ENGG103 – Materials in Design

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ENGG103 – Materials in Design

Week 5: Lecture 5 – Phase Diagrams

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Consultation hours:

Monday 10:30 – 12:30

https://uow.webex.com/meet/ciara

Please email first for appointment.

Phase Diagrams

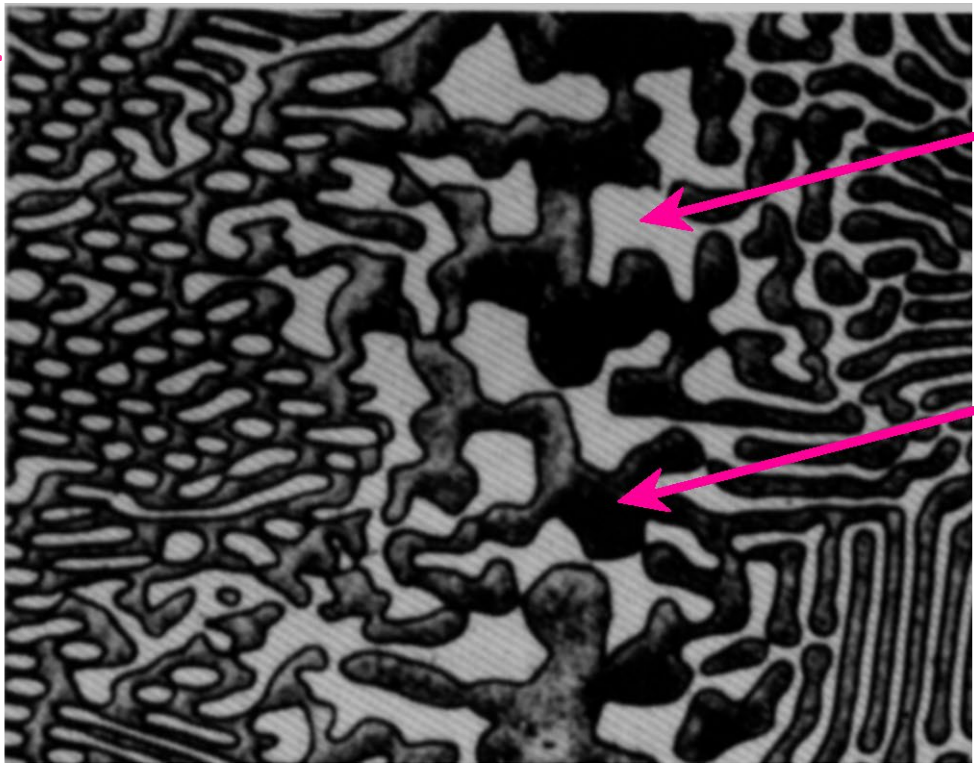
Phase diagrams are important for materials engineers

A phase diagram is a **graphical representation** of the phases that are present in a material at various temperatures and pressures and compositions.

Components and Phases

- **Components**:
  The elements or compounds that are mixed initially (**Al** and **Cu**).
- **Phases**:
  A phase is a homogenous, physically distinct and mechanically separable portion of the material with a given chemical composition and structure (α and β).

Aluminum-Copper Alloy



β (lighter phase) (Low Al content)

α (darker phase) (High Al content)

Phase Diagrams

Constitution of an alloy is described by

1. phases present
2. the weight fraction of each phase
3. the composition of each phase

Binary alloys: contain 2 components

Ternary alloys: contain 3 components

Quaternary: 4 components etc.

Phase Diagrams – Binary (2 components)

- When we combine two elements...
  what is the resulting equilibrium state?

- In particular, if we specify...
  -- the composition (e.g., wt% Cu - wt% Ni), and
  -- the temperature (*T*)

then we can determine the **Constitution**

- How many phases form?
- What is the composition of each phase?
- What is the amount of each phase?

Phase Equilibria: Solubility Limit

- Solution – solid, liquid, or gas solutions, single phase
- Mixture – more than one phase

Adapted from Fig. 9.1, *Callister & Rethwisch 8e.*

- Solubility Limit:

  Maximum concentration for which only a single phase solution exists.

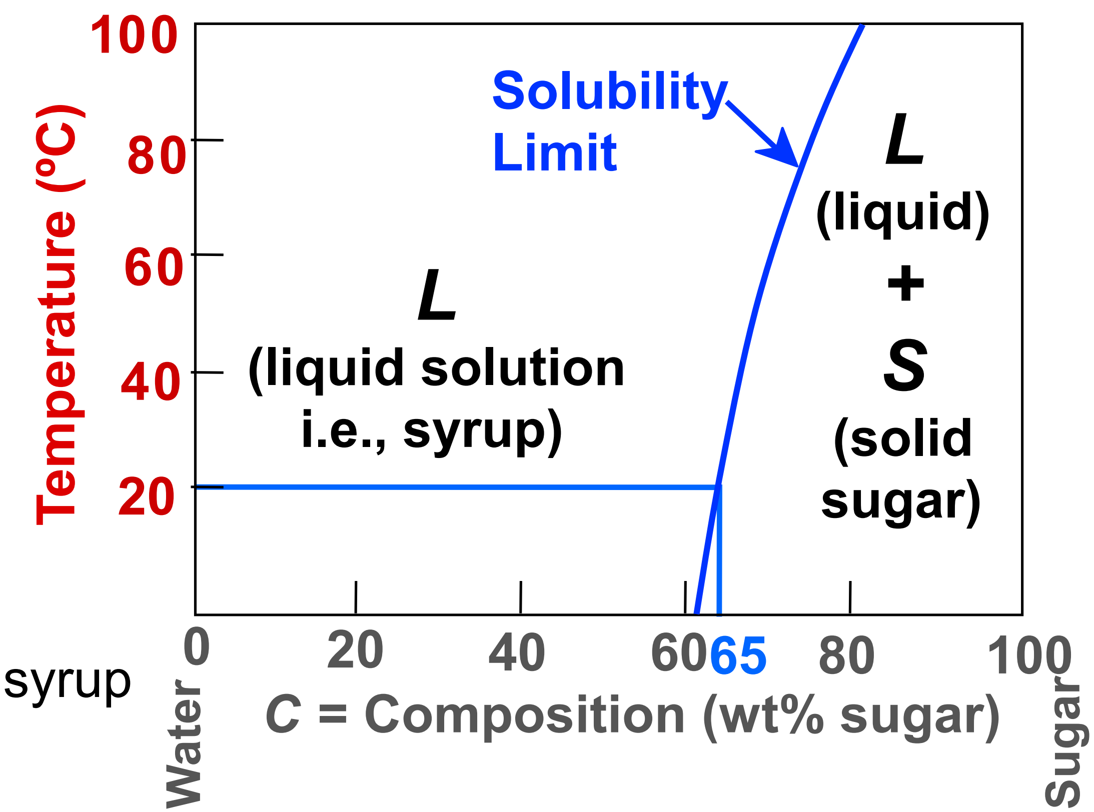
Question: What is the solubility limit for sugar in water at 20ºC?

Answer: 65 wt% sugar.

