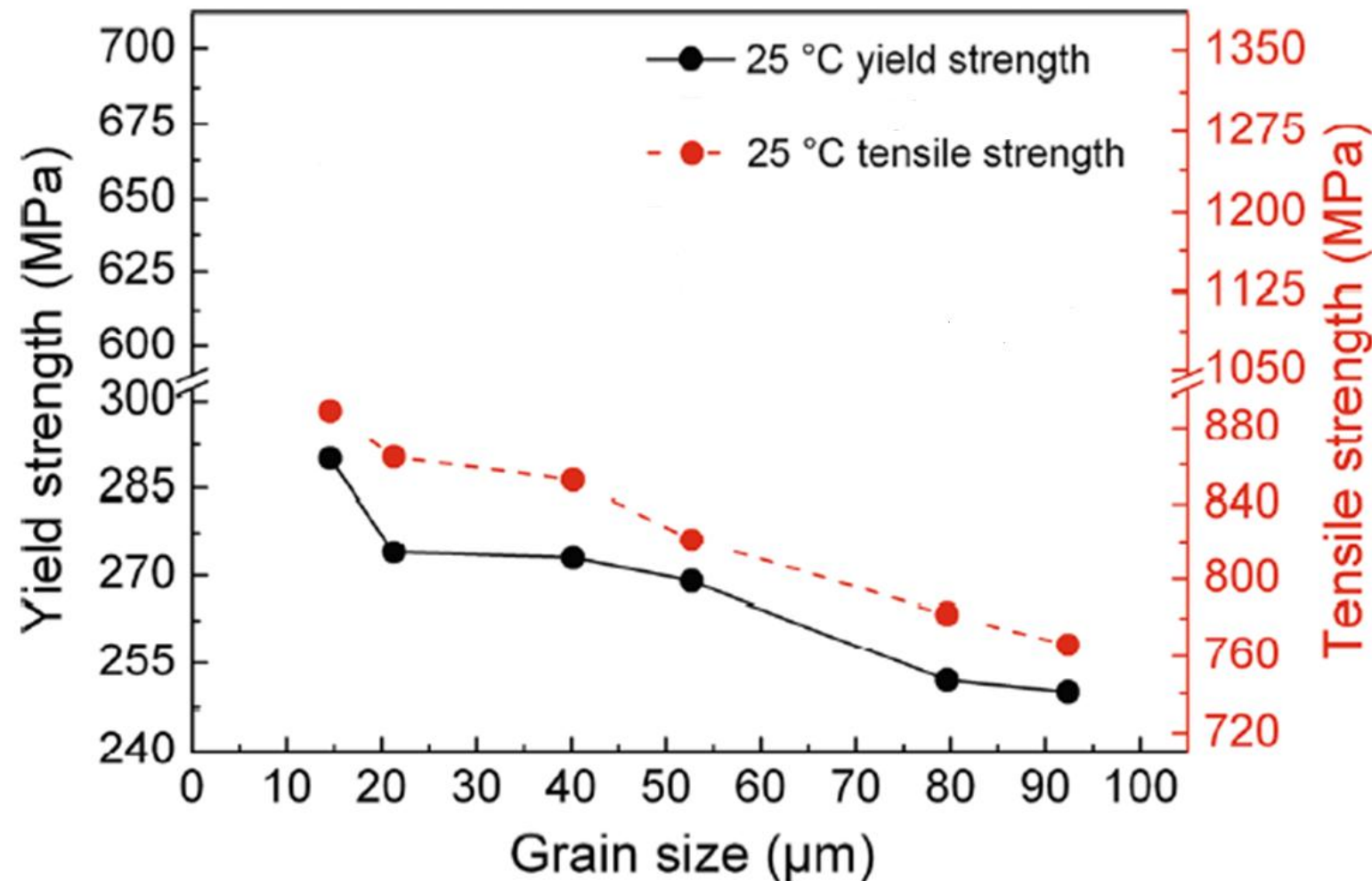
# Increasing Strength w/ Decreasing Grain Size for Metals

➤ Yield & tensile strength increase with decreasing grain size, as grain boundaries hinder dislocation motion. Meanwhile, ductility drops a little, but still adequate

➤ Empirically  $\sigma_y = \sigma_0 + \frac{K}{d^{1/2}}$

## High-Mn Austenitic Steel

[Wang and Pan et al., Acta Metallurgica Sinica, v 32 \(6\), 746-754 \(2019\)](#)

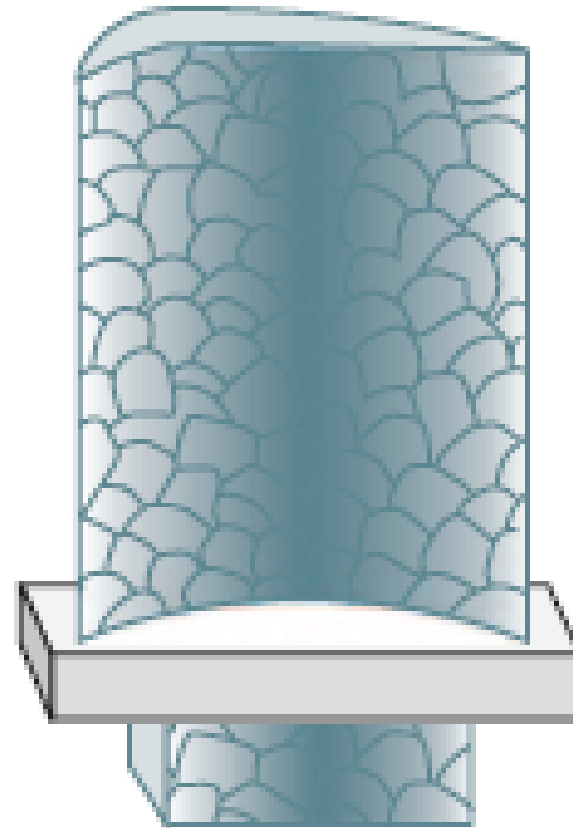


➤ Smaller grains achieved by proper “seeding” or sonication/vibration in solidification 18

# Directional Solidification (DS)

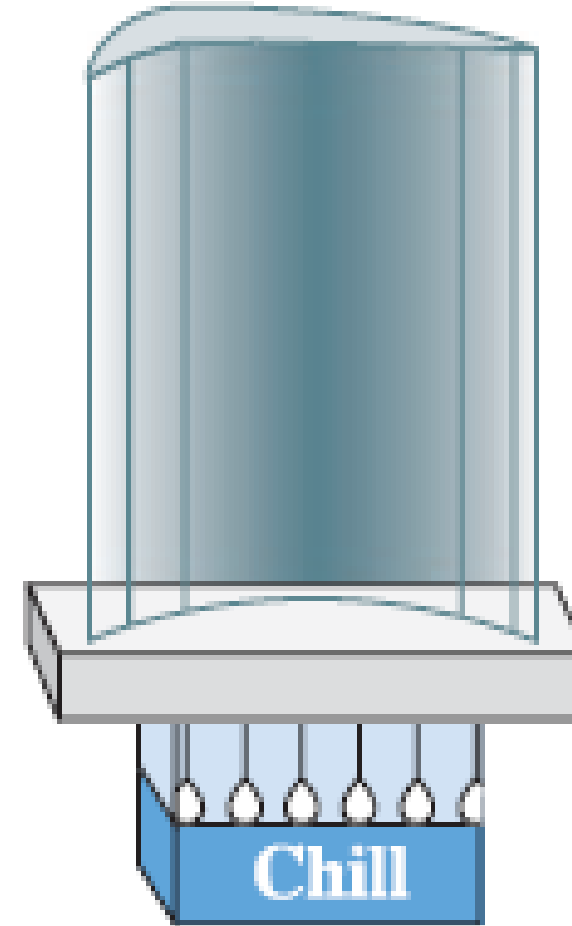
Control heat flow direction and seeding/confinement to control nucleation & growth to promote columnar or single crystal growth from liquid melt

Equiaxed grains



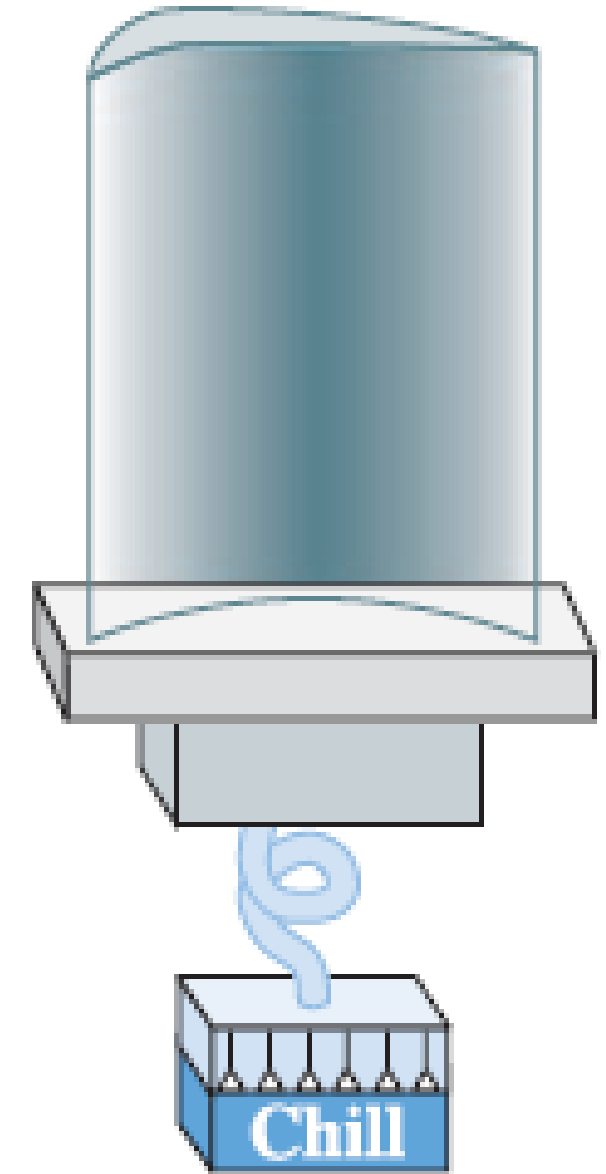
(a)

Columnar grains survive



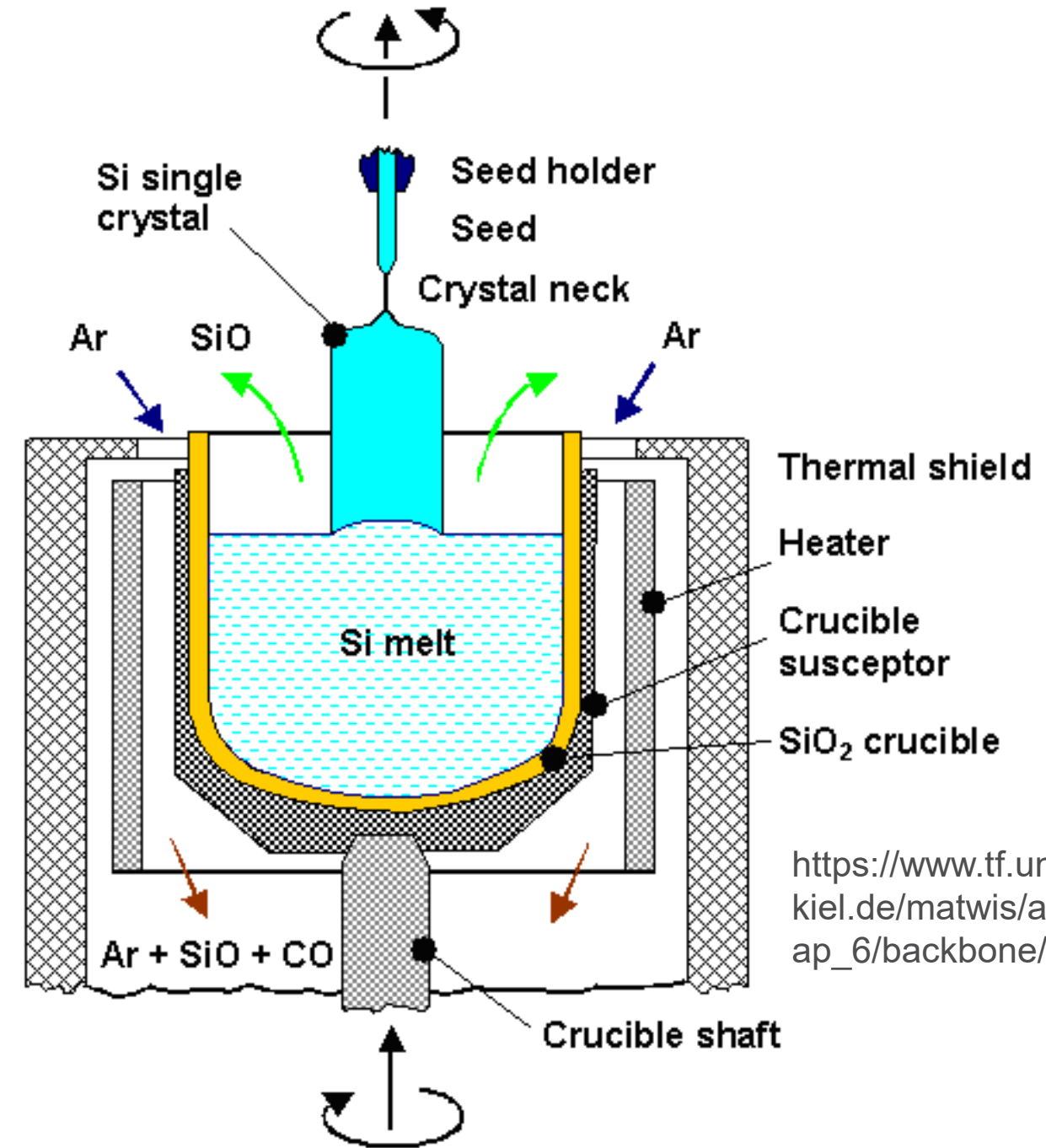
(b)

Only one grain survives



(c)

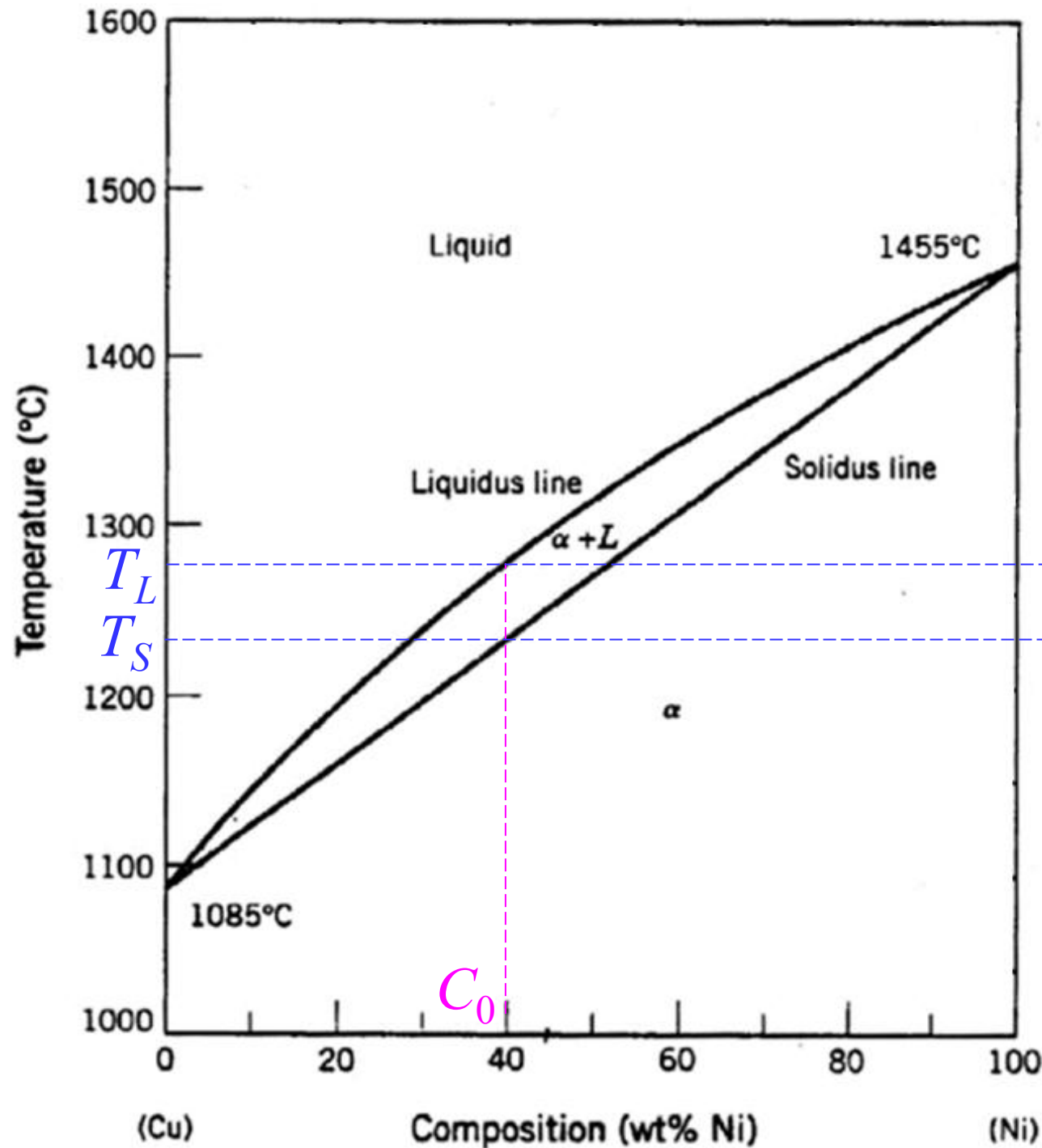
# Single Crystal Growth from Liquid Melt