At 20ºC, if *C* < 65 wt% sugar: syrup

At 20ºC, if *C* > 65 wt% sugar: syrup + sugar

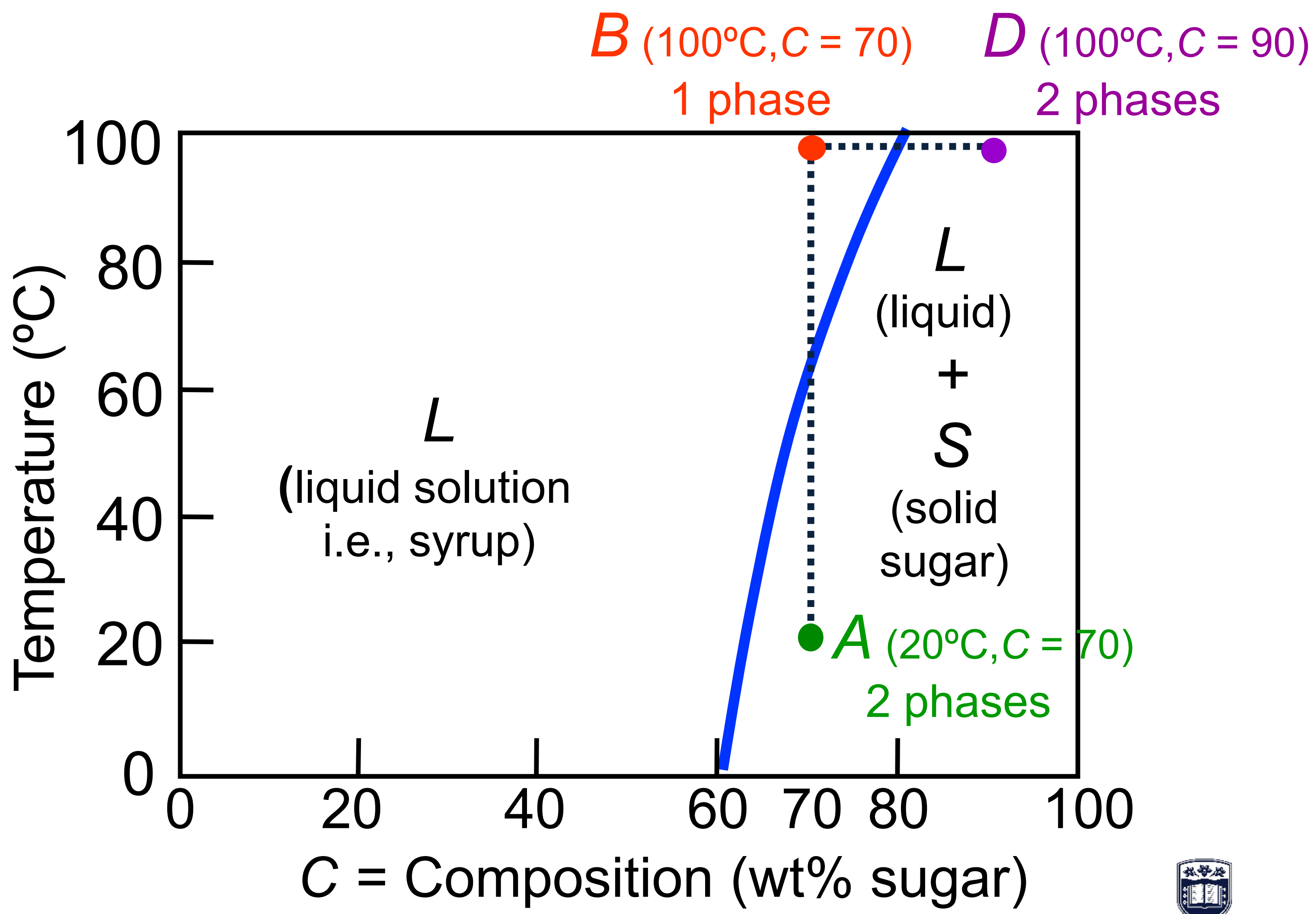
Sugar/Water Phase Diagram



Effect of Temperature & Composition

- Altering *T* can change # of phases: path *A* to *B*.
- Altering *C* can change # of phases: path *B* to *D*.

water-
sugar
system



Adapted from Fig. 9.1,
Callister & Rethwisch 8e.

Criteria for Solid Solubility

Simple system (e.g., Ni-Cu solution)

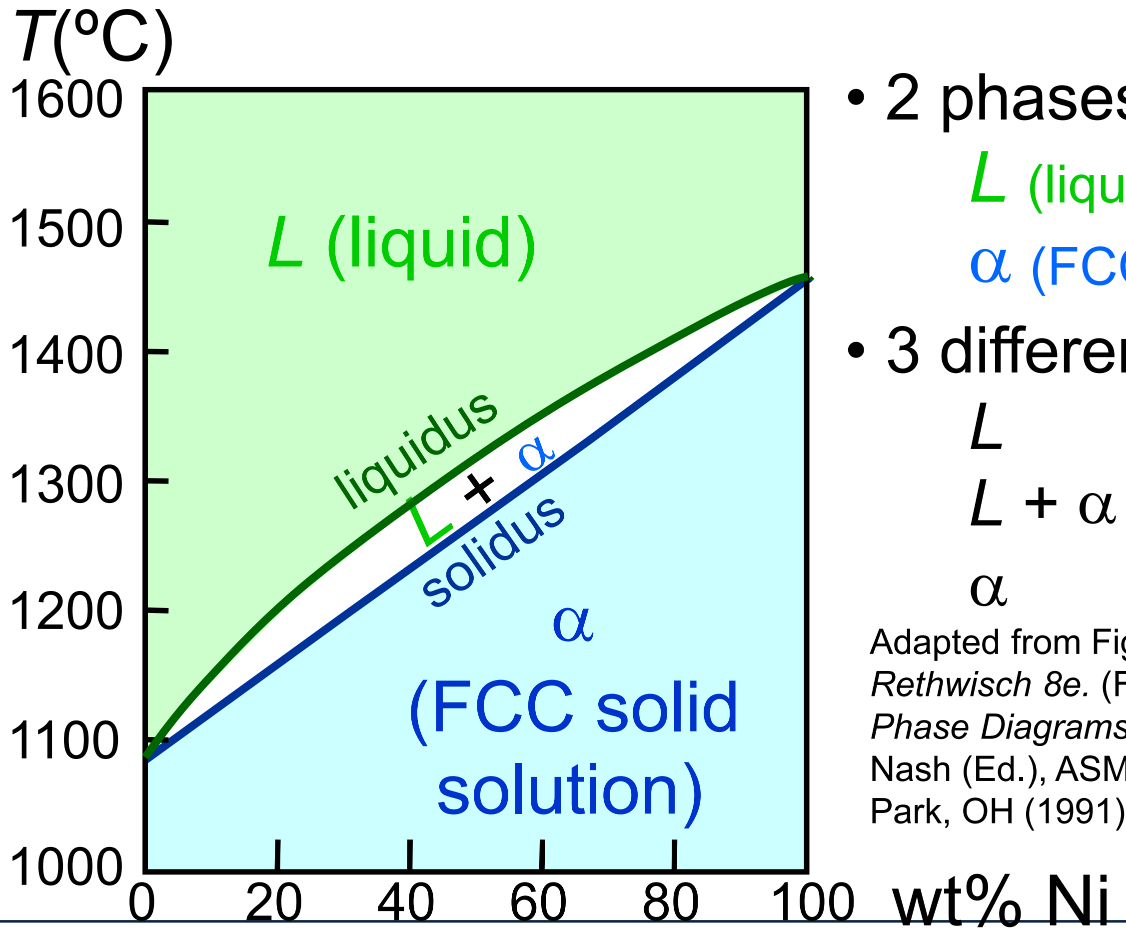
	Crystal Structure	electroneg	*r* (nm)
Ni	FCC	1.9	0.1246
Cu	FCC	1.8	0.1278

- Both have the same crystal structure (FCC) and have similar electronegativities and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.
- Ni and Cu are totally soluble in one another for all proportions.

Phase Diagrams

- Indicate phases as a function of *T*, *C*, and *P*.
- For this course:
  - binary systems: just 2 components.
  - independent variables: *T* and *C* (*P* = 1 atm is almost always used).

Phase Diagram for Cu-Ni system

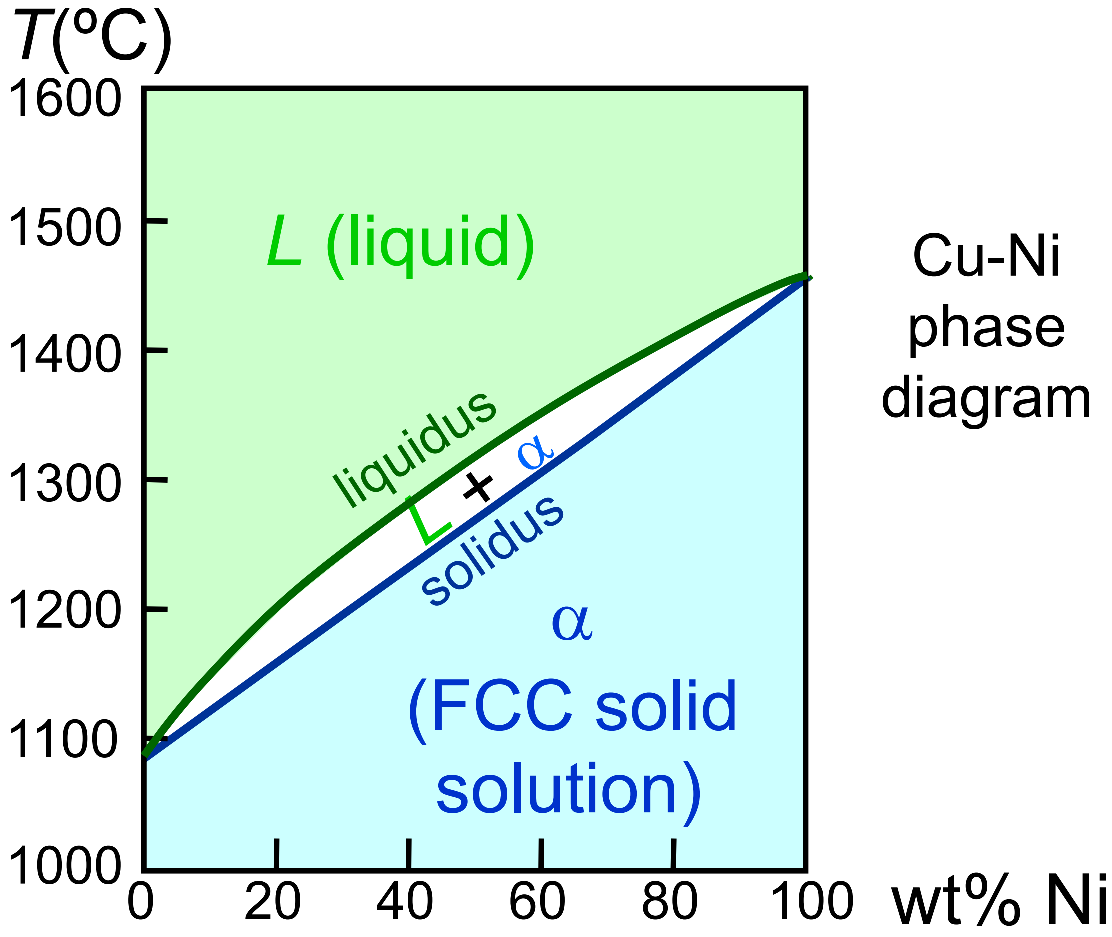


- 2 phases:
  - *L* (liquid)
  - α (FCC solid solution)
- 3 different phase fields:
  - *L*
  - *L* + α
  - α

Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Isomorphous Binary Phase Diagram

- Phase diagram:
  Cu-Ni system.
- System is:
  -- binary
  i.e., 2 components: Cu and Ni.
  -- isomorphous
  i.e., complete solubility of one component in another; α phase field extends from 0 to 100 wt% Ni.



Cu-Ni phase diagram

Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

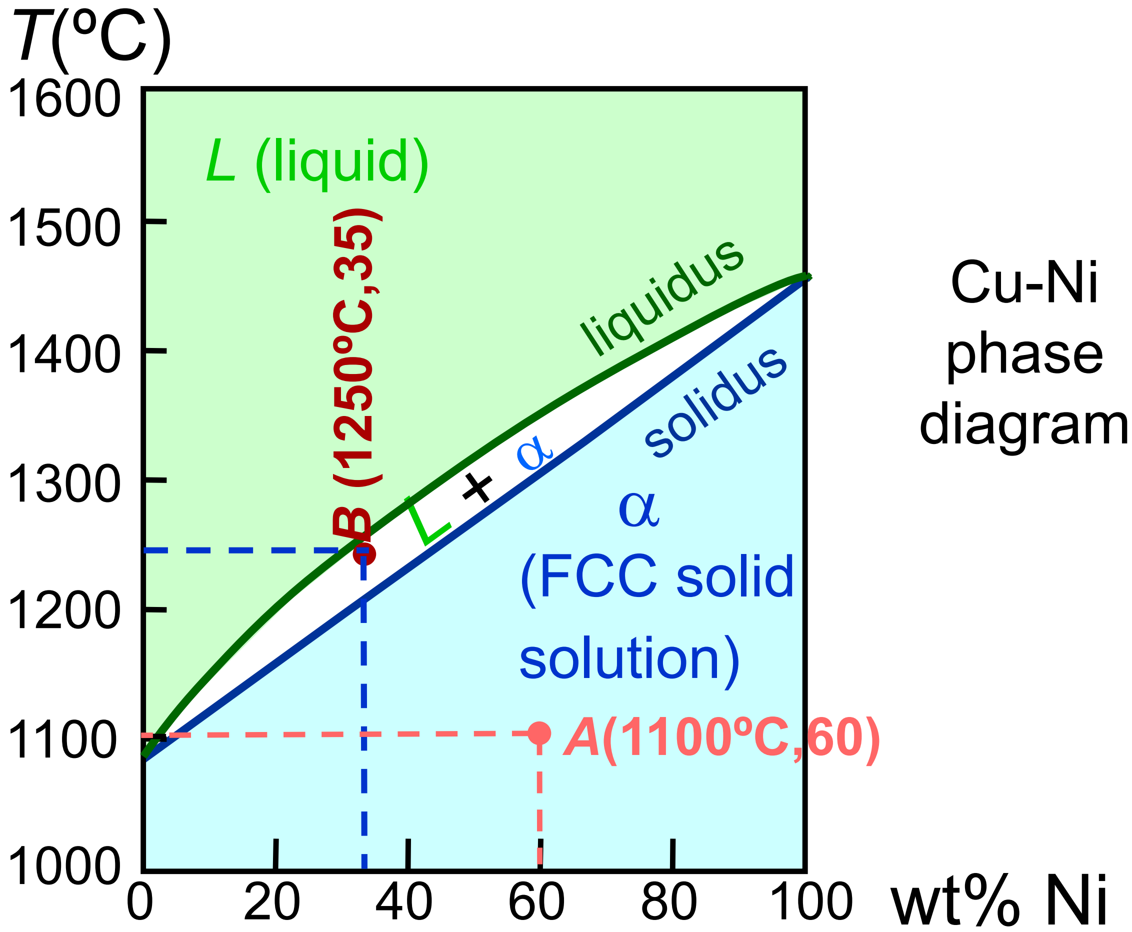
Phase Diagrams:
Determination of phase(s) present

- Rule 1: If we know *T* and C_o, then we know:
  -- which phase(s) is (are) present.

- Examples:

  A(1100ºC, 60 wt% Ni):
  1 phase: α

  B(1250ºC, 35 wt% Ni):
  2 phases: *L* + α



Cu-Ni phase diagram

Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Phase Diagrams:

Determination of phase compositions

- Rule 2: If we know T and C_0, then we can determine:
  -- the composition of each phase.