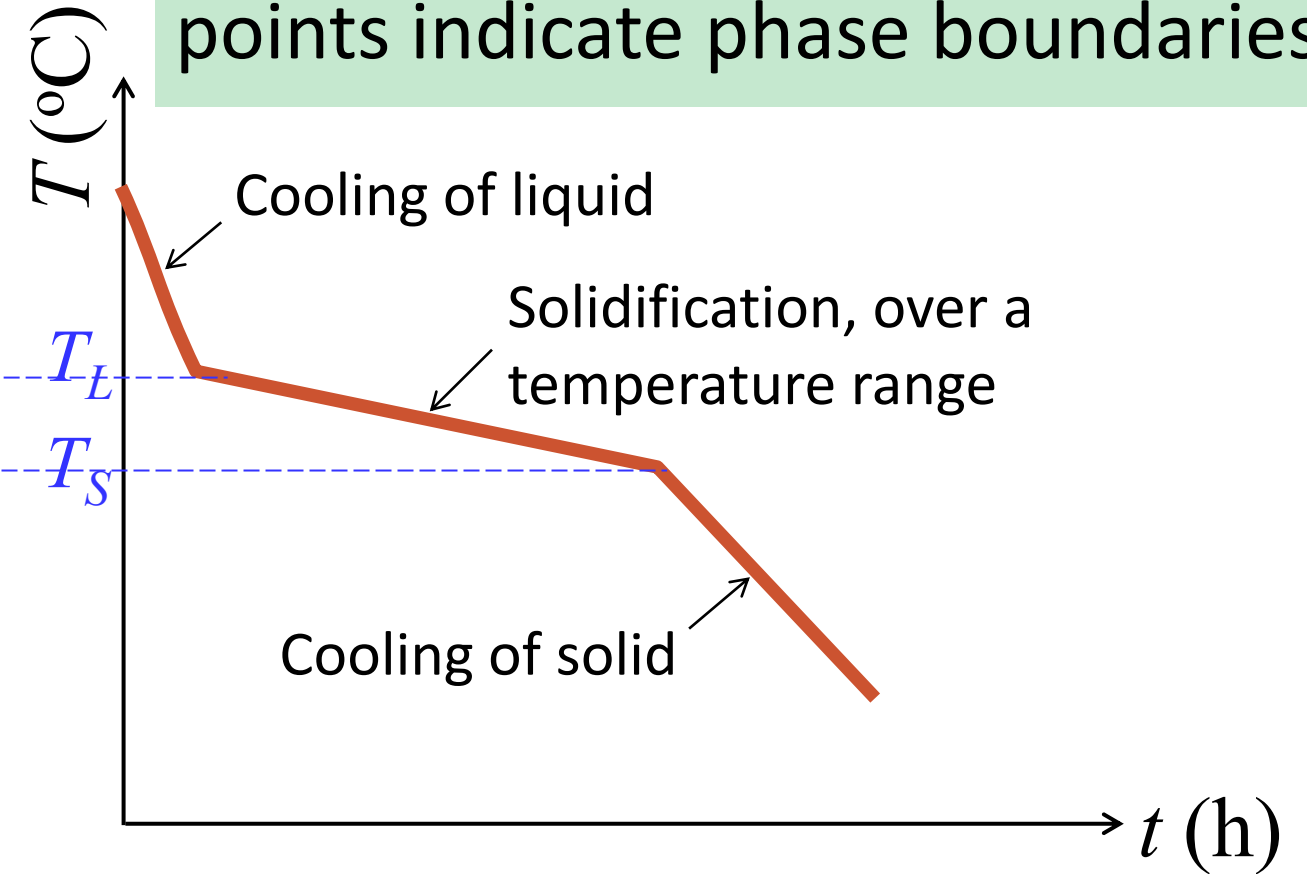
Large single crystal (e.g., Si) could be carefully grown/pulled from liquid

# Complication in Solidification of Alloys (1)

➤ Solidification occurs over a **temperature range**, instead of at a constant temperature



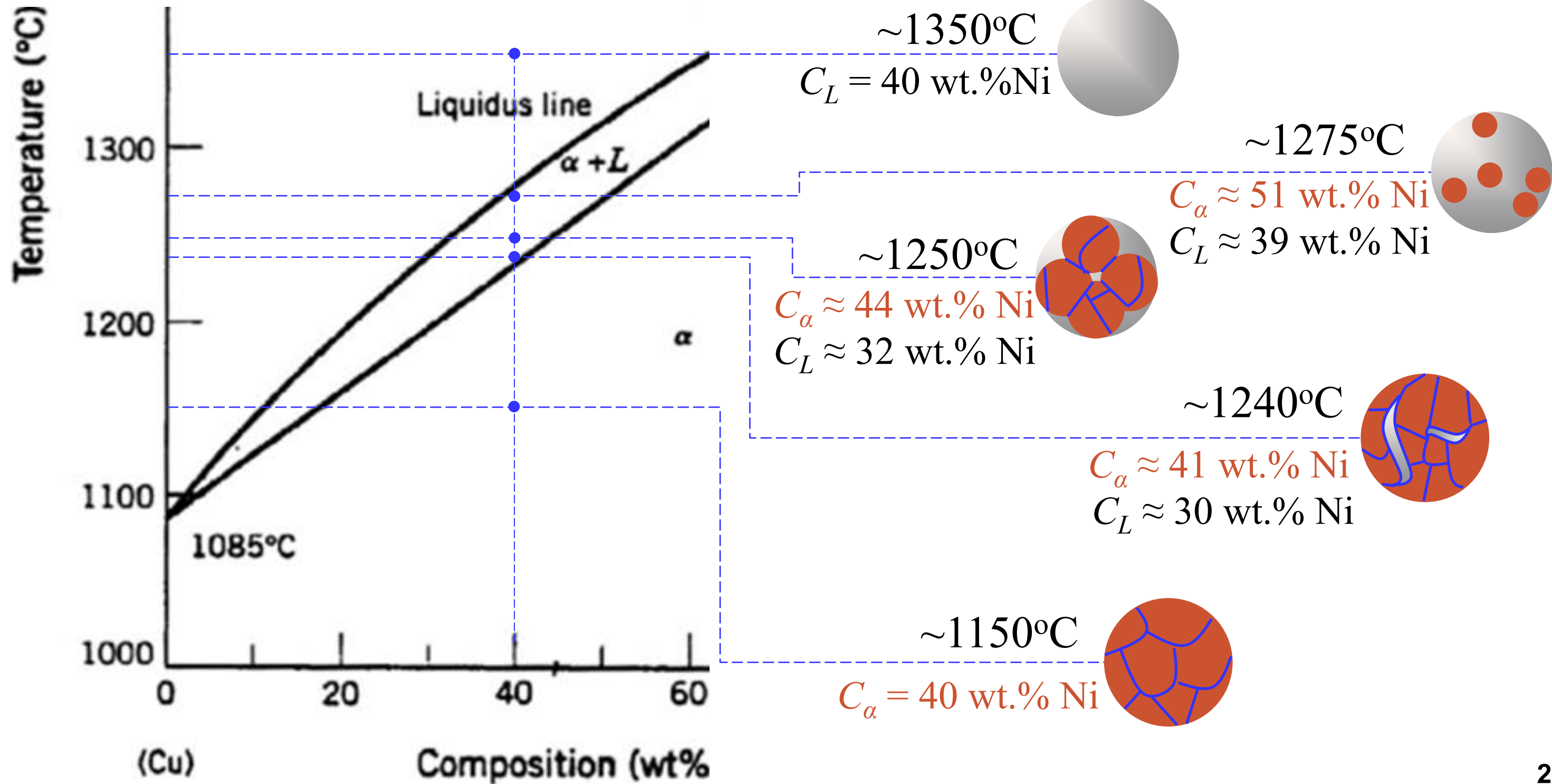
Cooling curve for a “**well-seeded**” alloy shows gradual drop in T during solidification & transition points indicate phase boundaries



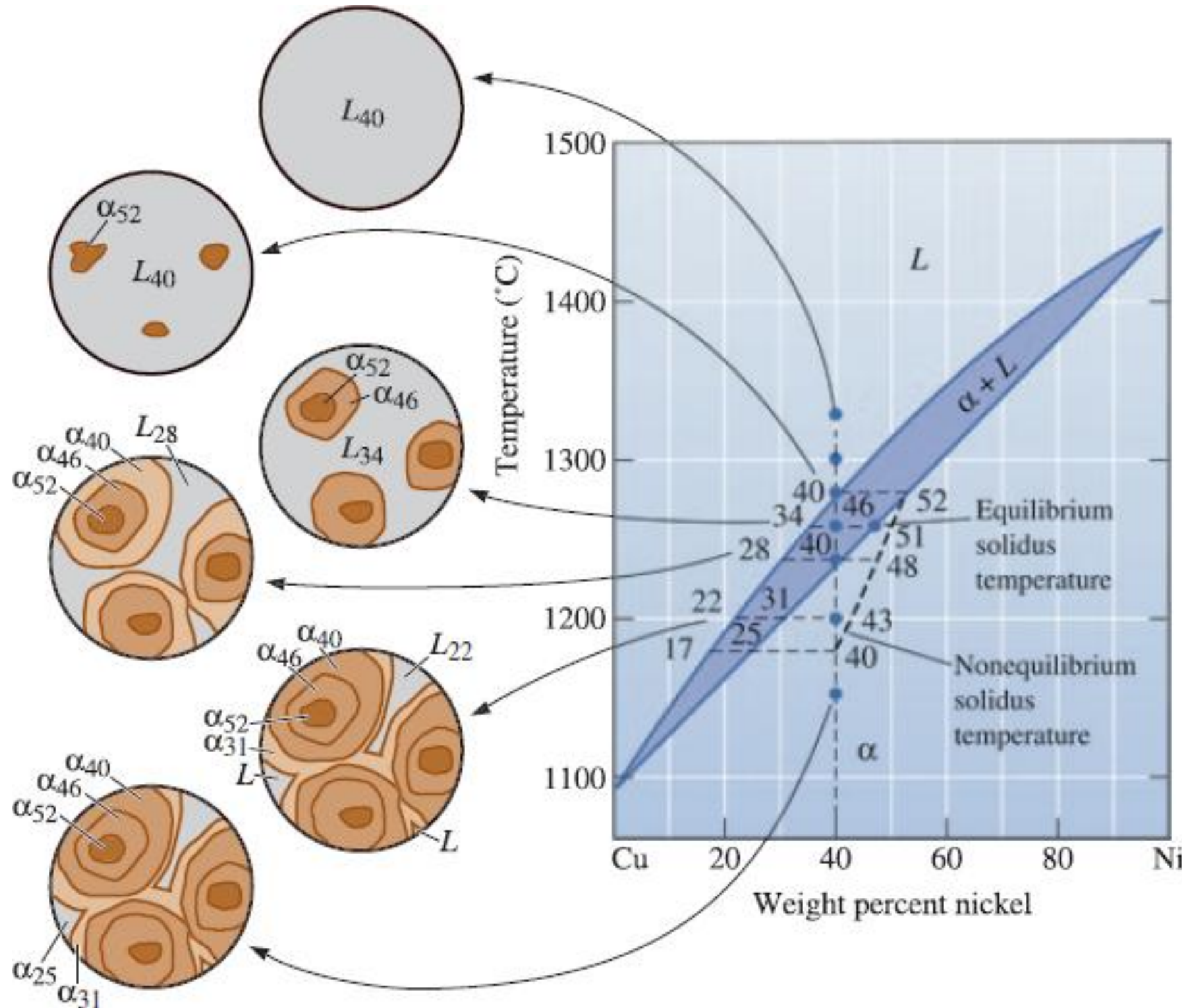
For alloy w/  $C_0 = 40$  wt.% Ni, under slow cooling  
 $T_L$  Highest temperature solid can exist  
 $T_S$  Lowest temperature liquid can exist

# Complications in Solidification of Alloys (2)

➤ Composition change in solid phase (as well as liquid phase) during alloy solidification



# Complications in Solidification of Alloys (3)



- Phase transformation & reaching equilibrium (e.g., by diffusion) takes **TIME!**
- **Non-uniformity** in solid phase after alloy solidification due to non-equilibrium (fast) cooling
- Mechanical properties non-uniform & less predictable, which **needs to be** avoided or **mitigated**, often through post solidification heat treatment or **homogenization**

# **Ch11 Phase Transformation in Eutectic System**

# Solidification of Very Dilute Alloy - Below Solubility Limit at RT

~340°C  
 $C_L = 1 \text{ wt.\% Sn}$

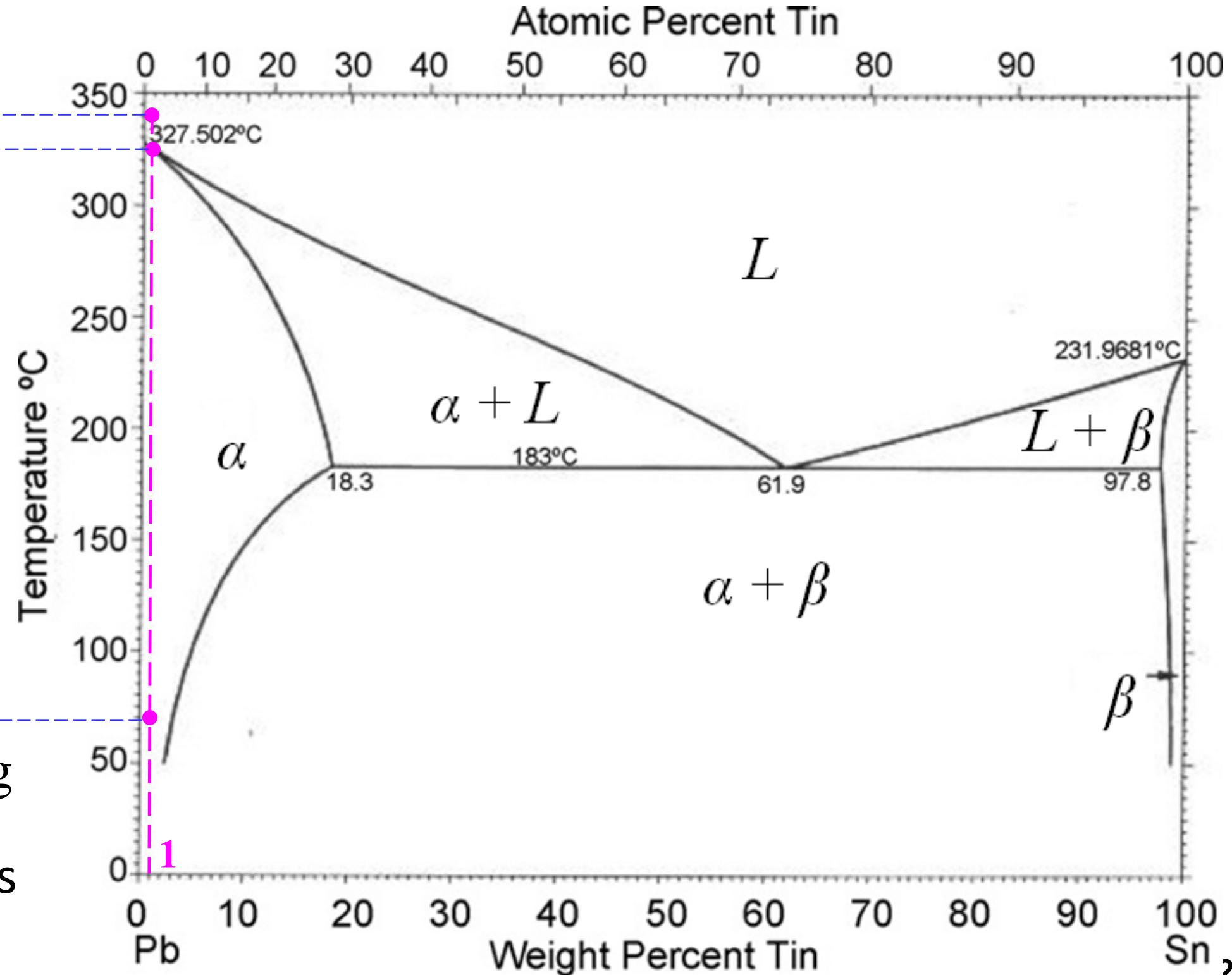
~325°C

~70°C  
 $C_\alpha = 1 \text{ wt.\% Sn}$

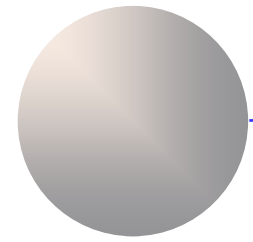
Solid solution strengthening

Multiple phase transformations

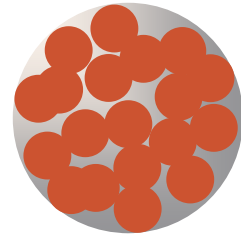
$L \rightarrow \alpha + L \rightarrow \alpha$



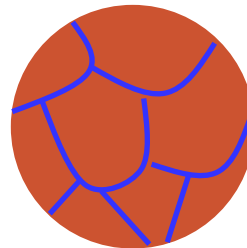
# Solidification of Alloys Exceeding Solubility Limit (at RT)



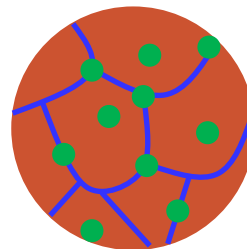
$\sim 340^\circ\text{C}$   
 $C_L = 12 \text{ wt.\% Sn}$



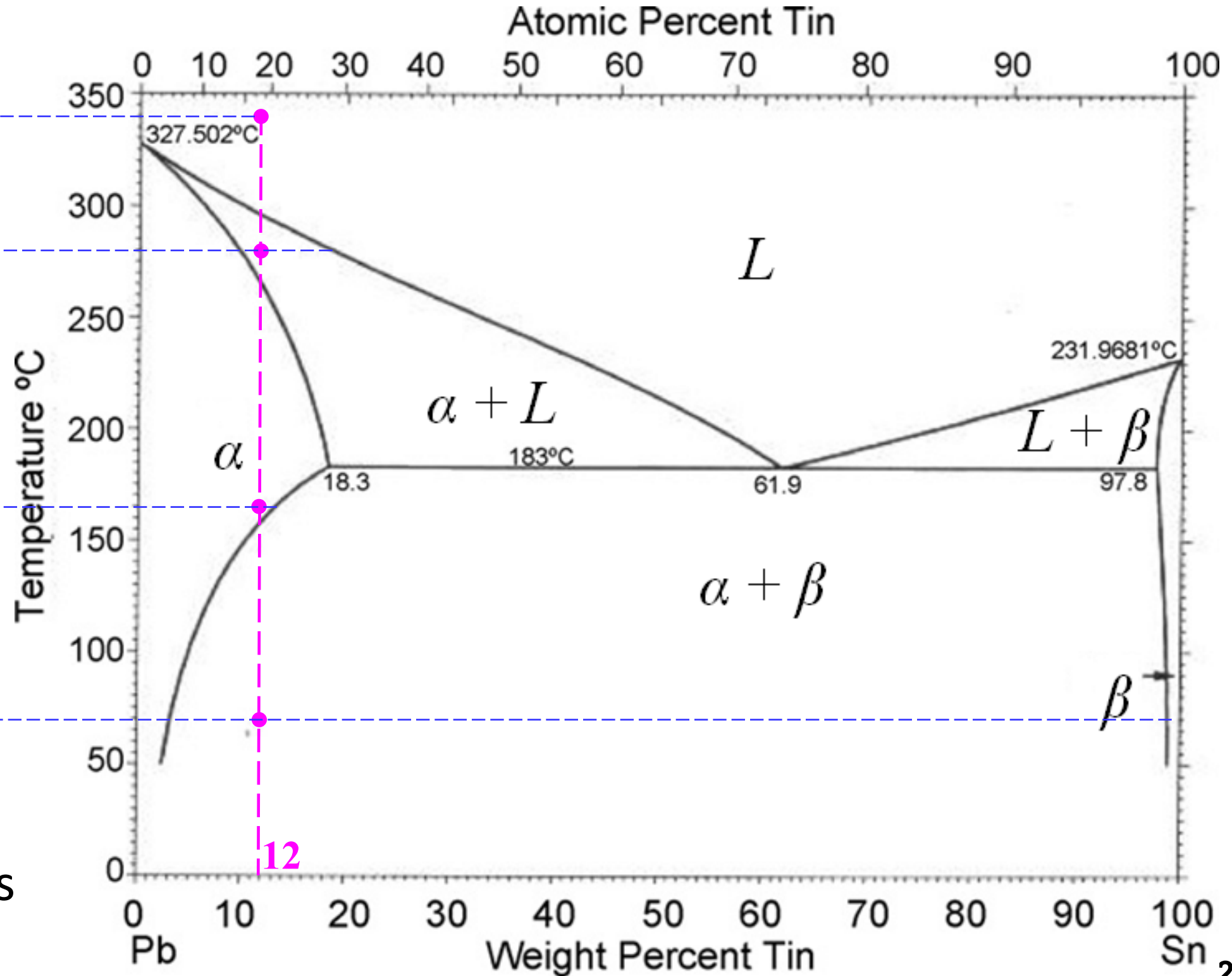
$\sim 280^\circ\text{C}$   
 $C_L = 18 \text{ wt.\% Sn}$   
 $C_\alpha = 10 \text{ wt.\% Sn}$