- Examples:

  Consider C_0 = 35 wt% Ni

  At T_A = 1320ºC:

  Only Liquid (L) present

  $C_L = C_0$ (= 35 wt% Ni)

  At T_D = 1190ºC:

  Only Solid (α) present

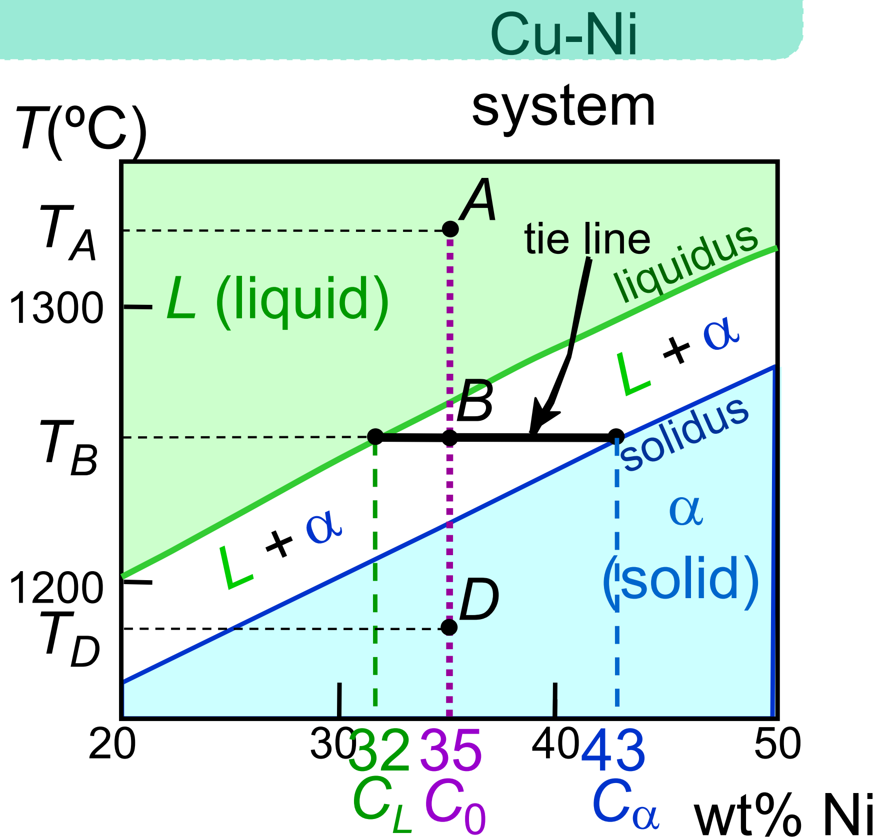
  $C_\alpha = C_0$ (= 35 wt% Ni)

  At T_B = 1250ºC:

  Both α and L present

  $C_L = C_{liquidus}$ (= 32 wt% Ni)

  $C_\alpha = C_{solidus}$ (= 43 wt% Ni)



Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Determination of phase weight fractions

- Rule 3: If we know T and C_0, then can determine:
  -- the weight fraction of each phase.

Cu-Ni system

- Examples:

Consider C_0 = 35 wt% Ni

At T_A : Only Liquid (L) present

W_L = 1.00, W_α = 0

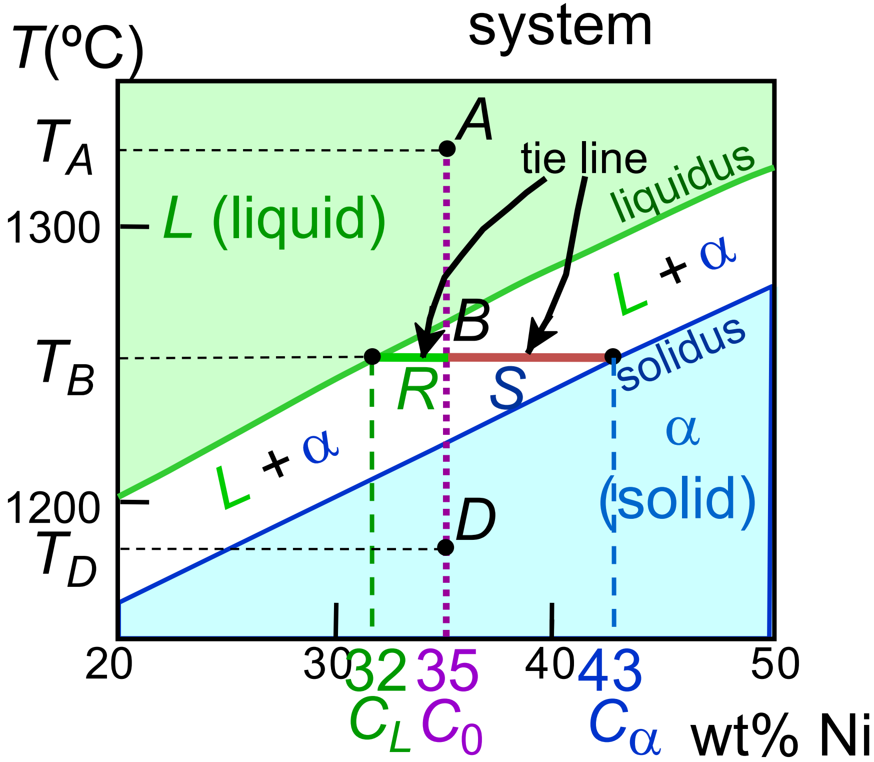
At T_D : Only Solid (α) present

W_L = 0, W_α = 1.00

At T_B : Both α and L present

$$W_L = \frac{S}{R+S} = \frac{43-35}{43-32} = 0.73$$

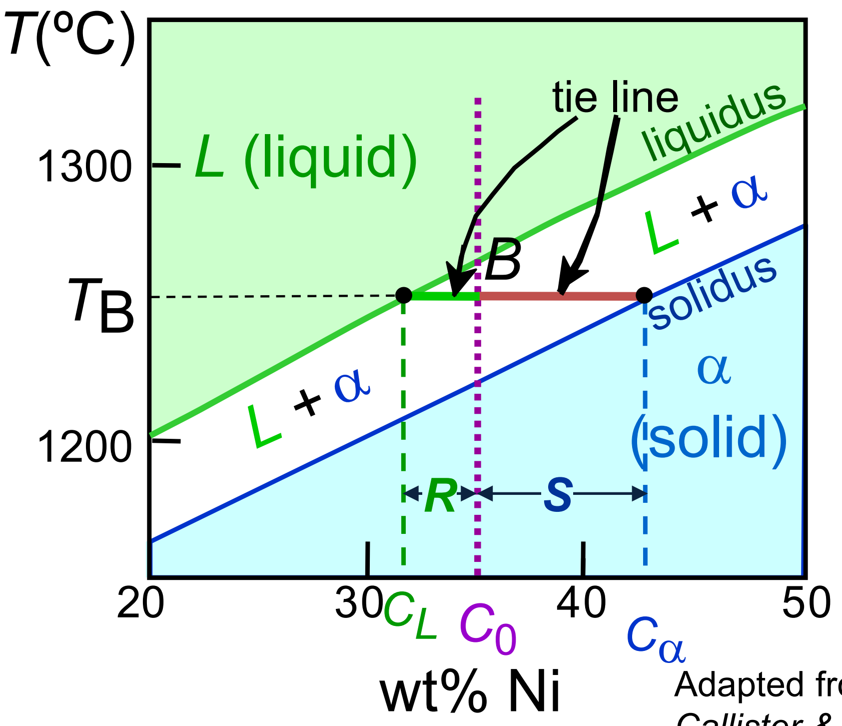
$$W_\alpha = \frac{R}{R+S} = 0.27$$



Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

The Lever Rule

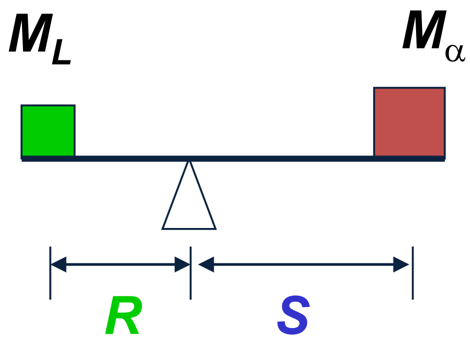
- Tie line – connects the phases in equilibrium with each other – also sometimes called an isotherm



Adapted from Fig. 9.3(b), *Callister & Rethwisch 8e.*

What fraction of each phase?