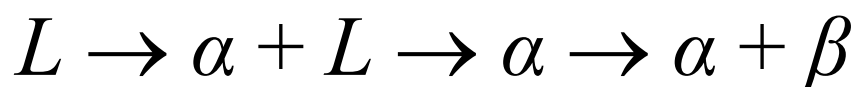
$\sim 165^\circ\text{C}$   
 $C_\alpha = 12 \text{ wt.\% Sn}$



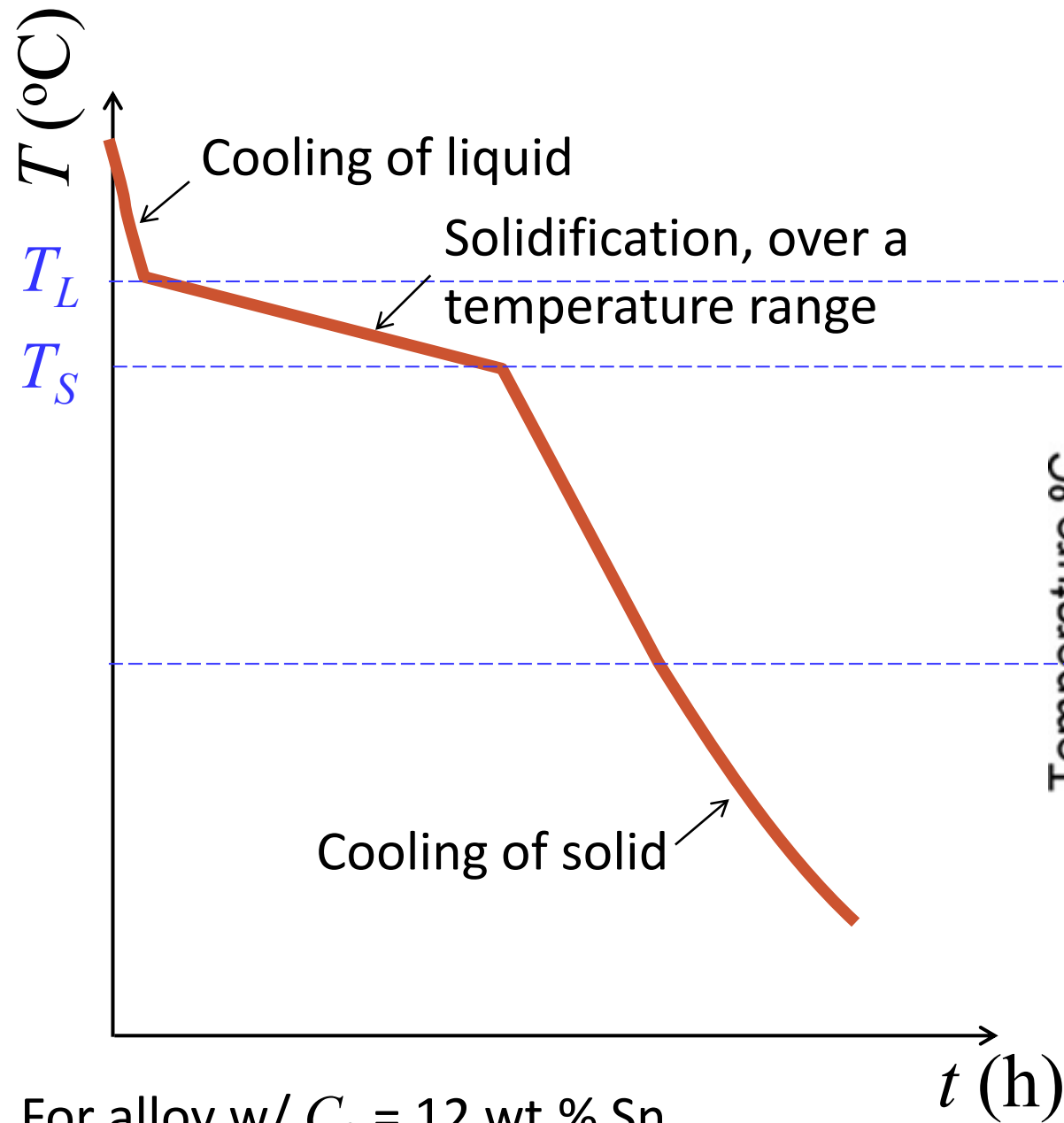
$\sim 70^\circ\text{C}$   
 $C_\alpha = 3 \text{ wt.\% Sn}$   
 $C_\beta = 99 \text{ wt.\% Sn}$



Multiple phase transformations



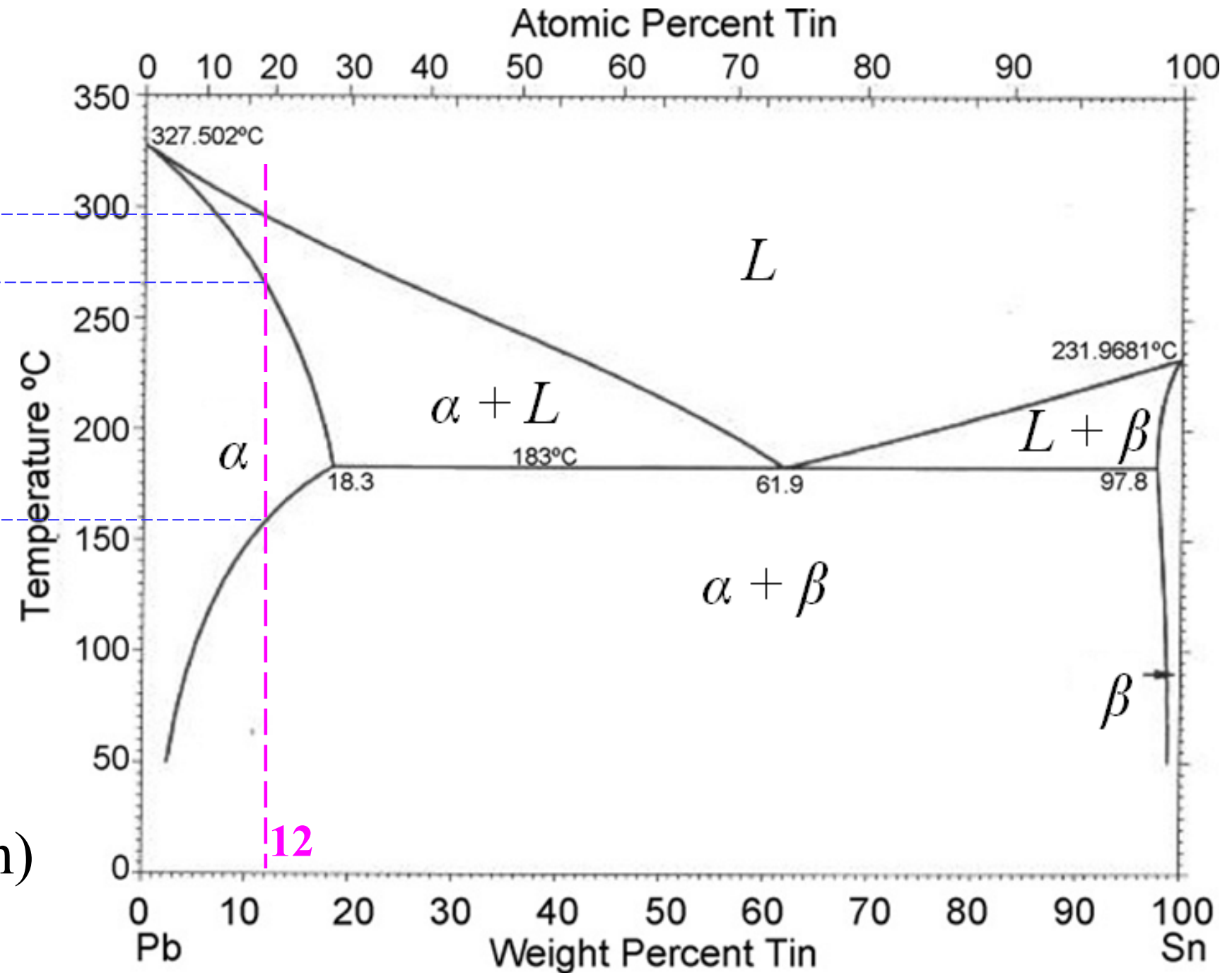
# Cooling Curve for Alloys Exceeding Solubility Limit (at RT)



For alloy w/  $C_0 = 12$  wt.% Sn

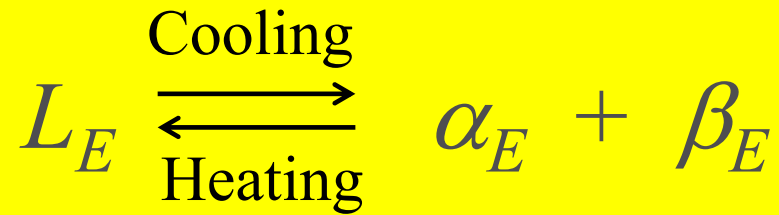
$T_L$  Highest temperature solid can exist

$T_S$  Lowest temperature liquid can exist



# Solidification of Alloy with Eutectic Composition

➤ Eutectic reaction:

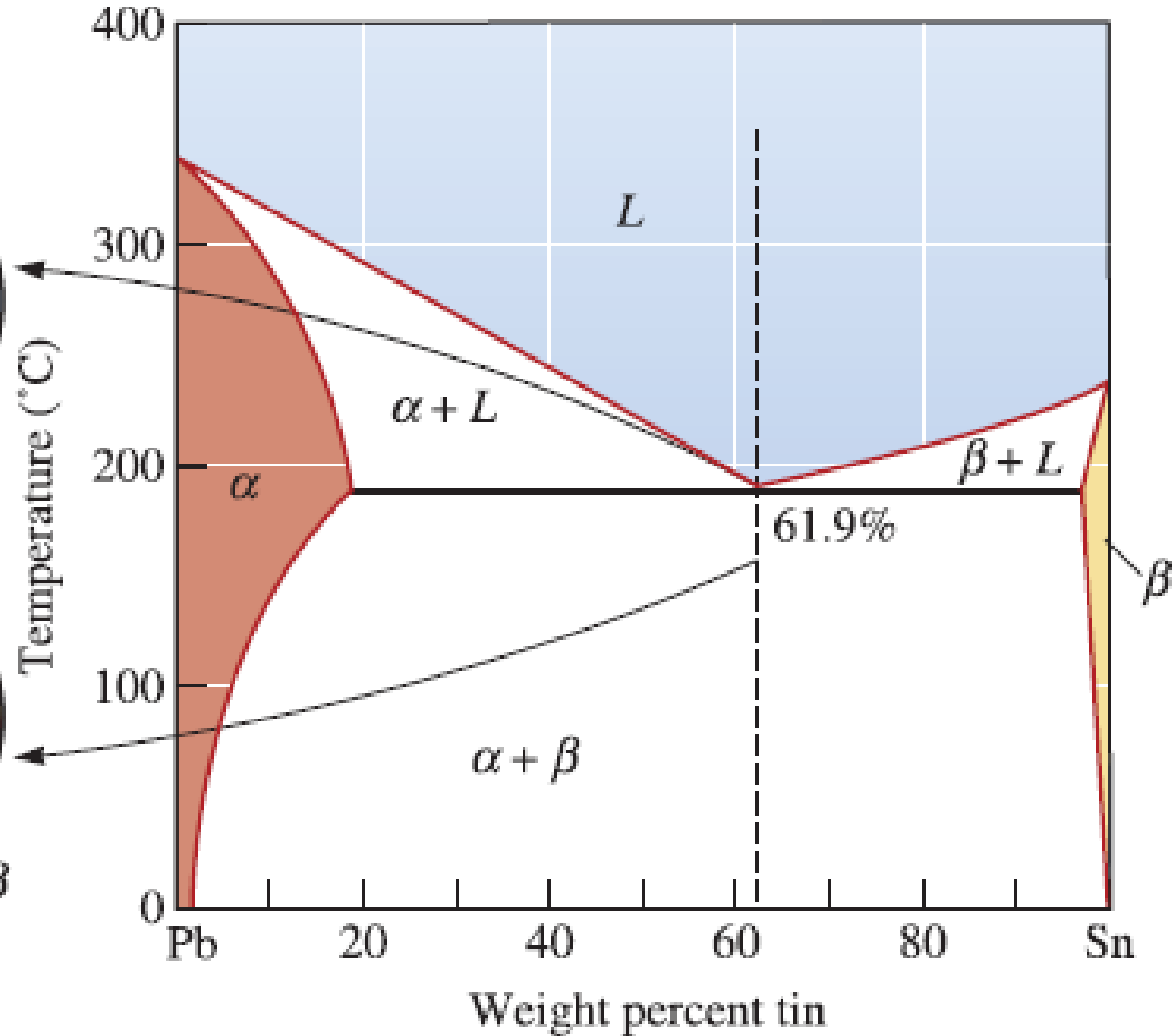
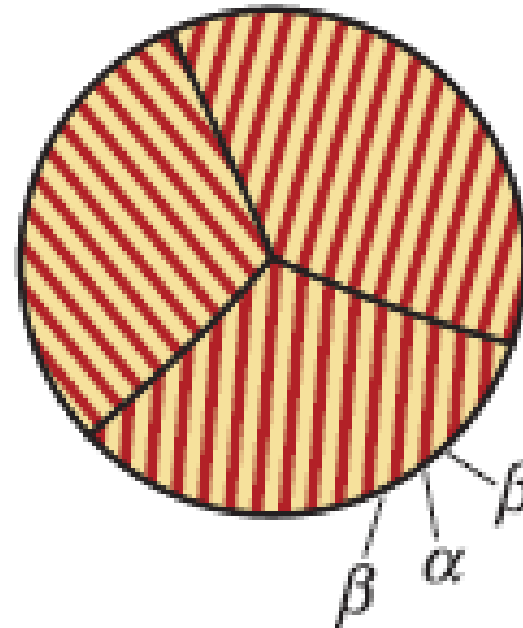
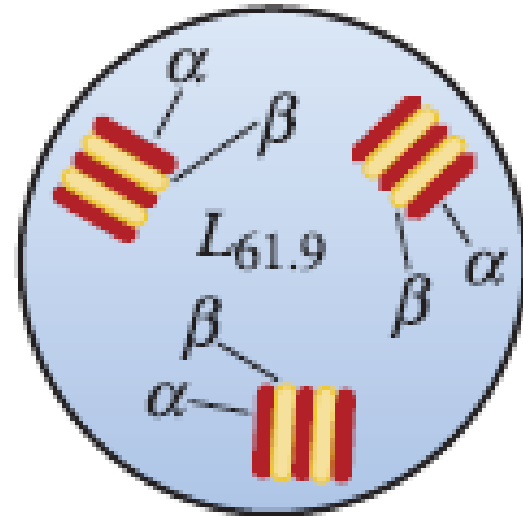