Think of the tie line as a lever (teeter-totter)



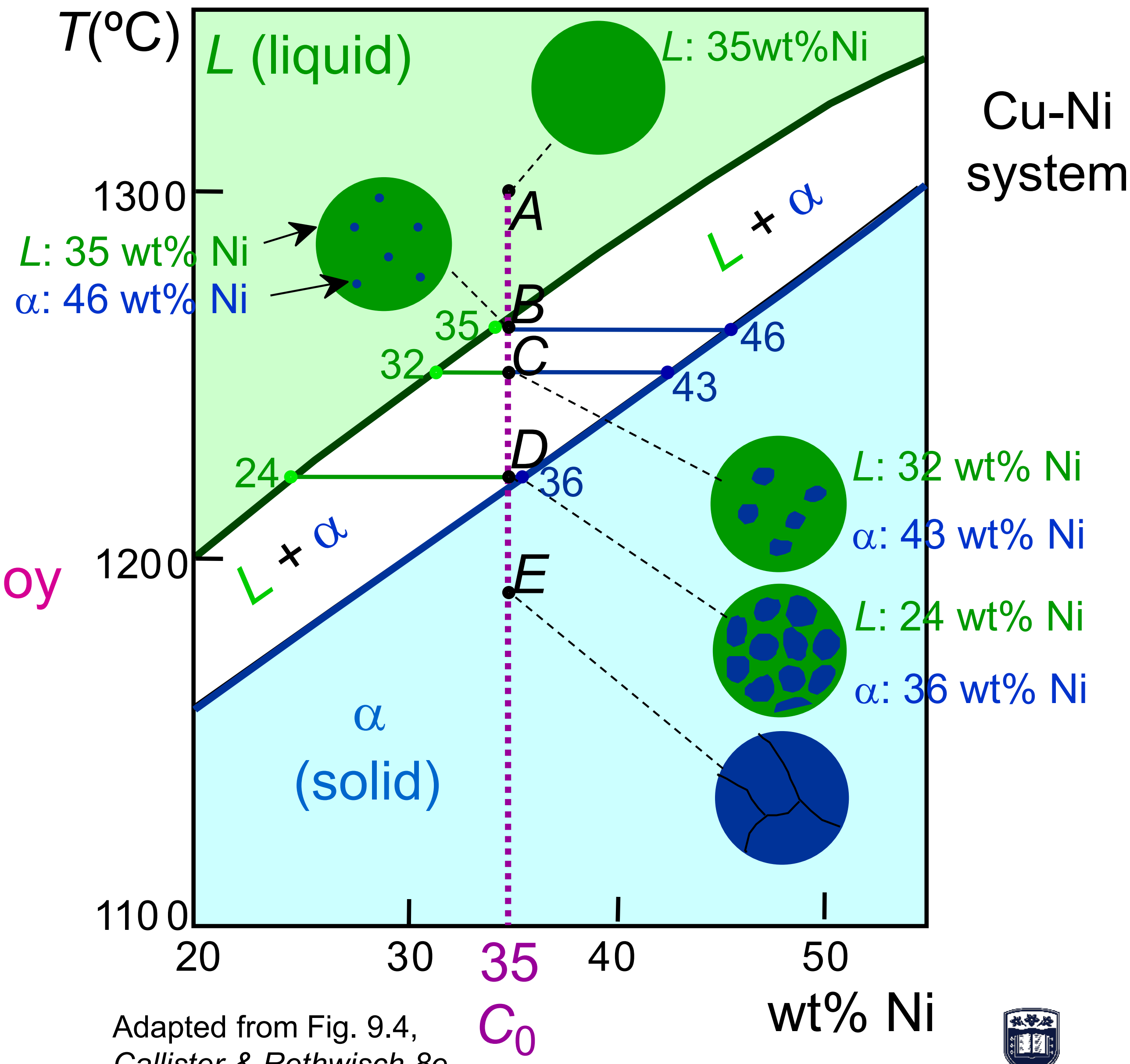
$$M_\alpha \times S = M_L \times R$$

$$W_L = \frac{M_L}{M_L + M_\alpha} = \frac{S}{R+S} = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{R}{R+S} = \frac{C_0 - C_L}{C_\alpha - C_L}$$

Ex: Cooling of a Cu-Ni Alloy

- Phase diagram: Cu-Ni system.
- Consider microstuctural changes that accompany the cooling of a C_0 = 35 wt% Ni alloy

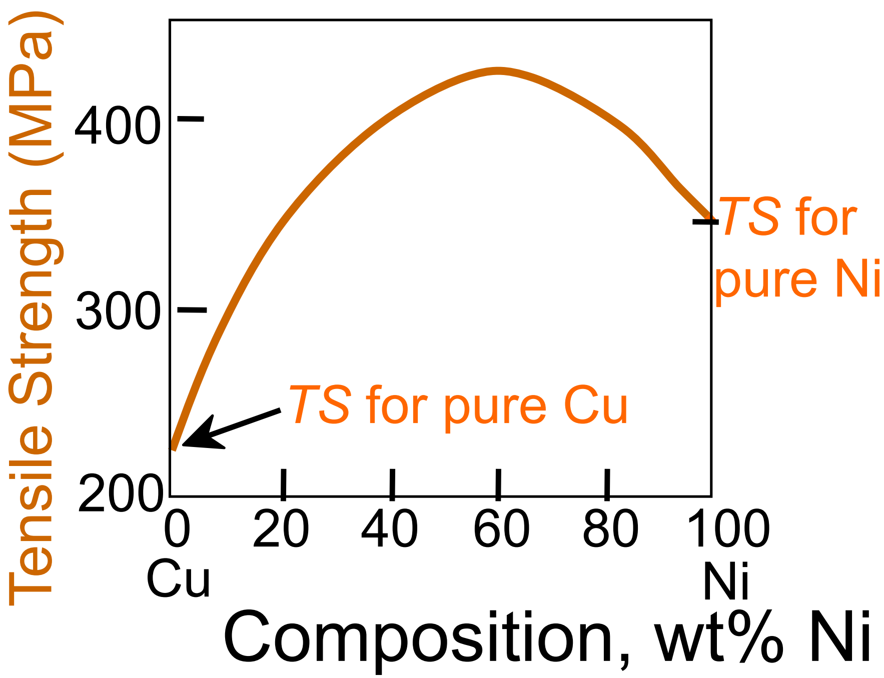


Adapted from Fig. 9.4, *Callister & Rethwisch 8e.*

Mechanical Properties: Cu-Ni System

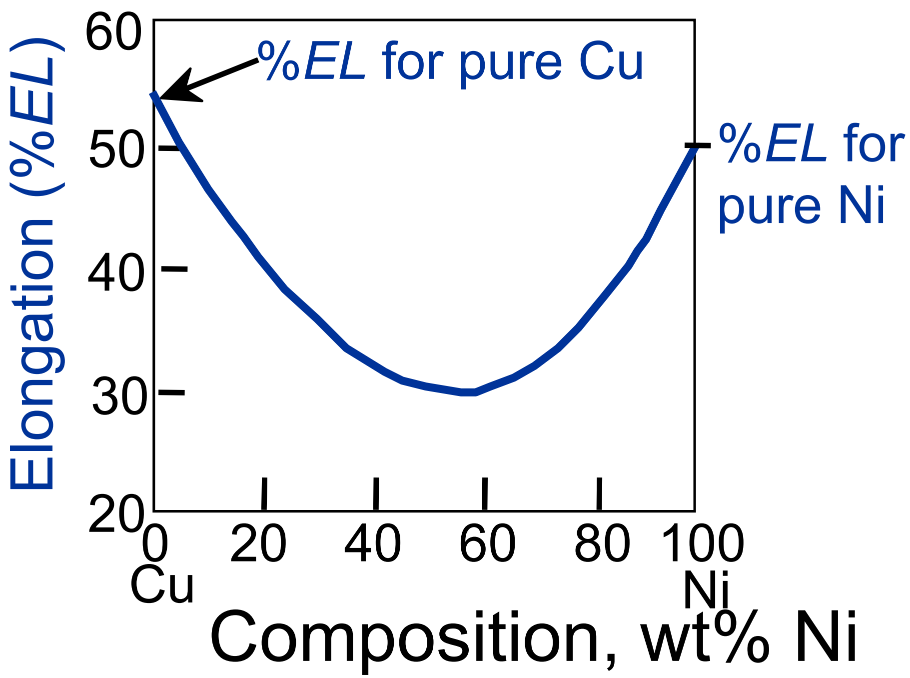
- Effect of solid solution strengthening on:

-- Tensile strength (*TS*)



Adapted from Fig. 9.6(a), *Callister & Rethwisch 8e.*

-- Ductility (%*EL*)



Adapted from Fig. 9.6(b), *Callister & Rethwisch 8e.*

Important information that can be extracted from a phase diagram

1. **The phase(s) present at a given temperature and composition**

2. **The chemical composition of each phase present**

3. **The mass fraction (%) of each phase present**

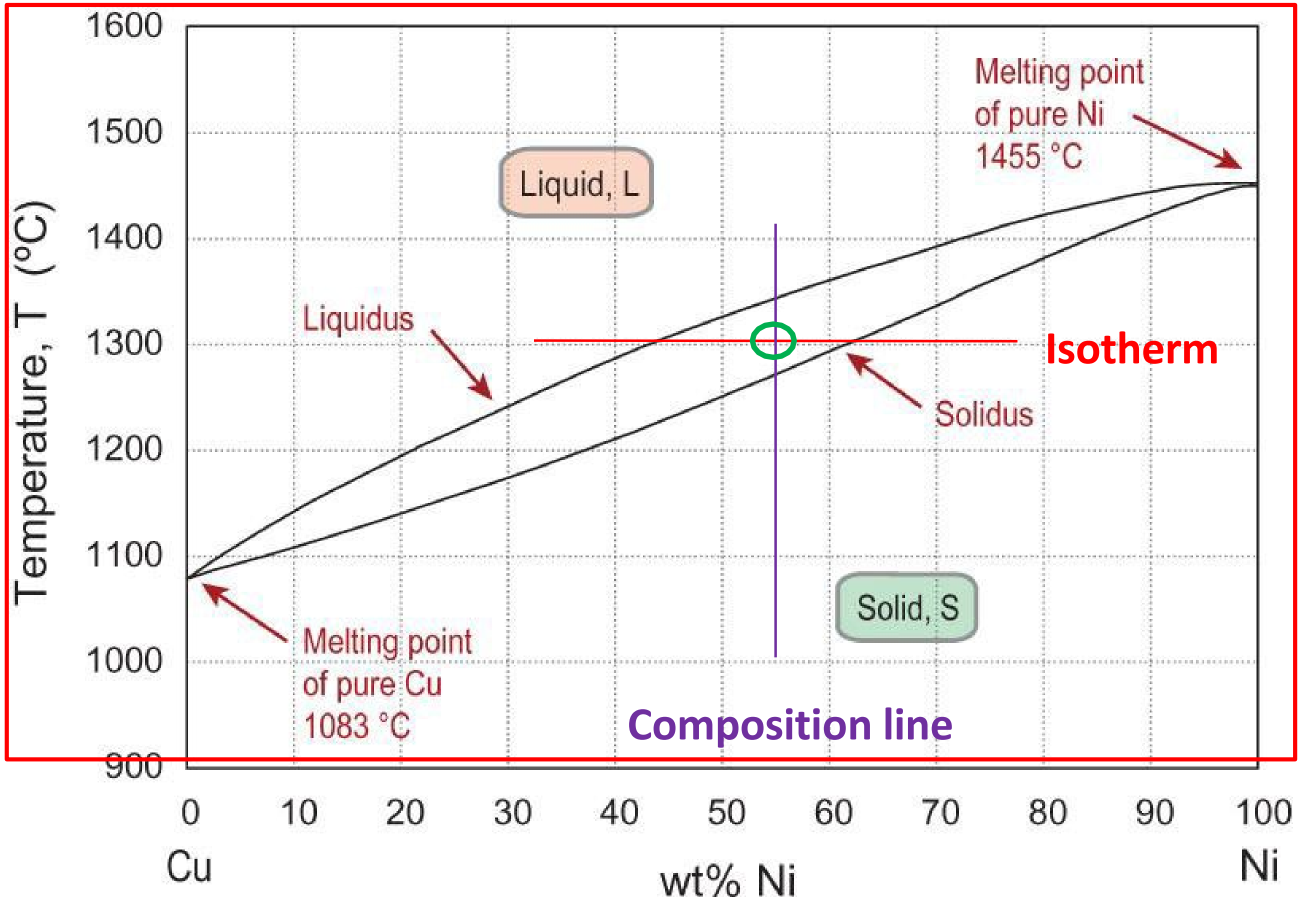
These three rules are of the utmost importance.

You need to make sure that you understand the rules the
implications thereof and
the application off these three rules

Important information that can be extracted from a phase diagram

1. The phase(s) present at a given temperature and composition

The intersection of the isotherm with the composition line define the phase(s) present