$$C_{LE} = 61.9 \text{ wt.\% Sn}$$

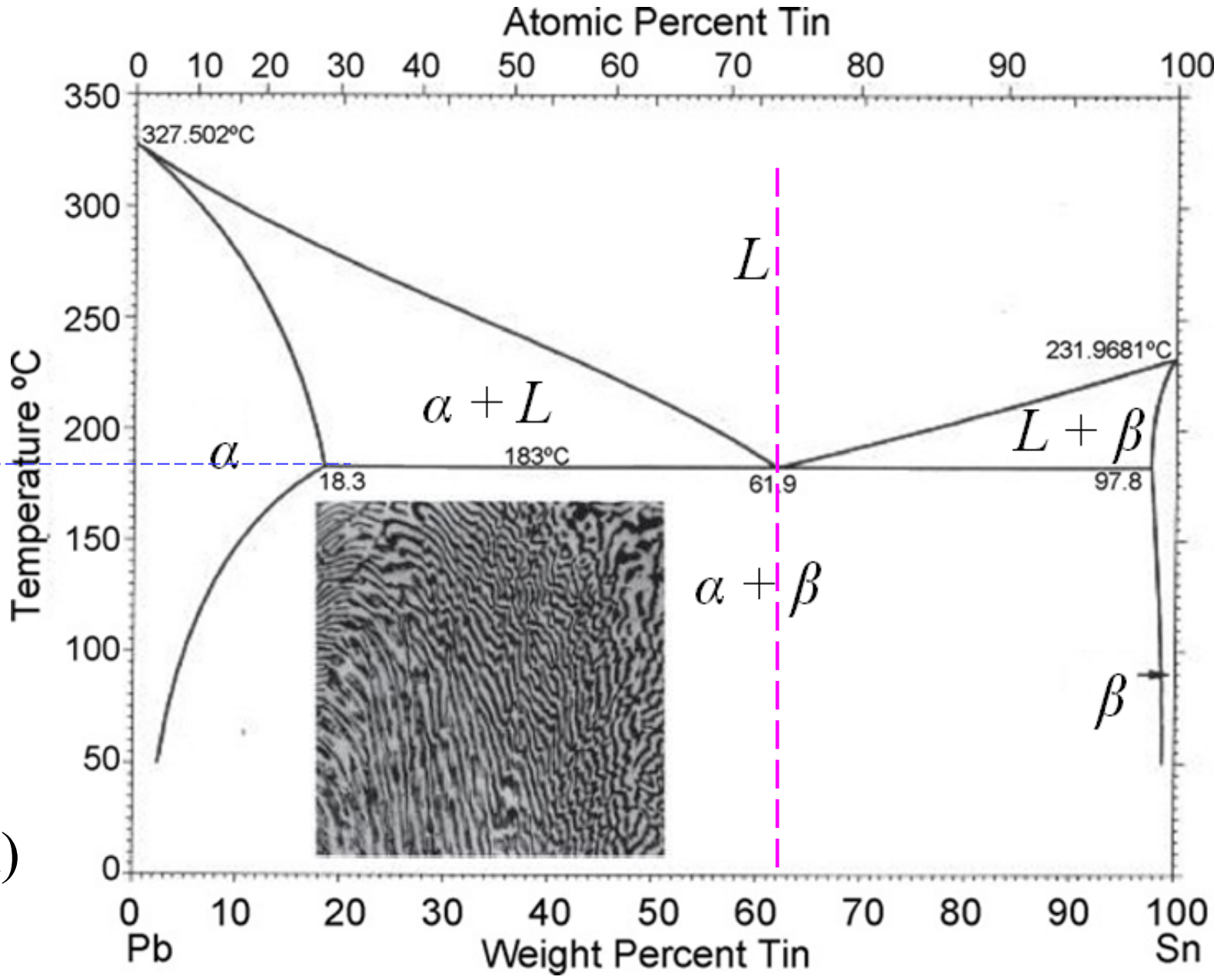
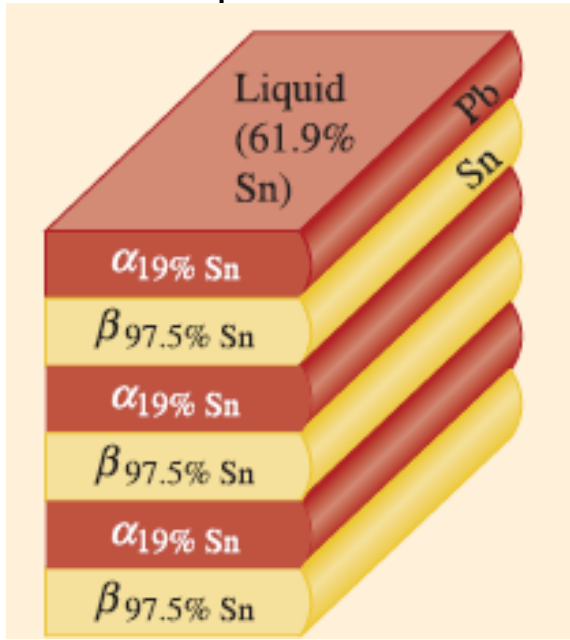
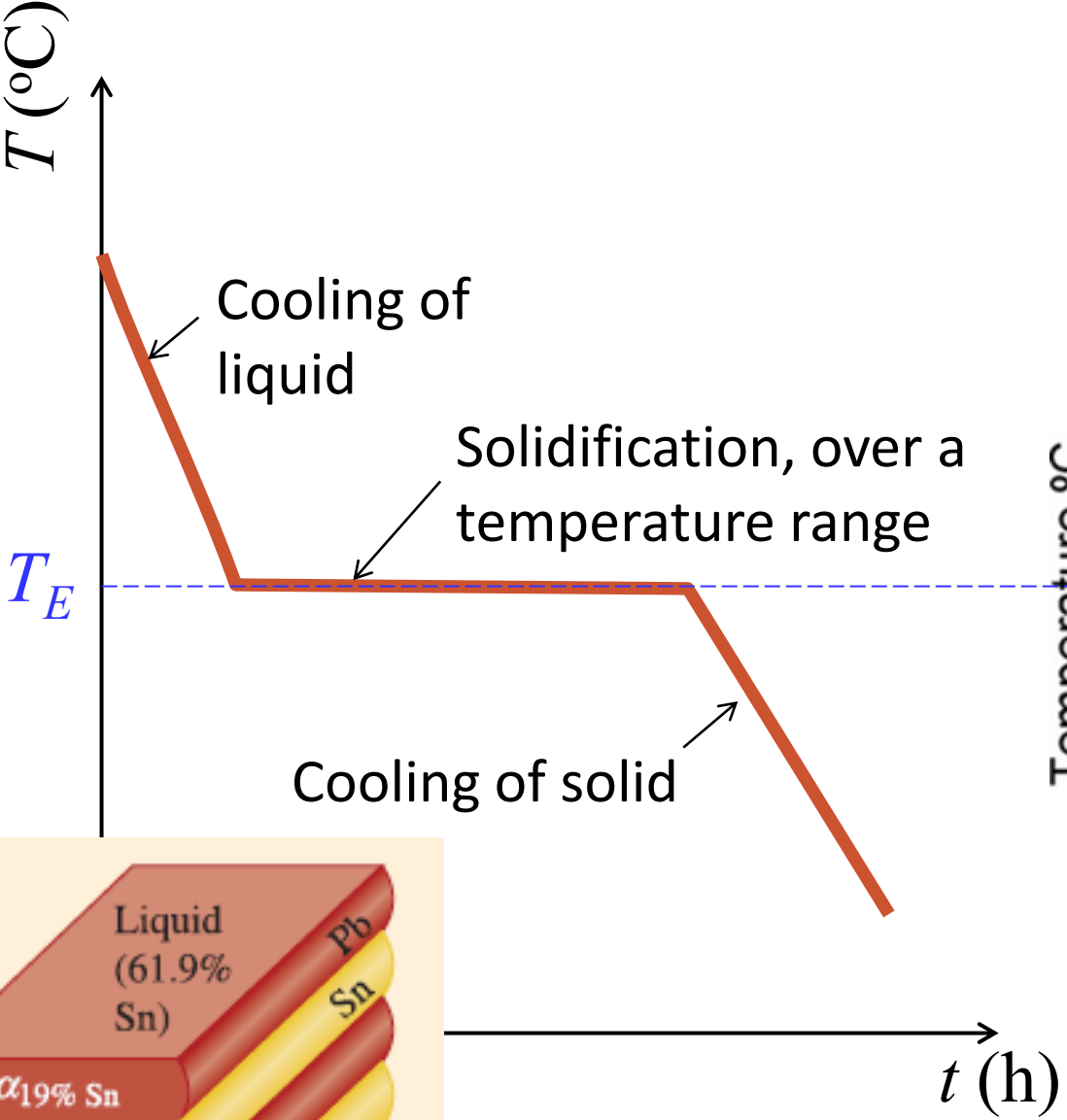
$$C_{\alpha E} = 18.3 \text{ wt.\% Sn}$$

$$C_{\beta E} = 97.8 \text{ wt.\% Sn}$$

➤ Due to large change in composition and the time constraint w/ mass transport (diffusion), **layered/lamellar structure** develop



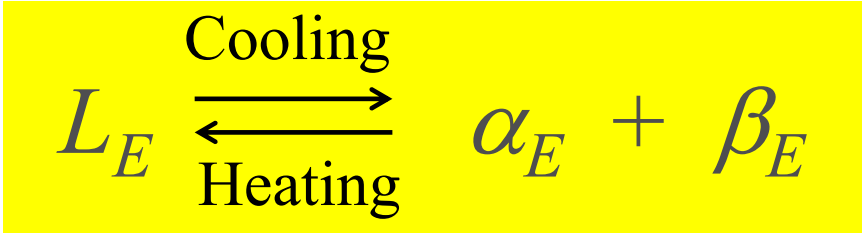
# Cooling Curve of Eutectic Alloy Solidification & Microstructure



**Layered/lamellar structure** for eutectic alloy solidification (due to mass transport limitation)

# Solidification of Hypoeutectic/Hypereutectic Alloy

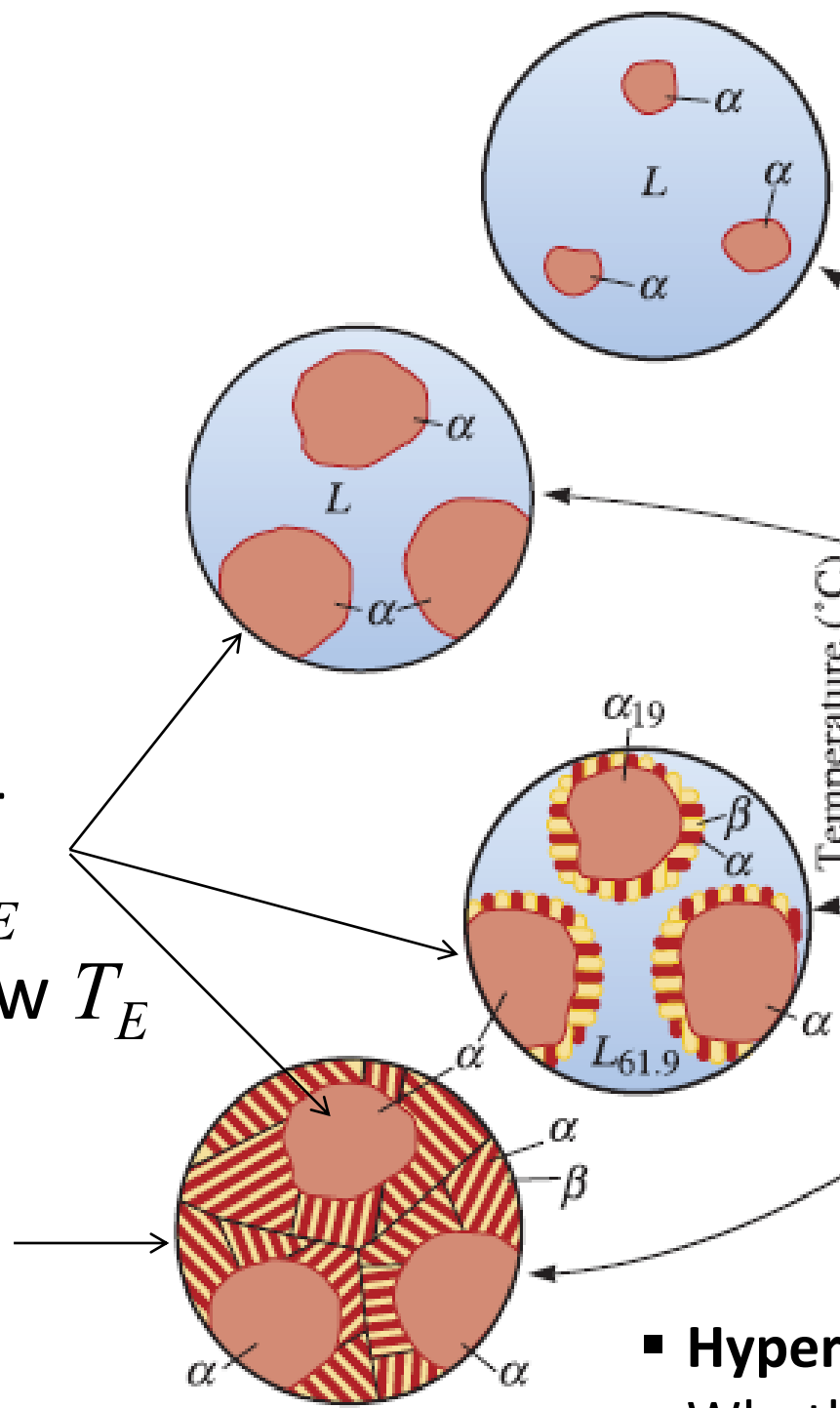
➤ Eutectic reaction:



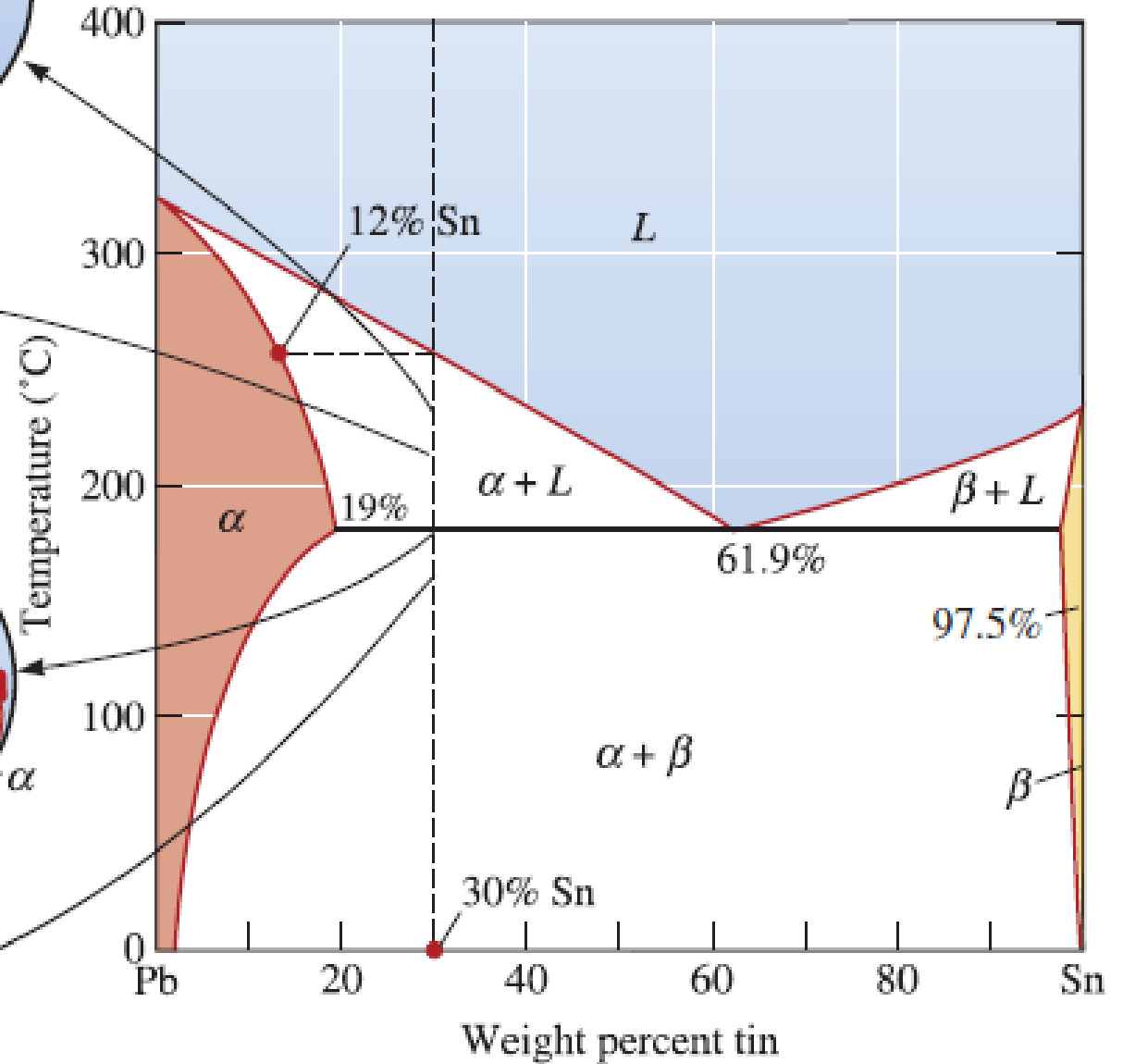
$C_{LE} = 61.9 \text{ wt.\% Sn}$   
 $C_{\alpha E} = 18.3 \text{ wt.\% Sn}$   
 $C_{\beta E} = 97.8 \text{ wt.\% Sn}$

**Primary  $\alpha$  phase** –  
 formed at above  $T_E$   
 Not much change below  $T_E$

**Layered  $\alpha/\beta$  eutectic  
 “structure”** – formed at  
 or just below  $T_E$

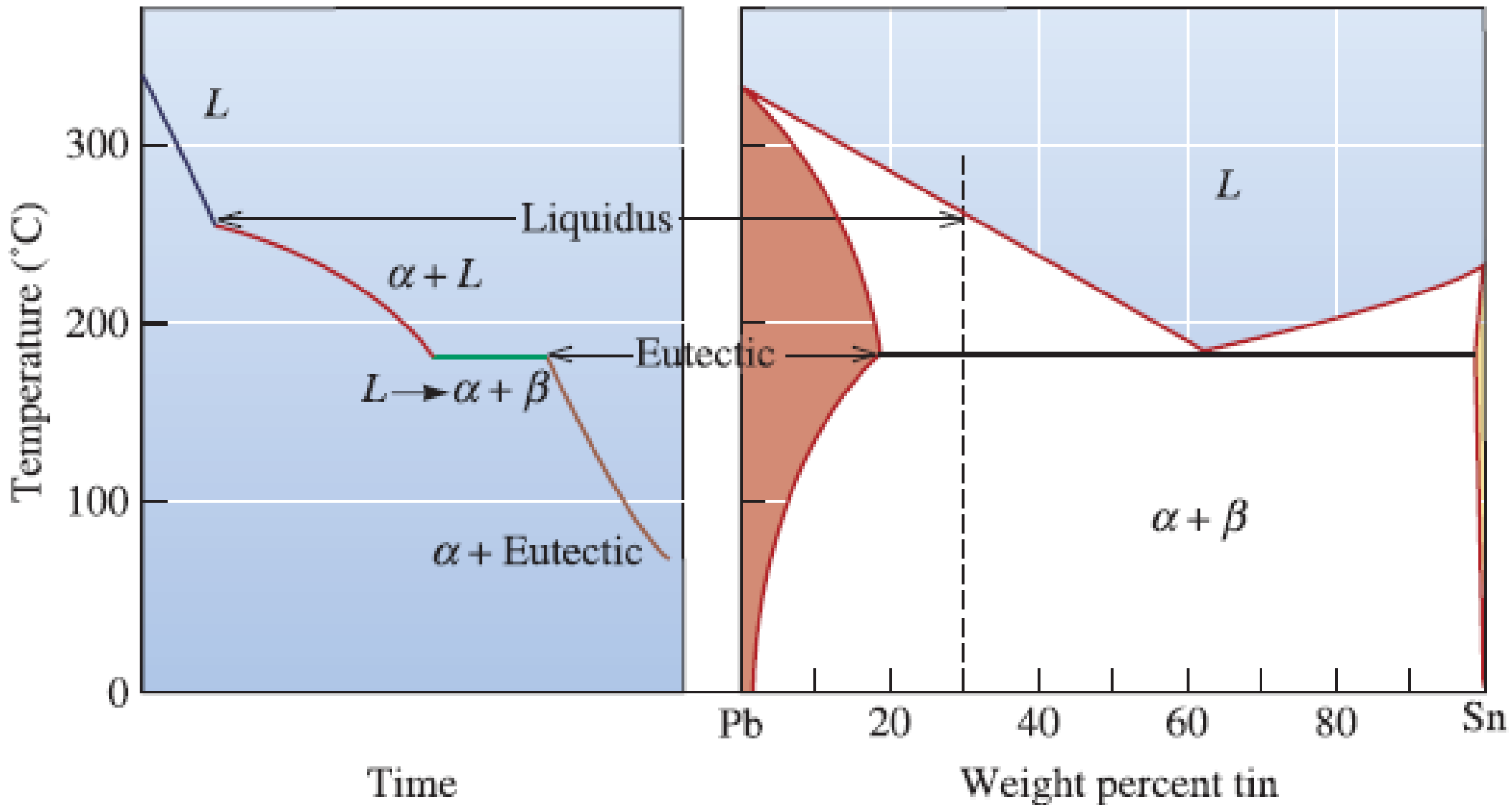


**Hypoeutectic – BELOW eutectic composition**



- **Hypereutectic – ABOVE eutectic composition**
- Whether hypo or hyper depends on perspective: “hypo” from Pb side means “hyper” from Sn side