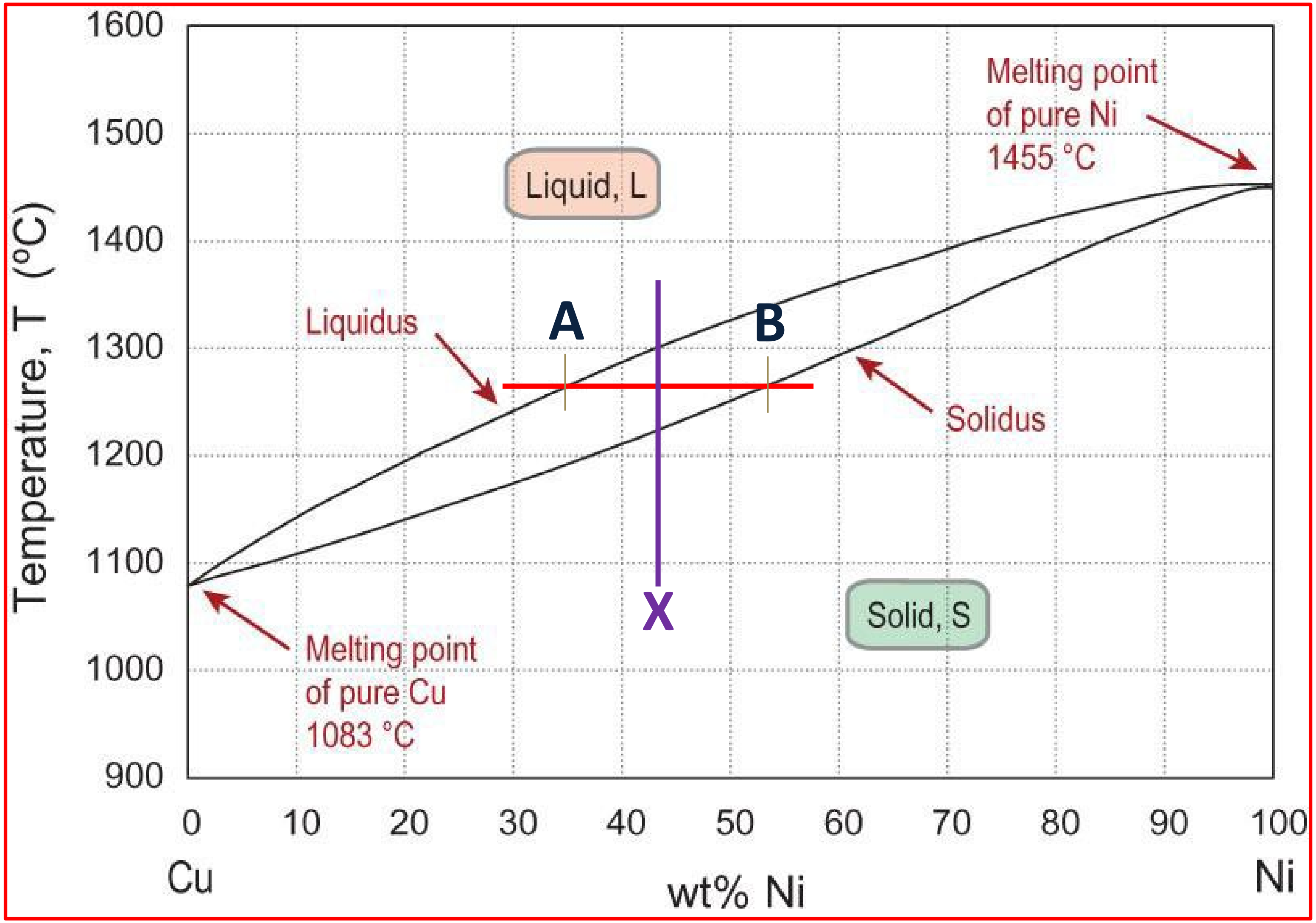
Phases present at 1300C

Liquid and Solid

Important information that can be extracted from a phase diagram

For composition X, the line A-B is called a tie-line

(The isotherm intersects the liquidus in **A** and the solidus in **B**)



We call the line that intersects an isotherm at the phase boundaries a Tie-Line

Important information that can be extracted from a phase diagram

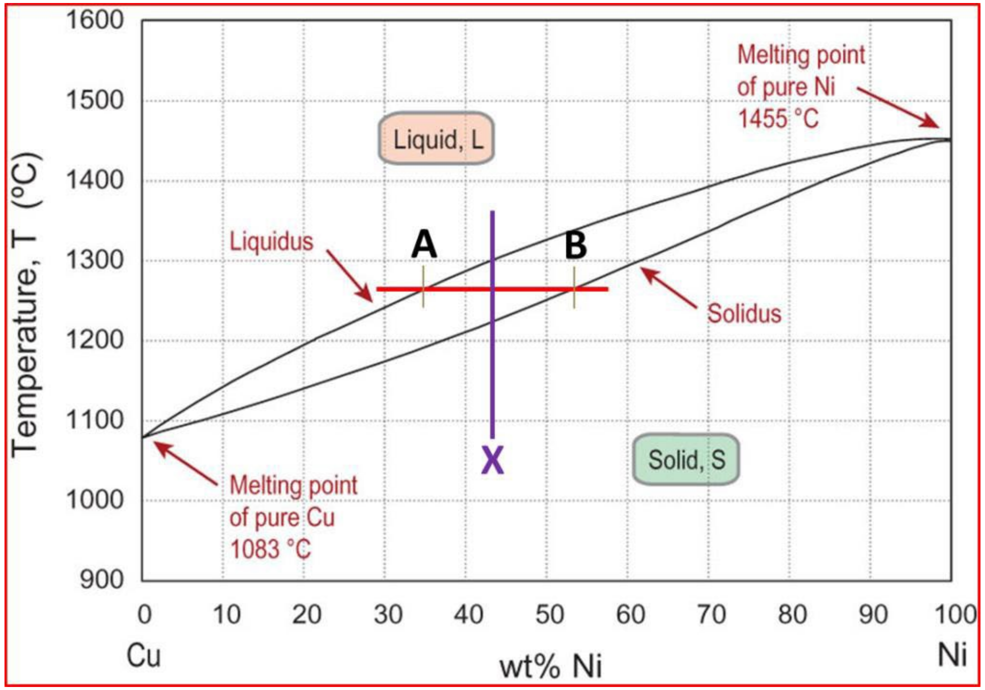
2. The chemical composition of each phase present

For a given composition, the intersections of the tie-line with the phase boundaries define the chemical composition of the respective phases

For composition X

The **tie-line** intersect the phase boundaries:

- The liquidus in **A**
- The solidus in **B**

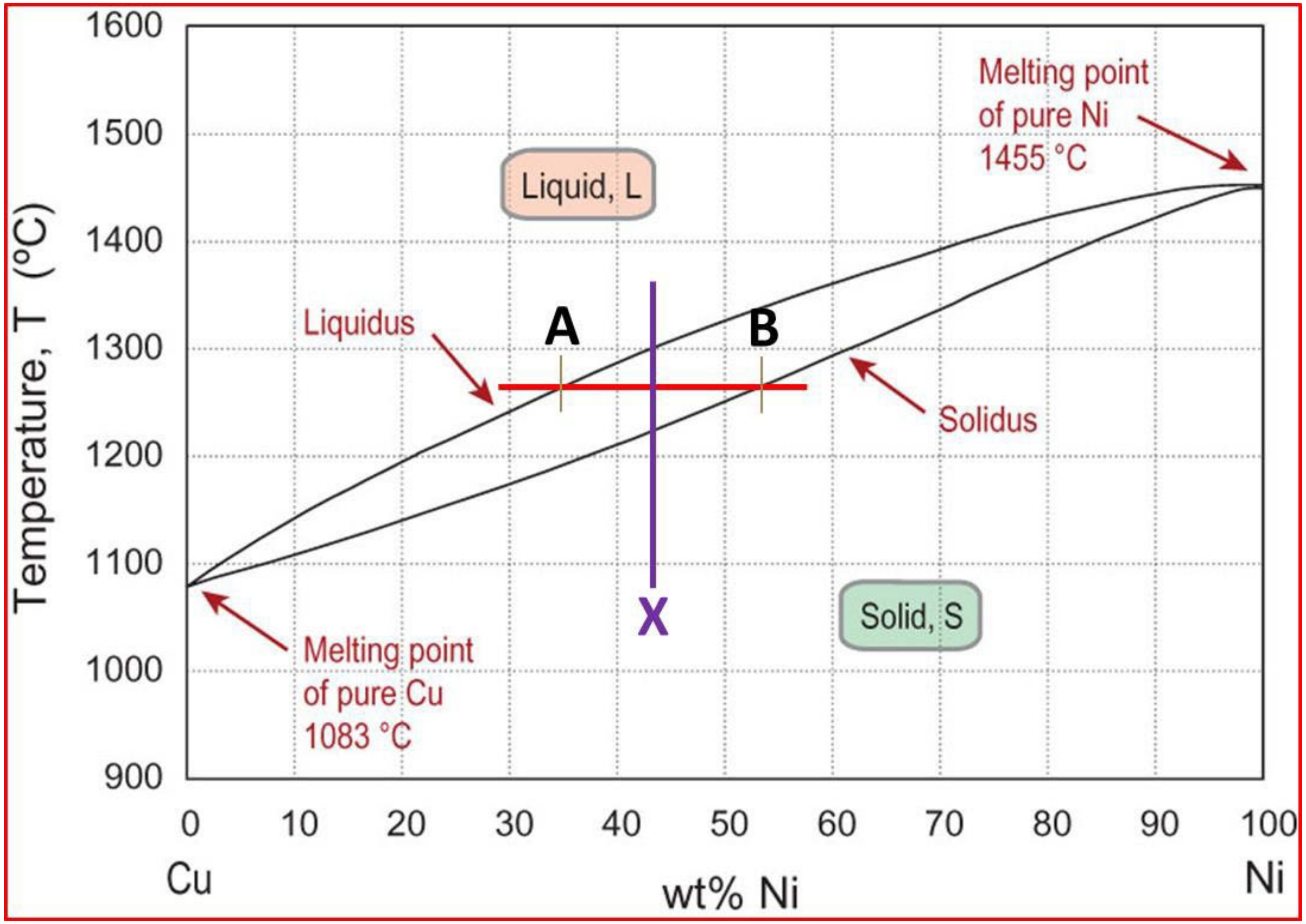


A gives the composition of the liquid (35% in this case)

B gives the chemical composition of the solid (53% in this case)

Important information that can be extracted from a phase diagram

3. The mass fraction (%) of each phase present



The **lever rule** is a tool used to determine the mole fraction of each **phase** of a binary **equilibrium phase diagram**.