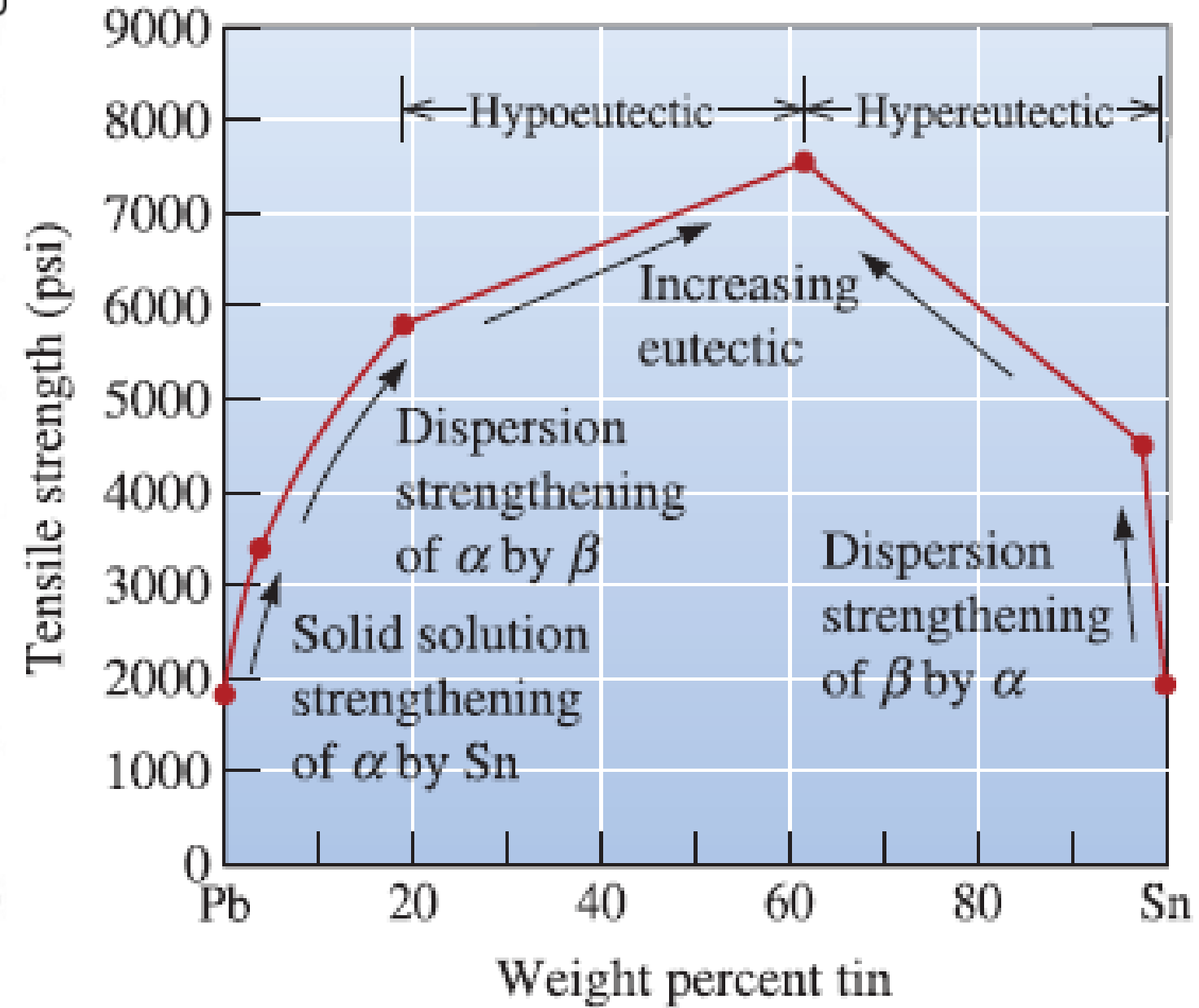
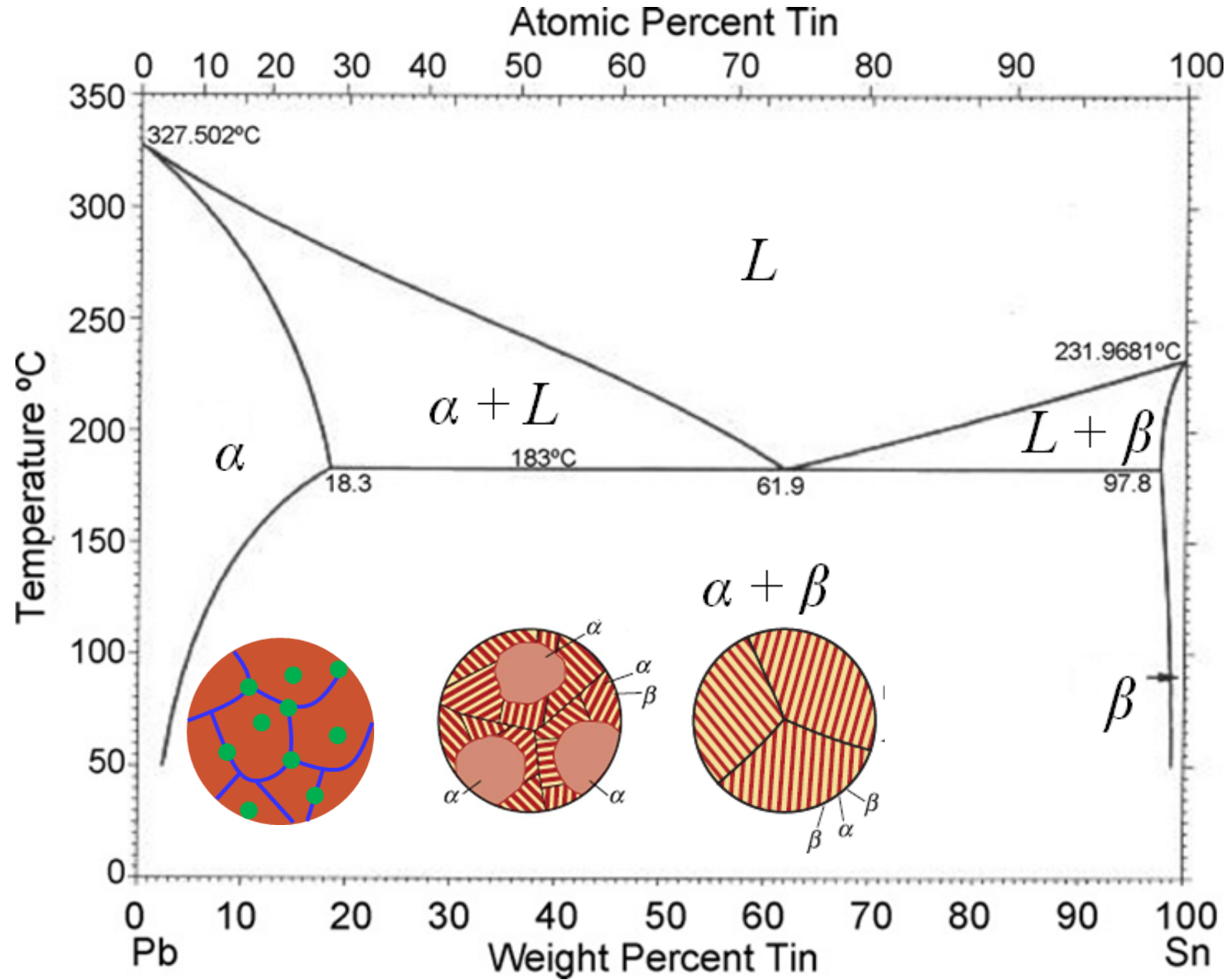
# Cooling Curve of Hypoeutectic Alloy



➤ Sectioned cooling curve showing different stages of cooling

➤ Roundish primary  $\alpha$   
+ Layered  $\alpha/\beta$   
eutectic structure

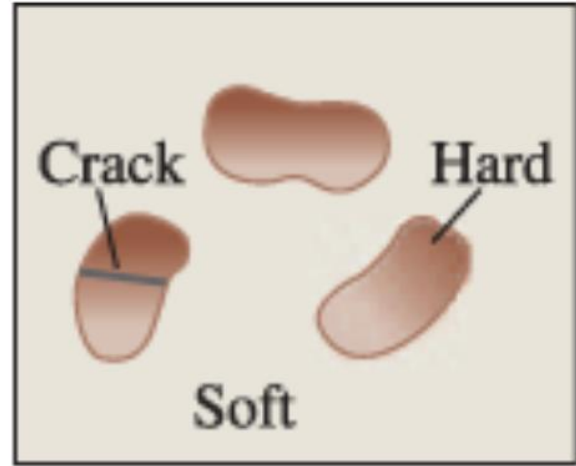
# Linkage of Structure to Mechanical Properties



➤ Significant change (increase) in strength, as composition & microstructure changes

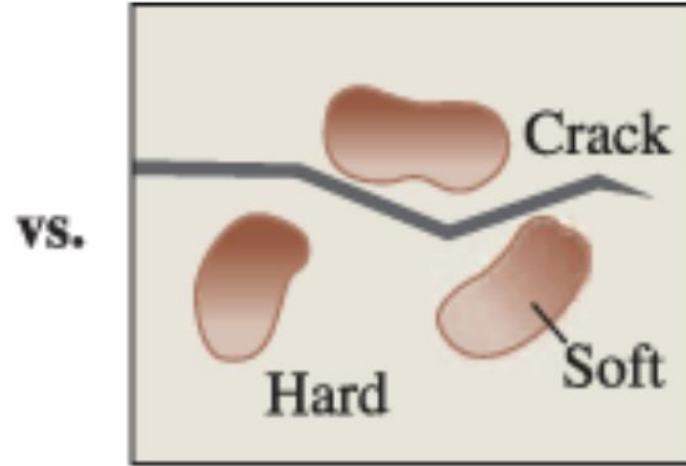
# Factors Influencing 2<sup>nd</sup> Phase Strengthening Effectiveness

Ductile matrix w/hard, dispersed 2<sup>nd</sup> phase



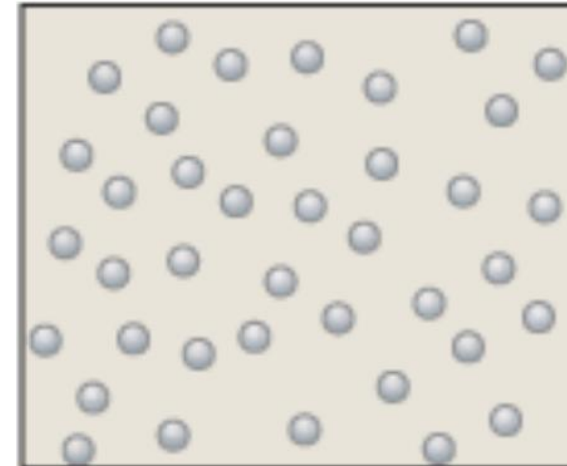
Good

Brittle matrix w/ ductile, dispersed 2<sup>nd</sup> phase



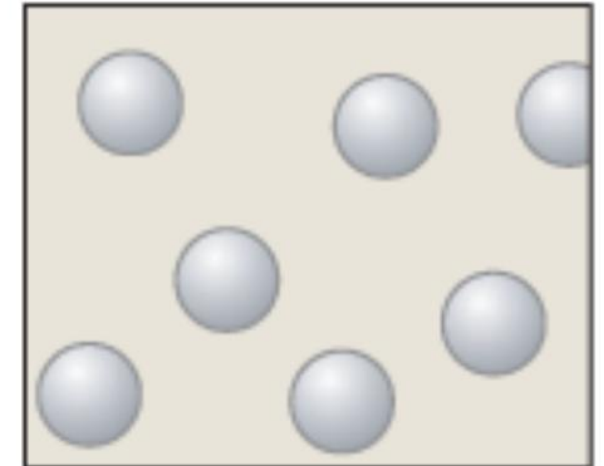
Poor

Small, numerous hard 2<sup>nd</sup> phase w/ small spacing

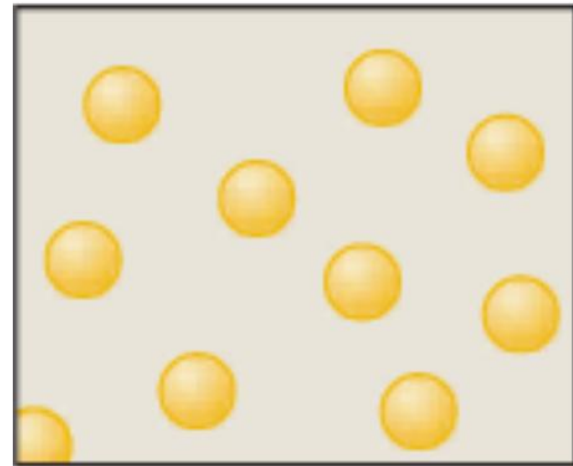


Good

Large, few hard 2<sup>nd</sup> phase w/ large spacing



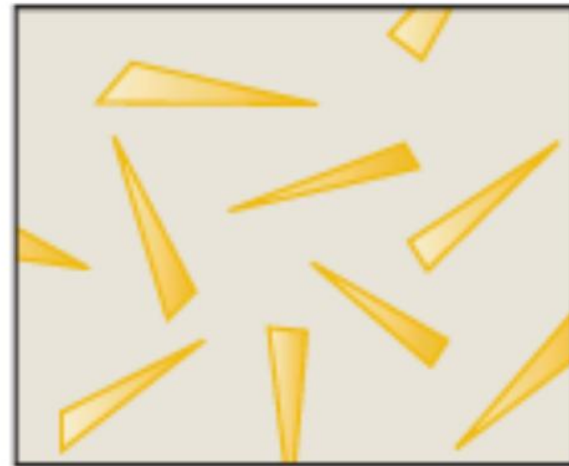
Poor



Good

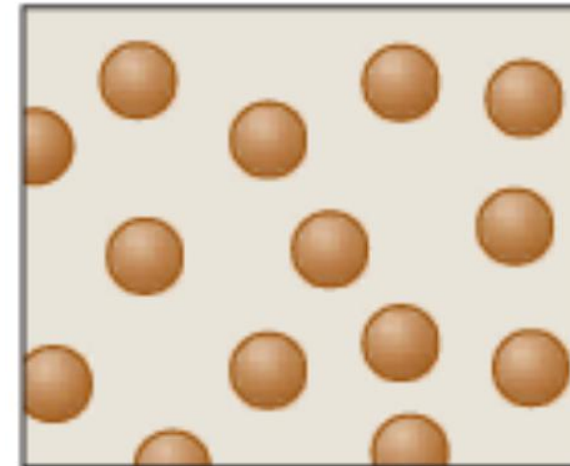
(Near) spherical 2<sup>nd</sup> phase

vs.



Poor

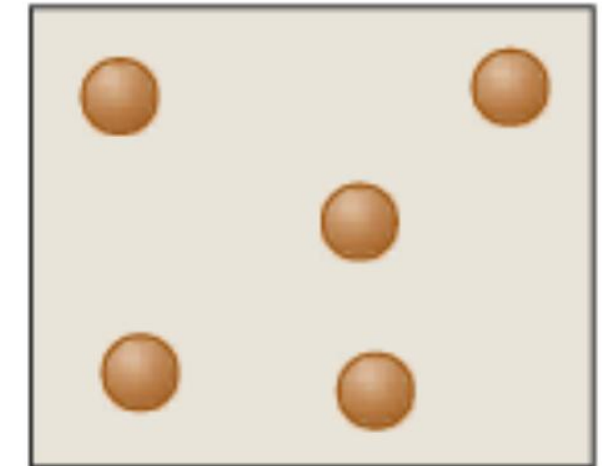
Sharp edged 2<sup>nd</sup> phase



Good

Higher density hard 2<sup>nd</sup> phase w/ small spacing

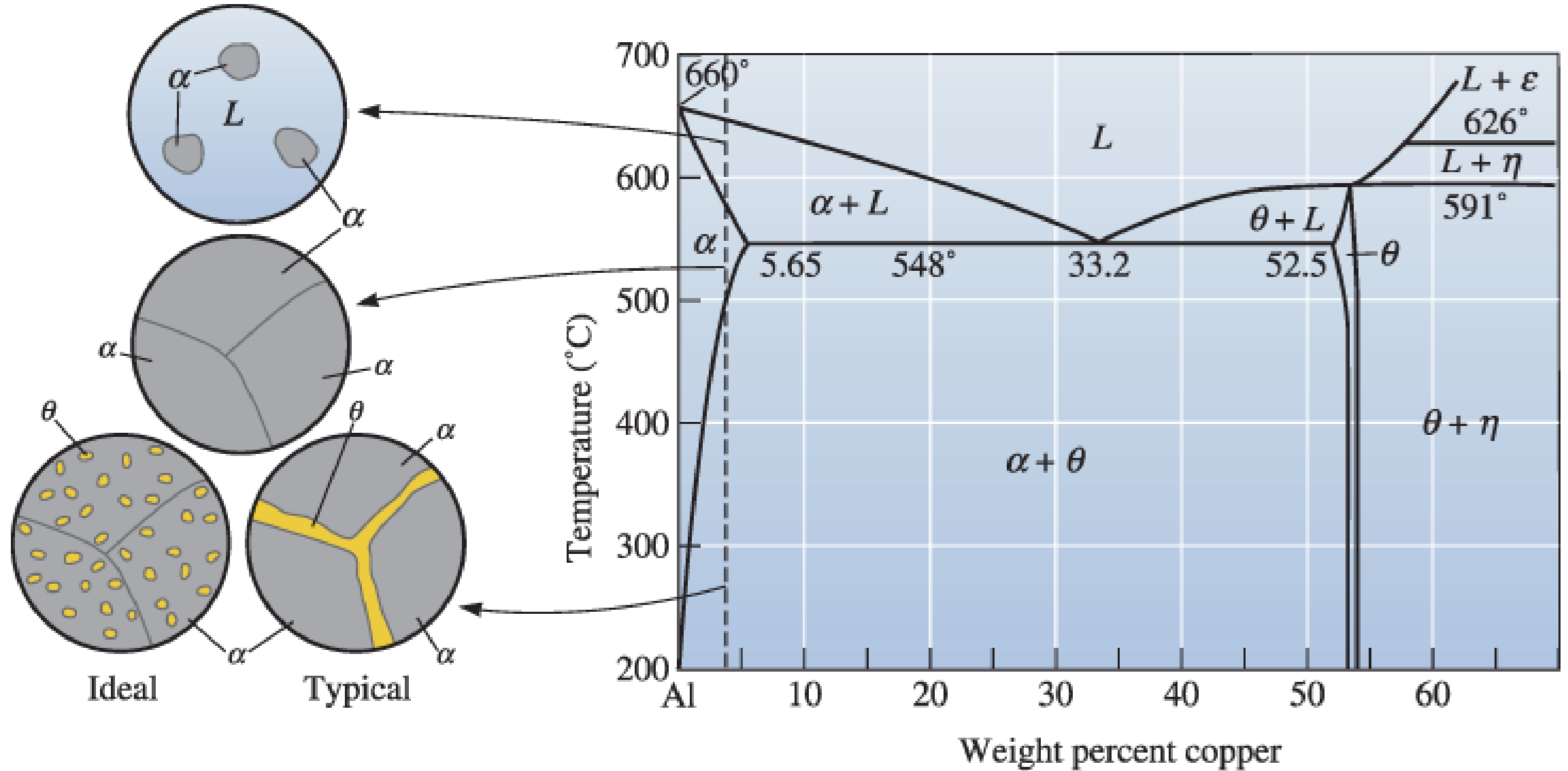
vs.



Poor

Lower density hard 2<sup>nd</sup> phase w/ large spacing

# 2<sup>nd</sup> Phase Distribution in Dilute Cu in Al Alloy: Ideal vs. Typical



Conventional slow/equilibrium cooling →  
**Typically** large secondary phase w/ very large spacing →  
 Not much improvement in strength →  
 Need **ideal** structure of finer, closely spaced 2<sup>nd</sup> phase

# Age/Precipitation Hardening for Dilute Cu in Al Alloy

## 3 steps for Age Hardening

### (1) Solution treatment

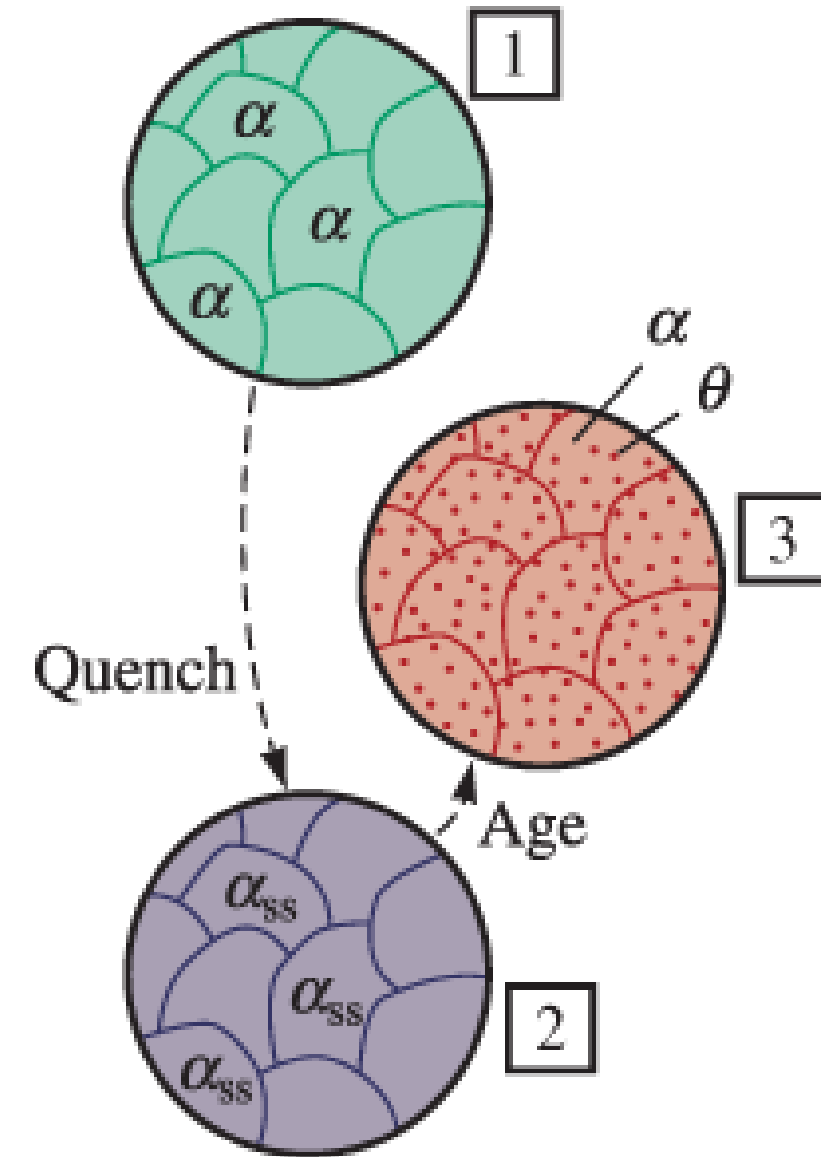
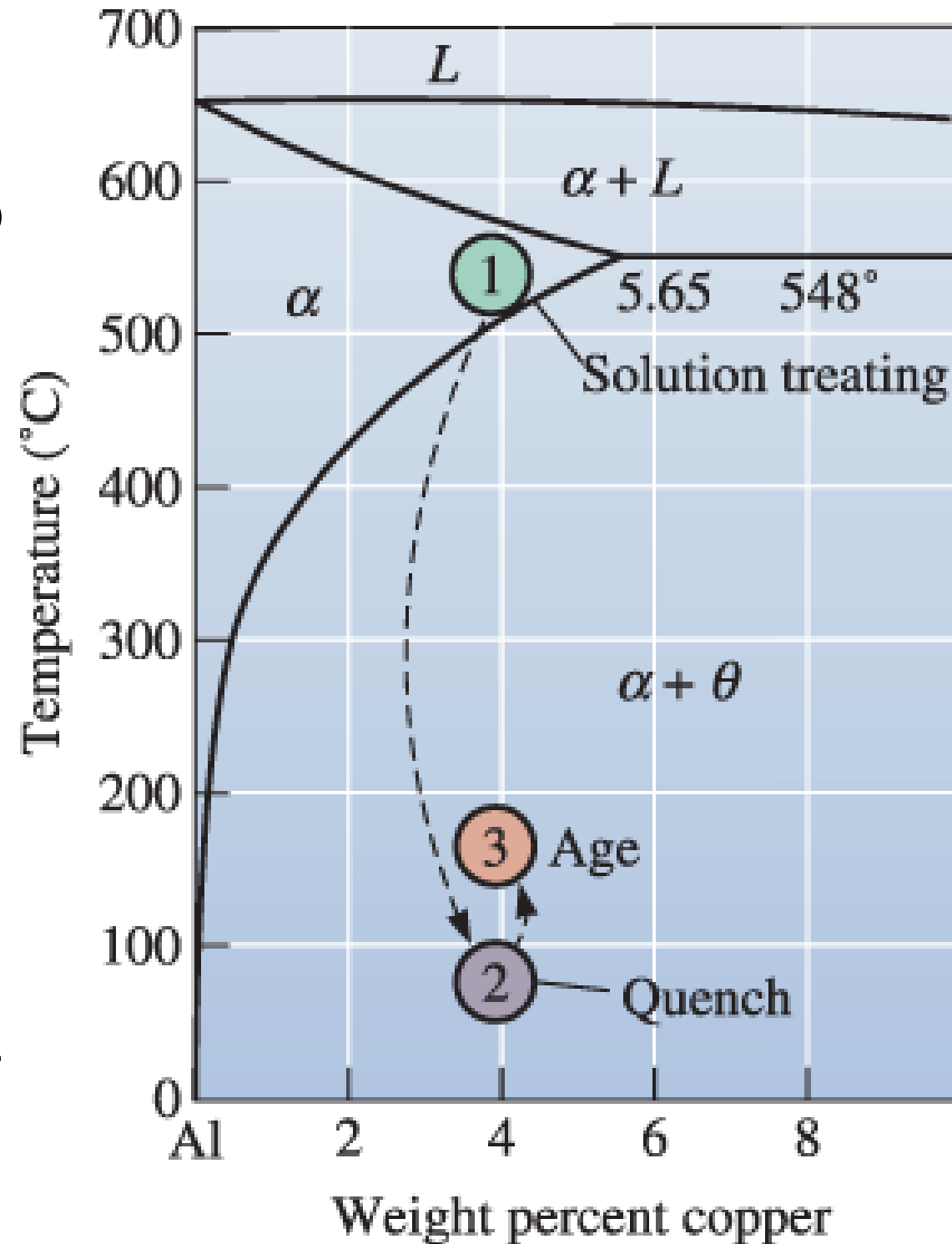
Heat to single phase region to get uniform composition & structure

### (2) Quench

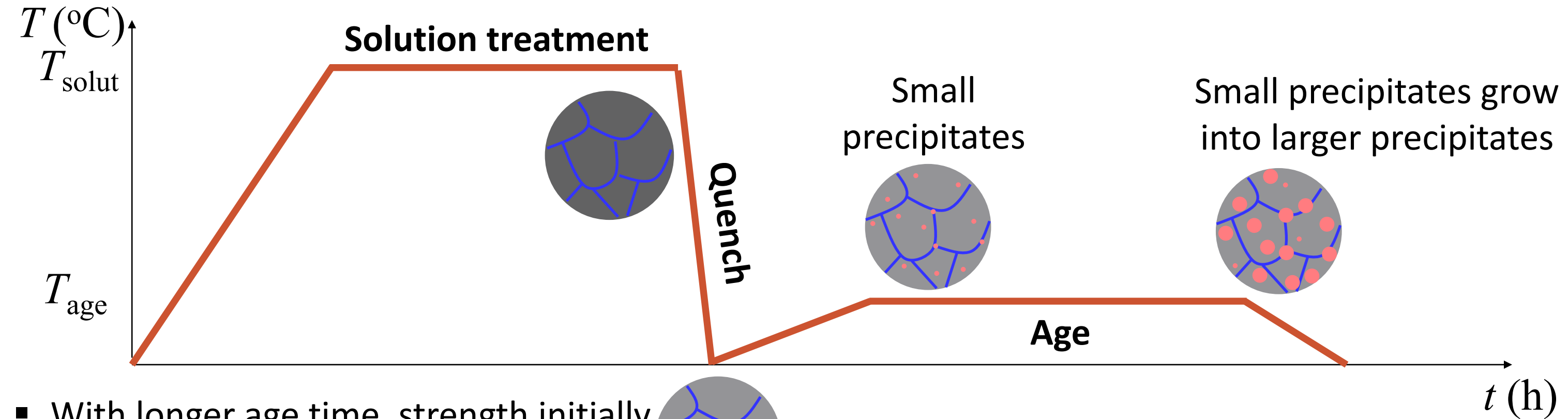
Rapidly cool to two phase region

### (3) Age

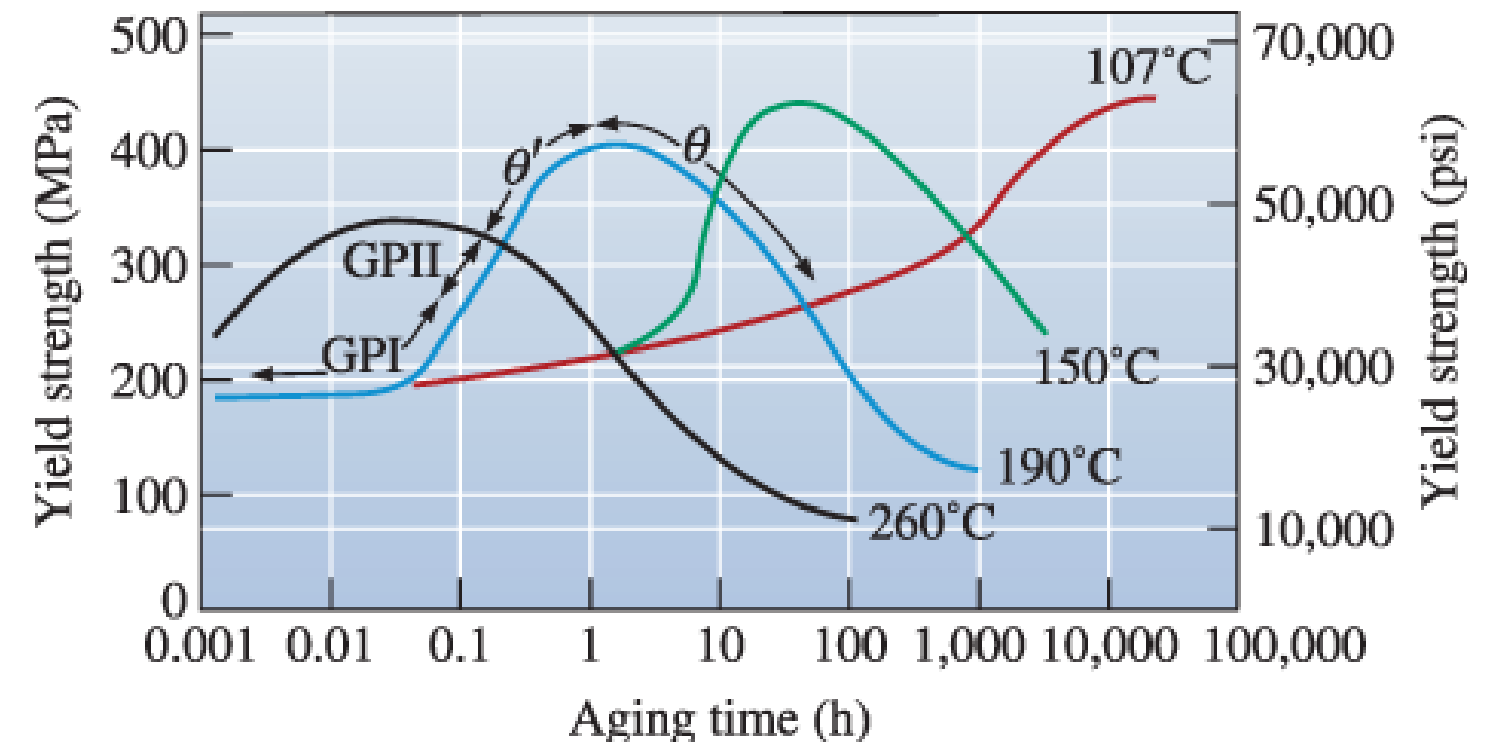
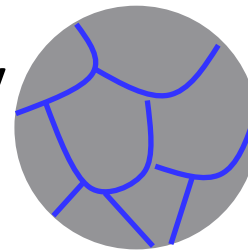
Reheat to slightly higher temperature and wait for phase separation - the formation of fine 2<sup>nd</sup> phase or precipitates from matrix, strengthening the material



# Temperature & Time Effects in Age Hardening



- With longer age time, strength initially increases due to precipitates formation & increase in number
- Further age (beyond optimal) leads to drop in strength due to coarsening/grain growth of precipitates
- Lower temperature for aging gives smaller precipitates and higher strength, but prolongs required aging time



# Lamellar Structure from Eutectoid Phase Transformation

Eutectoid Reaction:

**Solid 1 = Solid 2 + Solid 3**

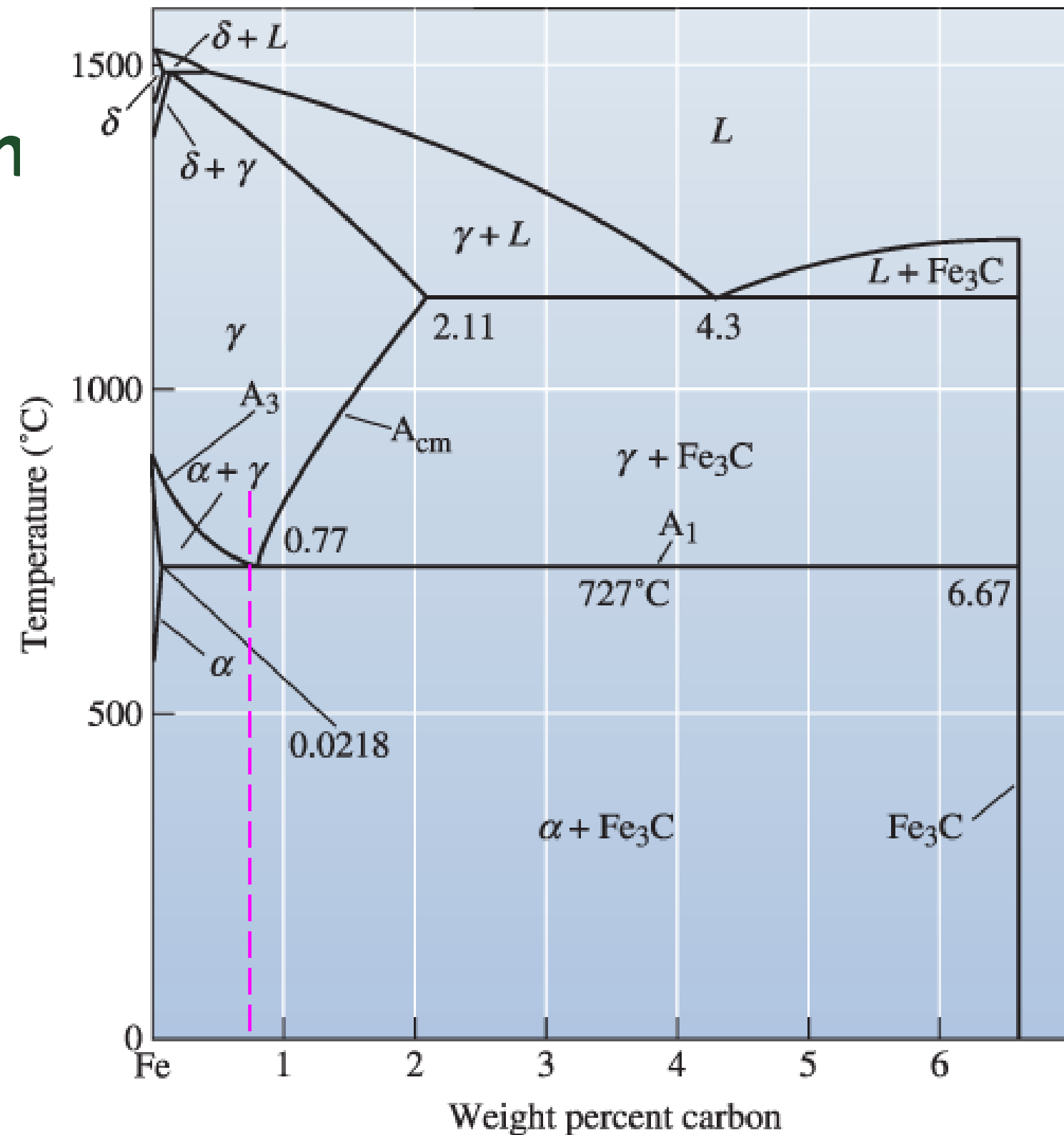
Fe-Fe<sub>3</sub>C pseudo binary system example:



$$C_{LE} = 0.77 \text{ wt.\% C}$$

$$C_{\alpha E} = 0.0218 \text{ wt.\% C}$$

$$C_{\text{Fe}_3\text{C}} = 6.67 \text{ wt.\% C}$$



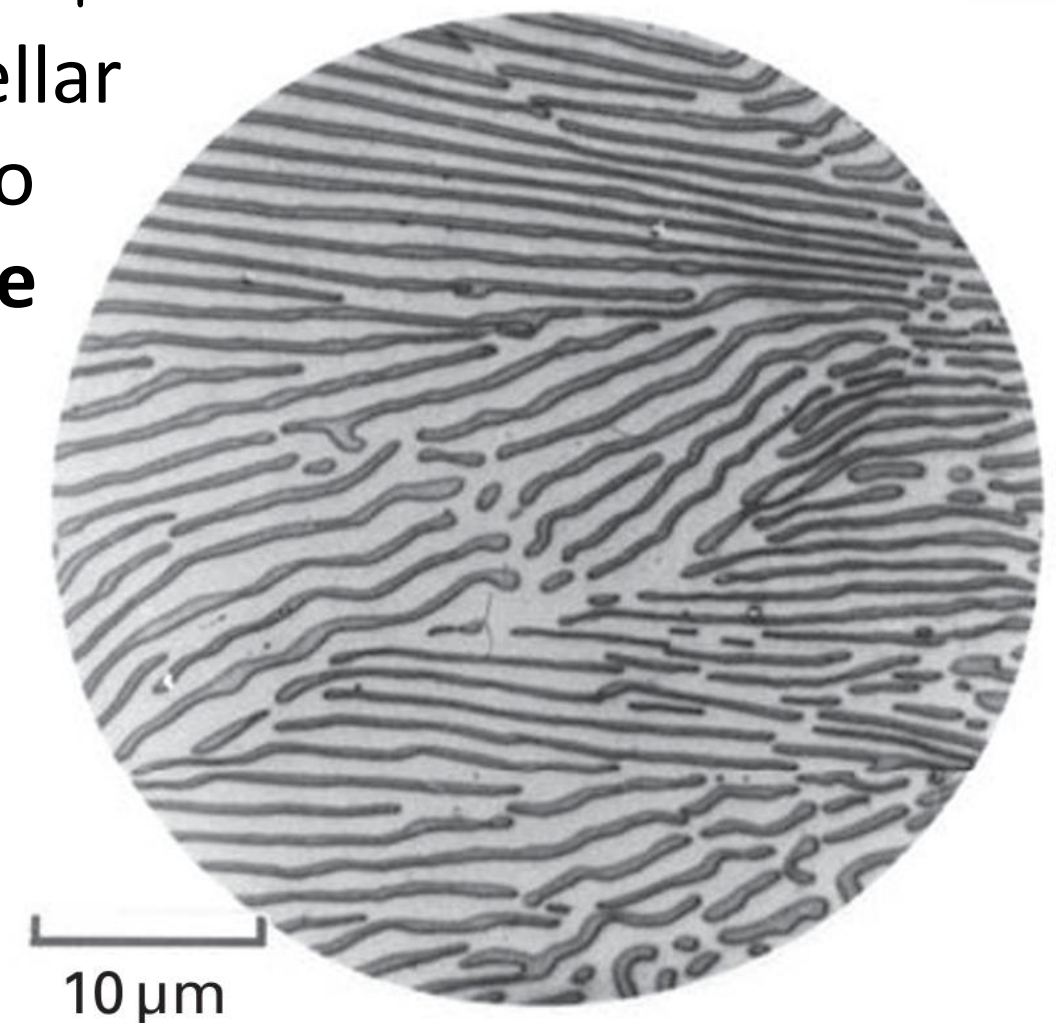
# Layered/Lamellar Eutectoid Structure for Carbon Steel

Eutectoid transformation in the Fe-Fe<sub>3</sub>C pseudo binary system:

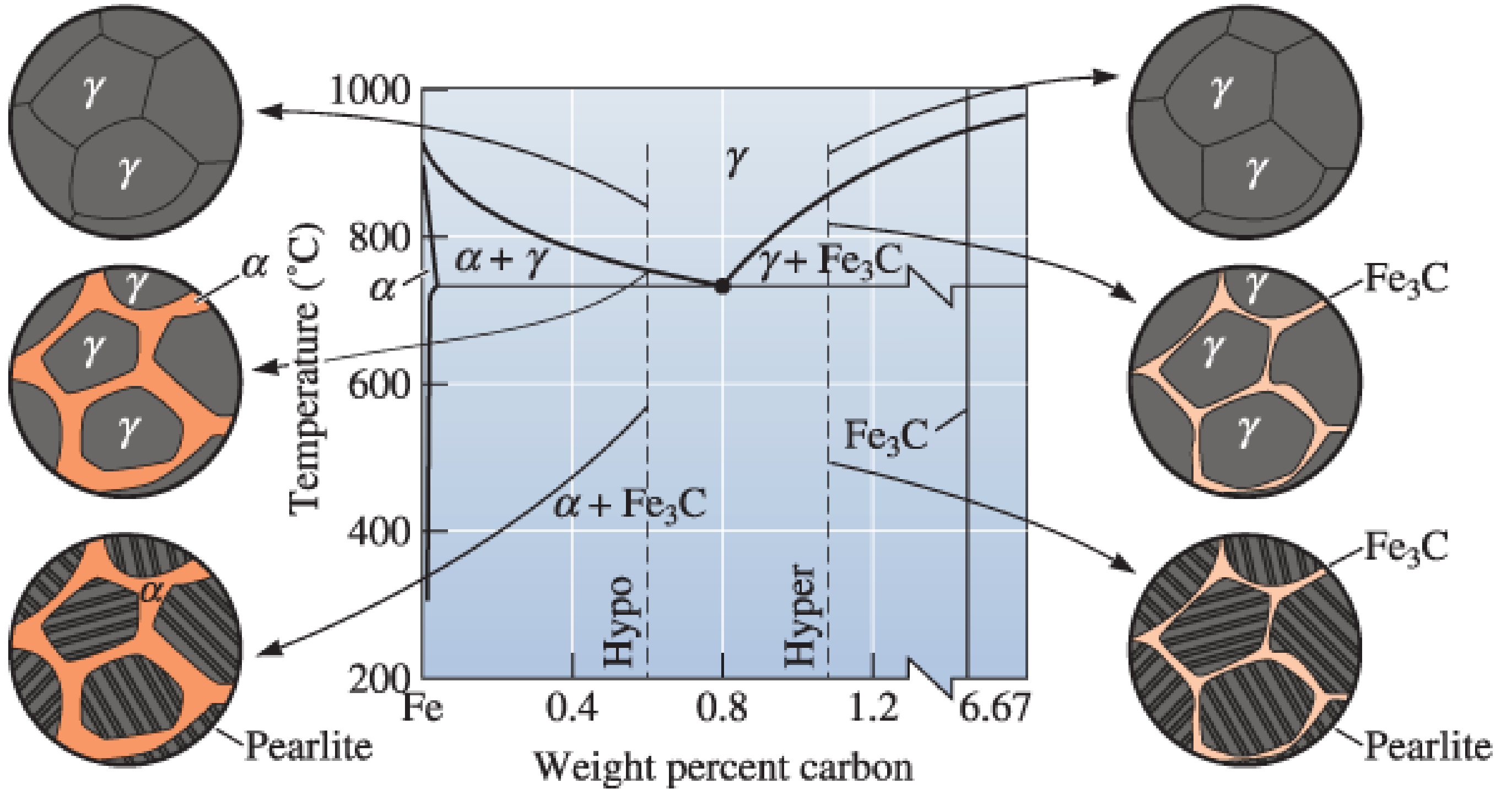


- Similar to eutectic transformation, layered or **lamellar structure** from eutectoid transformation occur, due to slow diffusion
- Pearlite actually an metal-ceramic composite
- Lamellar eutectic structure or pearlite (also called micro-constituent) significantly increase strength of steel

$\alpha$  / Fe<sub>3</sub>C lamellar structure, also called **pearlite**



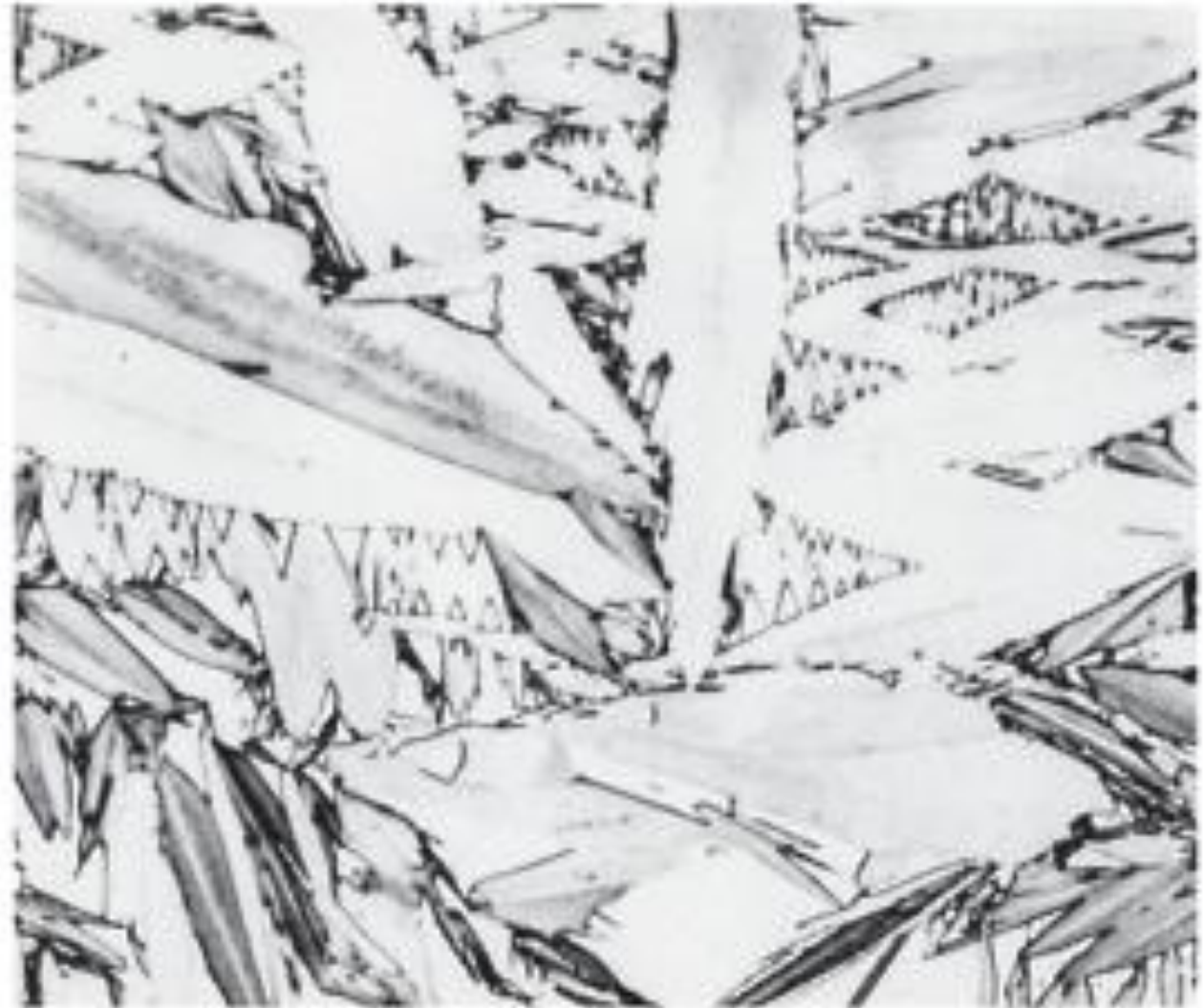
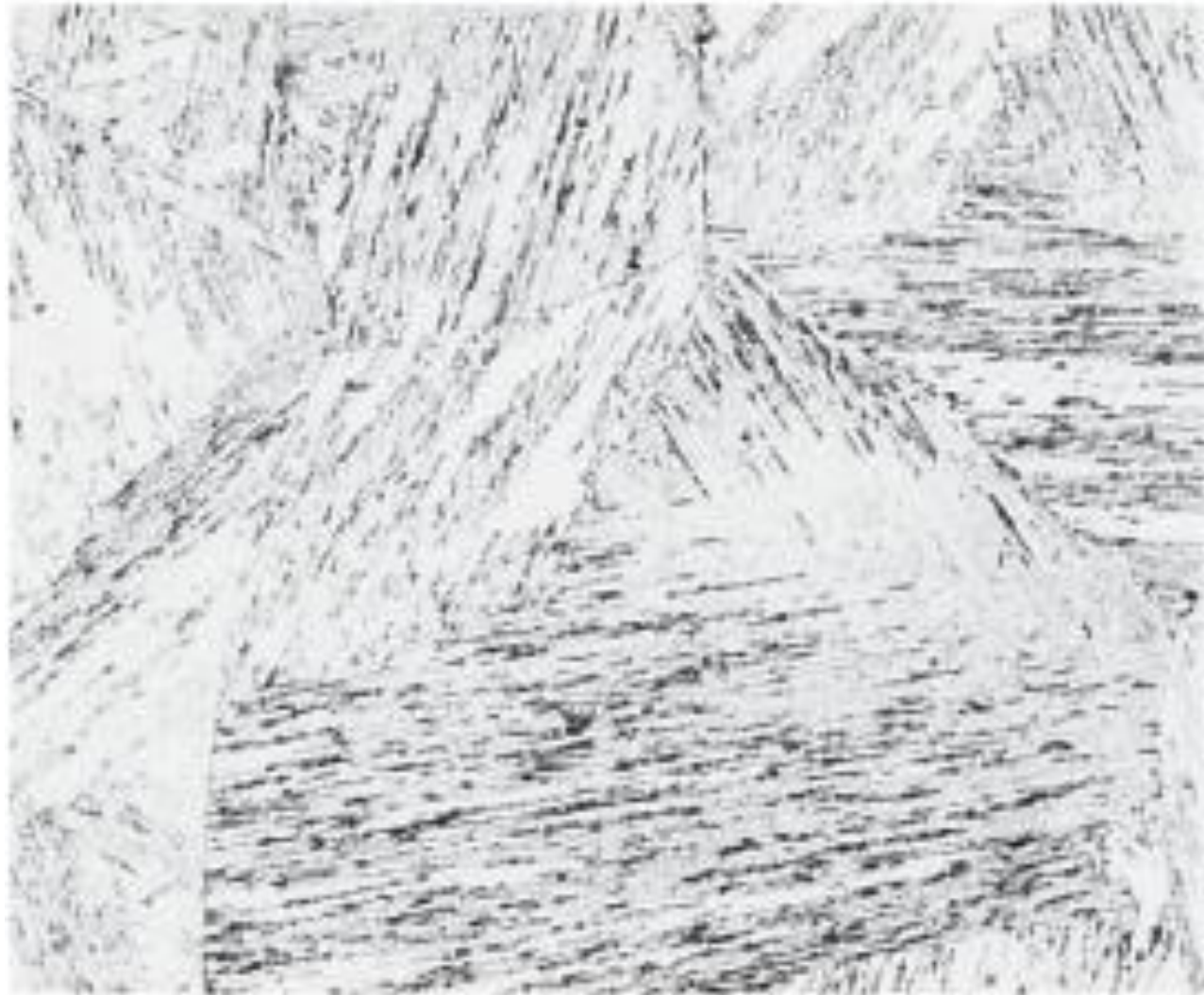
# Hypo- & Hyper-eutectoid Microstructure in Carbon Steel



Various structures depending on phase transformation (composition & temperature) 39

# Diffusionless Martensite Phase Transformation

- Fe-C system is rather complex: under certain condition (rapid cooling/**quench**), **non-equilibrium phase (Martensite) form, giving even higher strength**
- Closely spaced structure greatly enhance strength & hardness (by several times), while ductility drops



END

# Homework 0

Carefully review chapter 9, 11, and 12 lecture slides and, if time allows, read textbook sections of Askeland 9.1-9.13; 11.1-11.7; 12.2-12.8, 12.10-12.12 (some numerical example problems such as 9-1 to 9-8, 12-1, 12-7 to 12-10 could be omitted) and give an honor statement confirming the reading

# Homework 1

- Please write down one (or more) question that you are not clear or feel interested about in these three chapters (Chapters 9, 11, & 12).
- Check for answers using any AI tool and give brief comments on **your challenge to or suspicion of** the answer given by the AI.

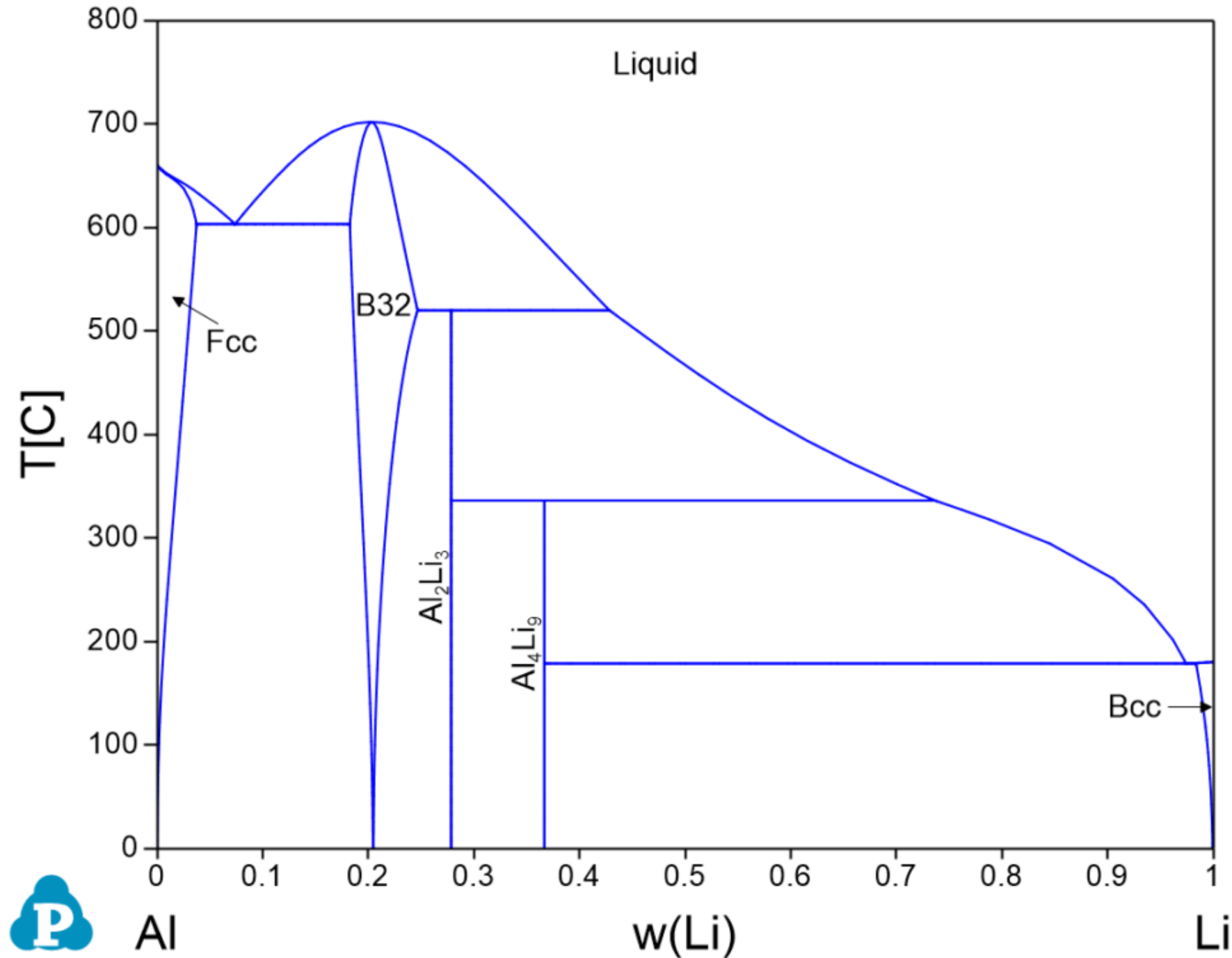
# Homework 2

Based on the Al-Li phase diagram below, please do the followings:

1) Identify the intermetallics (line compound) that may exist in the Al-Li system

2) Write down the eutectic reaction at around 600C as well as peritectic reactions at both ~520C and 340C in the system.

Please also write down the estimated composition for each of the phases involved in those reactions.



Al

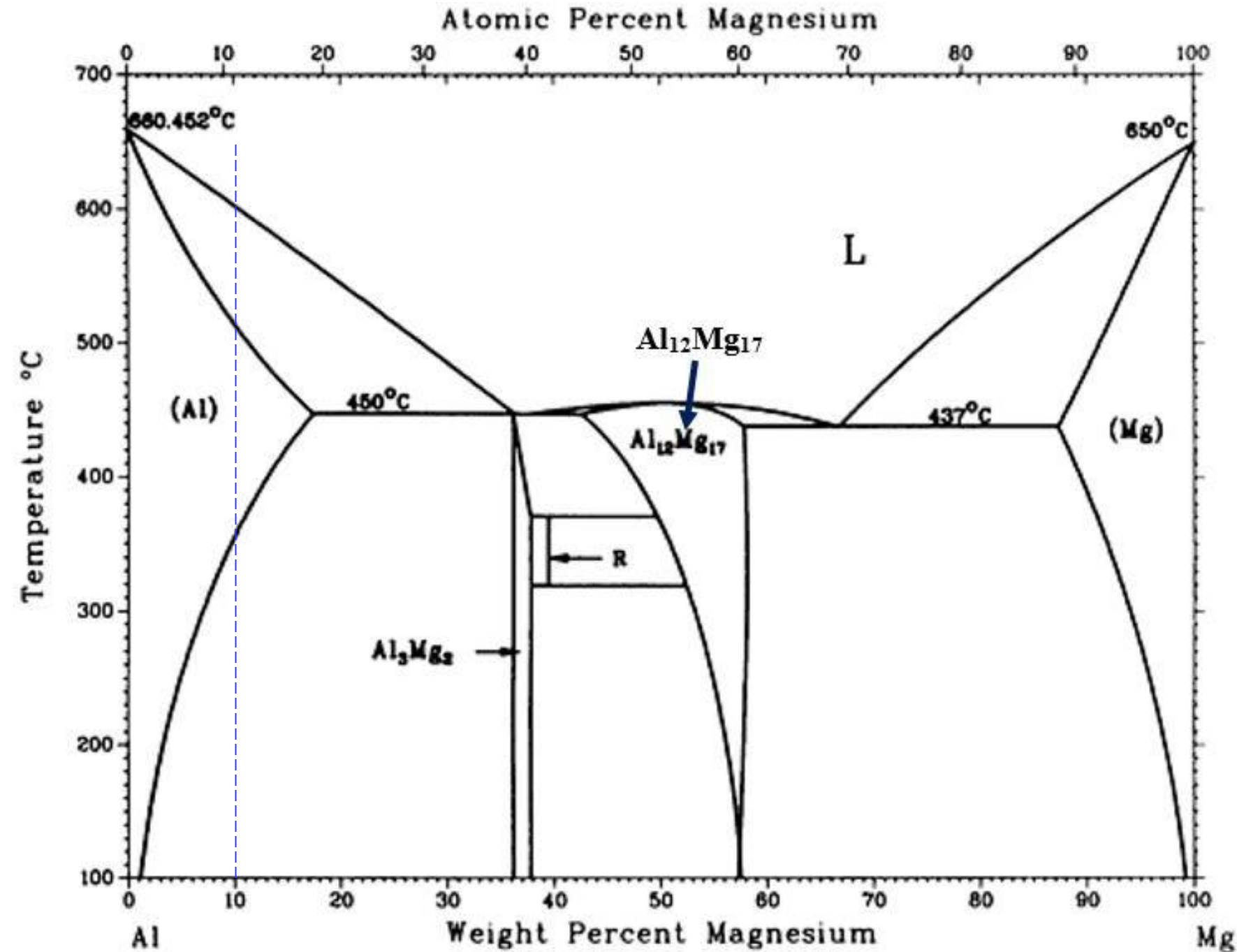
w(Li)

Li

# Homework 3

Based on the Al-Mg phase diagram:

1. What are the melting point for pure Al and pure Mg?
2. For an Al-Mg alloy with 10 wt.% Mg
  - a. At what temperature does solid first form and what is its composition?
  - b. At 550°C, what are the phases present, under equilibrium? What is their composition or chemistry? What is the relative amount or weight fraction for each phase?
  - c. At what temperature does last liquid disappear? What is its composition?
  - d. What about answers for b, but at 400°C?
  - e. What about answers for b, but at 100°C?



*Remember between two (neighboring) single-phase regions/line, there would be a two-phase region*

# Homework 4

Based on the Al-Mg phase diagram:

1. For an Al-Mg alloy with

80 wt.% Mg

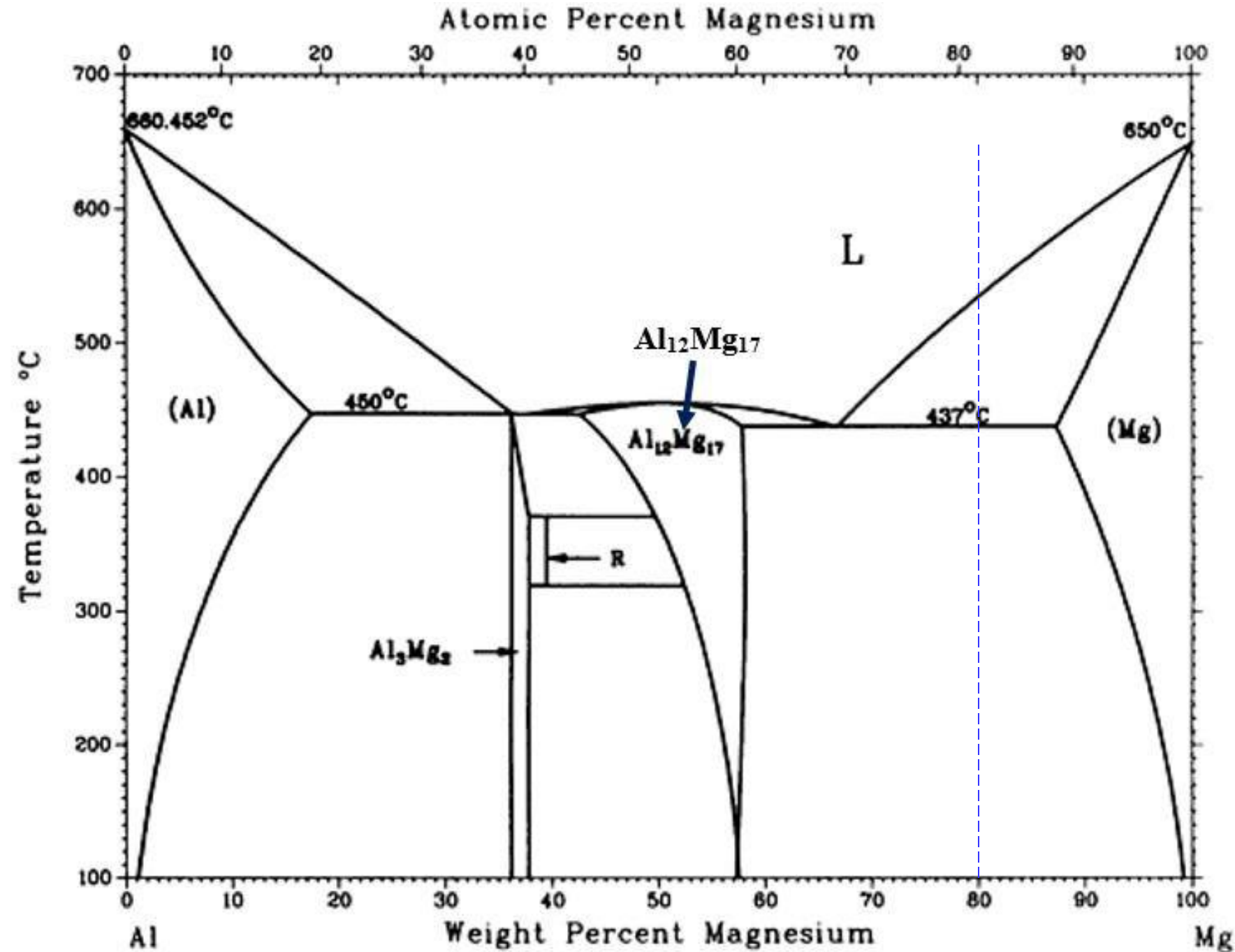
a. At 440°C (just above eutectic

temperature, what are the phases present, under equilibrium?

What is their composition or chemistry? What is the relative amount or weight fraction for each phase? Please also roughly illustrate the microstructure

b. What about answers for a, but at

435°C (just below eutectic temperature)? Please also roughly illustrate the microstructure

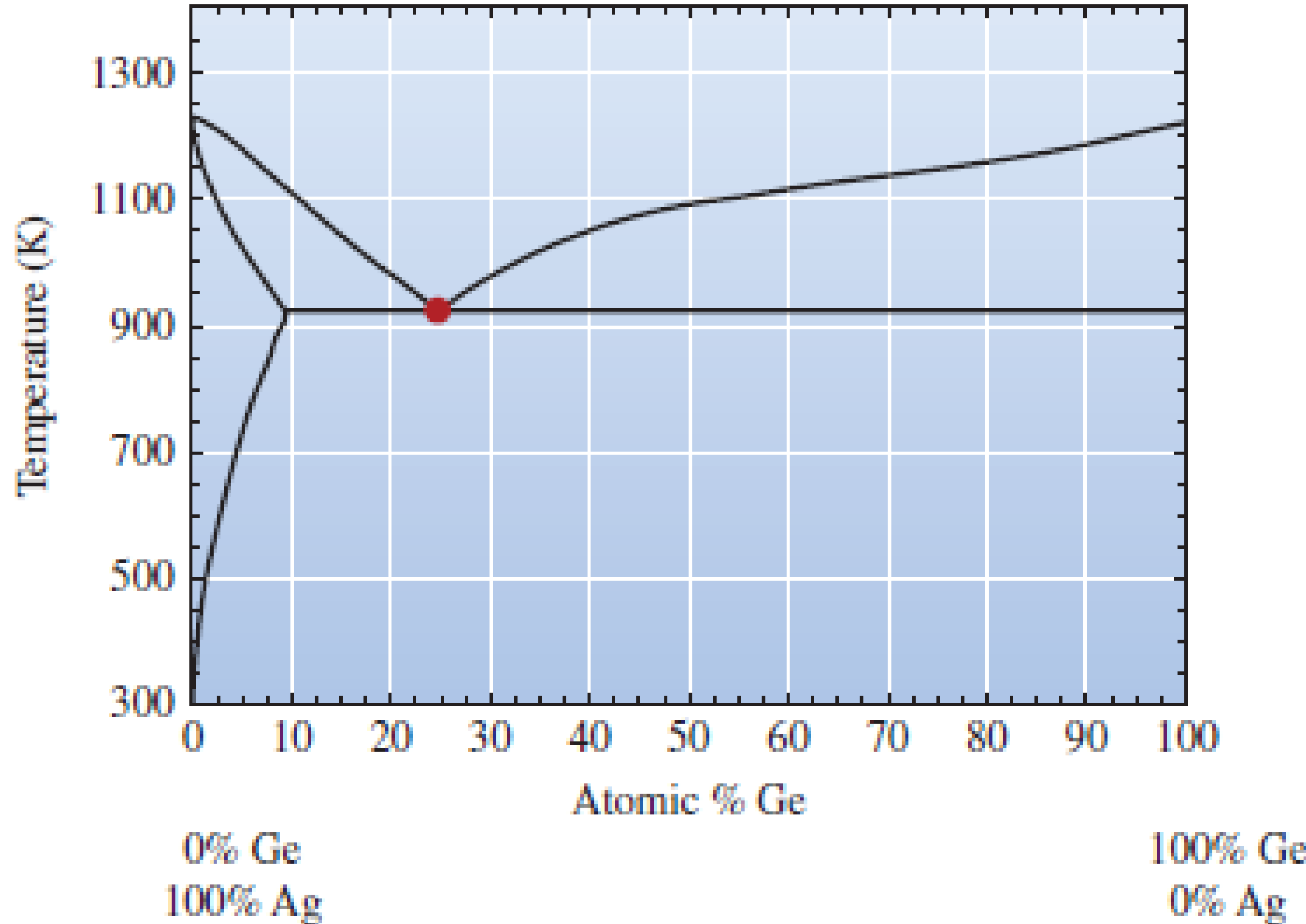


*Remember between two (neighboring) single-phase regions/line, there would be a two-phase region*

# Homework 5

Based on the phase diagram for the Ag-Ge system, roughly draw the cooling curves and indicate the appropriate temperatures, for the following Ag-Ge alloys:

1. 100 at.% Ag
2. 95 at.% Ag-5 at.% Ge
3. 85 at.% Ag-15 at.% Ge
4. 75 at.% Ag-25 at.% Ge
5. 55 at.% Ag-45 at.% Ge
6. 100 at.% Ge

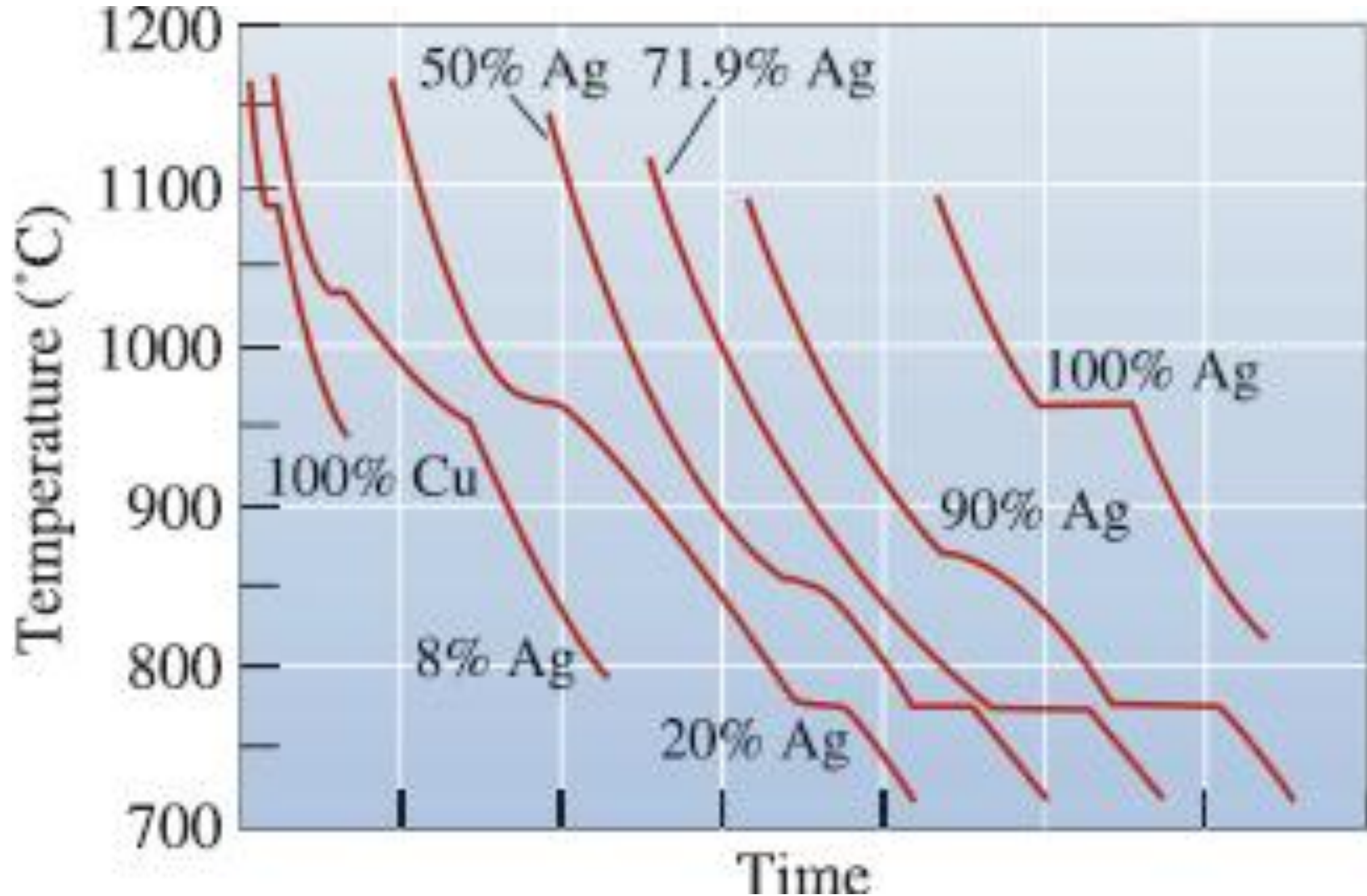


# Homework 6

Based on the series of cooling curves, please roughly re-construct the phase diagram.

Note the max solubility for Ag in Cu is 7.9 wt.%, while the max solubility of 8.8 wt.%.

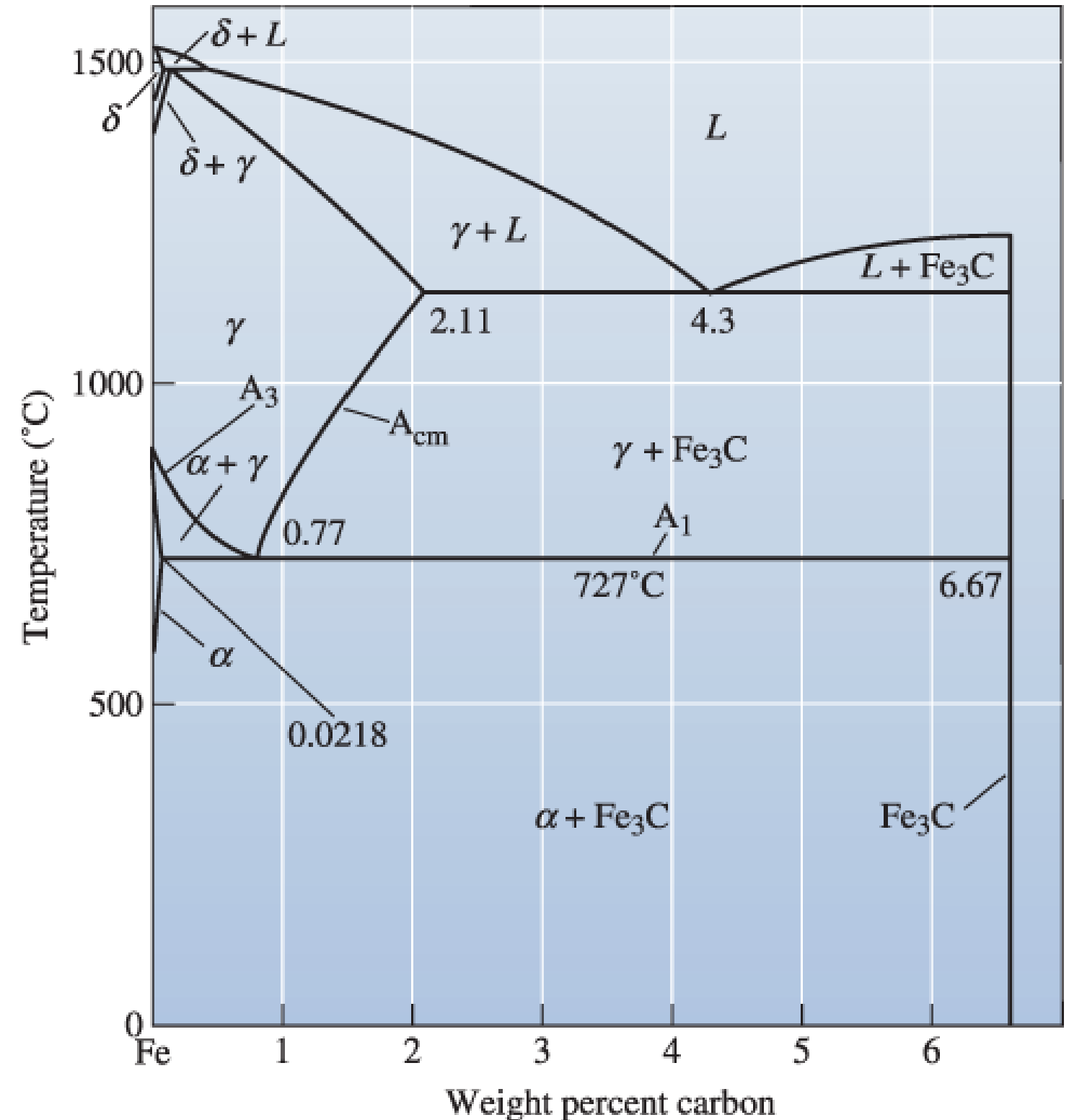
Please be sure to explain your work and label the relevant points



# Homework 7

For carbon steel w/ 1 wt.% C on slow (**equilibrium**) cooling, determine:

- The temperature when the  $\gamma$  phase (called austenite) start to first transform to other phases?
- The composition/chemistry and relative amount of each phase present at  $730^\circ\text{C}$
- The composition/chemistry and relative amount of each phase present at  $725^\circ\text{C}$
- If the primary  $\text{Fe}_3\text{C}$  (i.e.,  **$\text{Fe}_3\text{C}$**  formed above eutectoid temperature) is treated as a **microconstituent**, while the **eutectoid Fe/Fe<sub>3</sub>C lamellar** is regarded as **another microconstituent**, what the is composition and relative amount for each of the two micro-constituents?
- Draw microstructure for (b) and (c)



# Homework 8

Based on the partial phase diagram for the  $\text{ZrO}_2$ -CaO system (sometimes also called as CSZ or CaO stabilized  $\text{ZrO}_2$ ), determine the eutectoid temperature, the eutectoid phase transformation, and the composition for each of the phase involved in the eutectoid phase transformation