This rule gives the **fraction** of a phase by the **ratio of the lengths** of the tie line between C_o and composition of the other phase to the total length of the tie line.

Stop and check video on moodle

Lecture 5: Distance Learning Resources folder – Phase Diagrams video

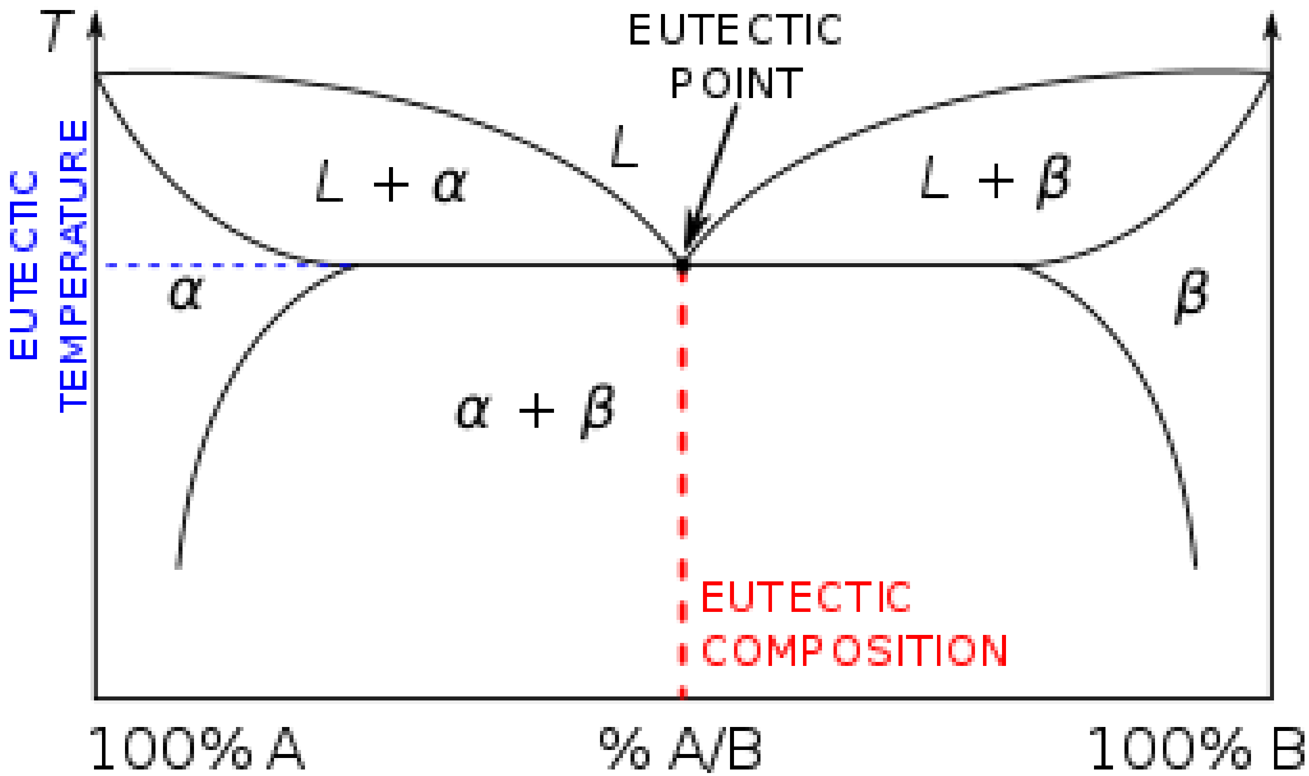
Eutectic alloy systems

In the Cu-Ni system we dealt with two elements that display complete solubility in the liquid as well as in the solid state.

Not all metals display complete solid solubility

An important alloy system of this type is the **eutectic system** of which the Pb-Sn (Lead – Tin) system is an example

Phase Diagrams II



Eutectics and **Eutectoids** are important and common in engineering alloys and allow the production of special, strong microstructure.

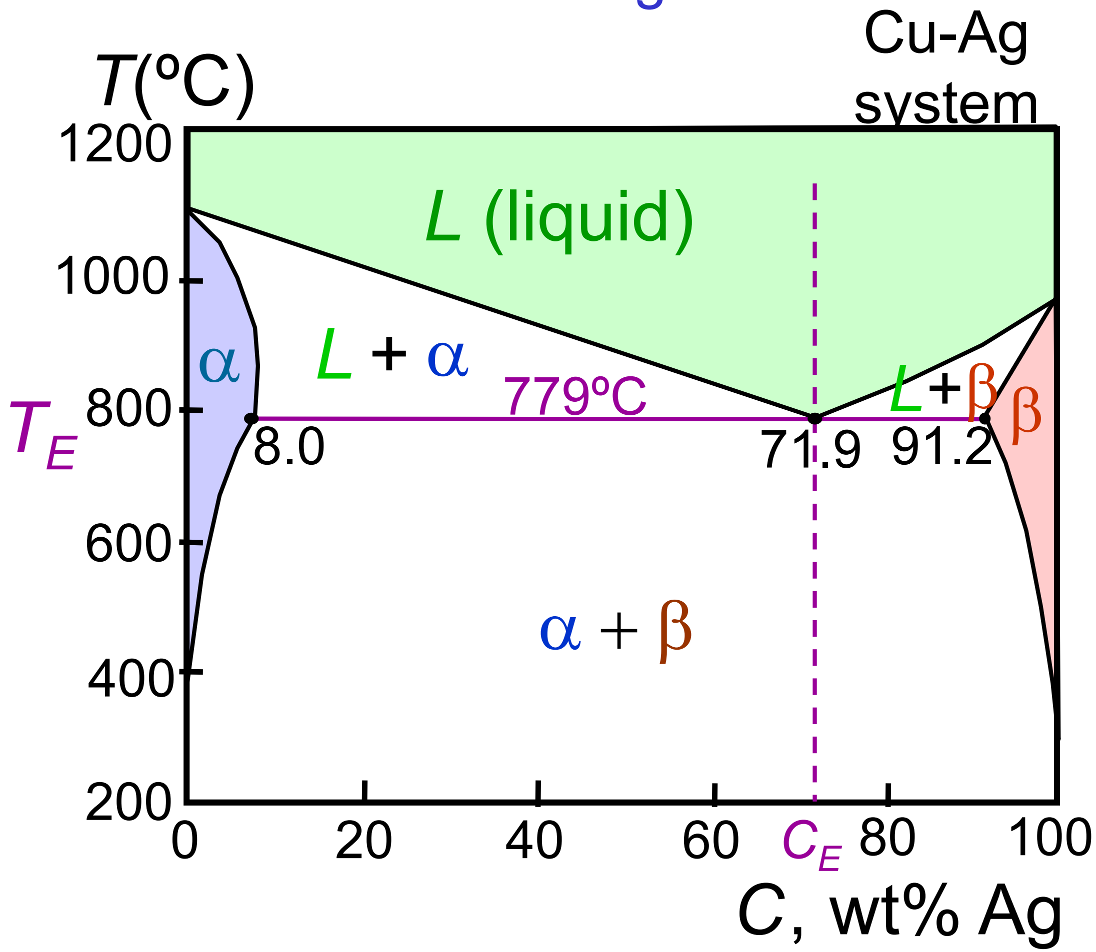
Binary-Eutectic Systems

2 components

has a special composition with a min. melting T.

Ex.: Cu-Ag system

- 3 single phase regions (L, α, β)
- Limited solubility:
  α: mostly Cu
  β: mostly Ag
- T_E : No liquid below T_E
- C_E : Composition at temperature T_E



Adapted from Fig. 9.7, *Callister & Rethwisch 8e.*

- **Eutectic reaction**

$$L(C_E) \rightleftharpoons \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

$$L(71.9\text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0\text{ wt\% Ag}) + \beta(91.2\text{ wt\% Ag})$$

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EX 1: Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 150ºC, determine:
  - -- the phases present

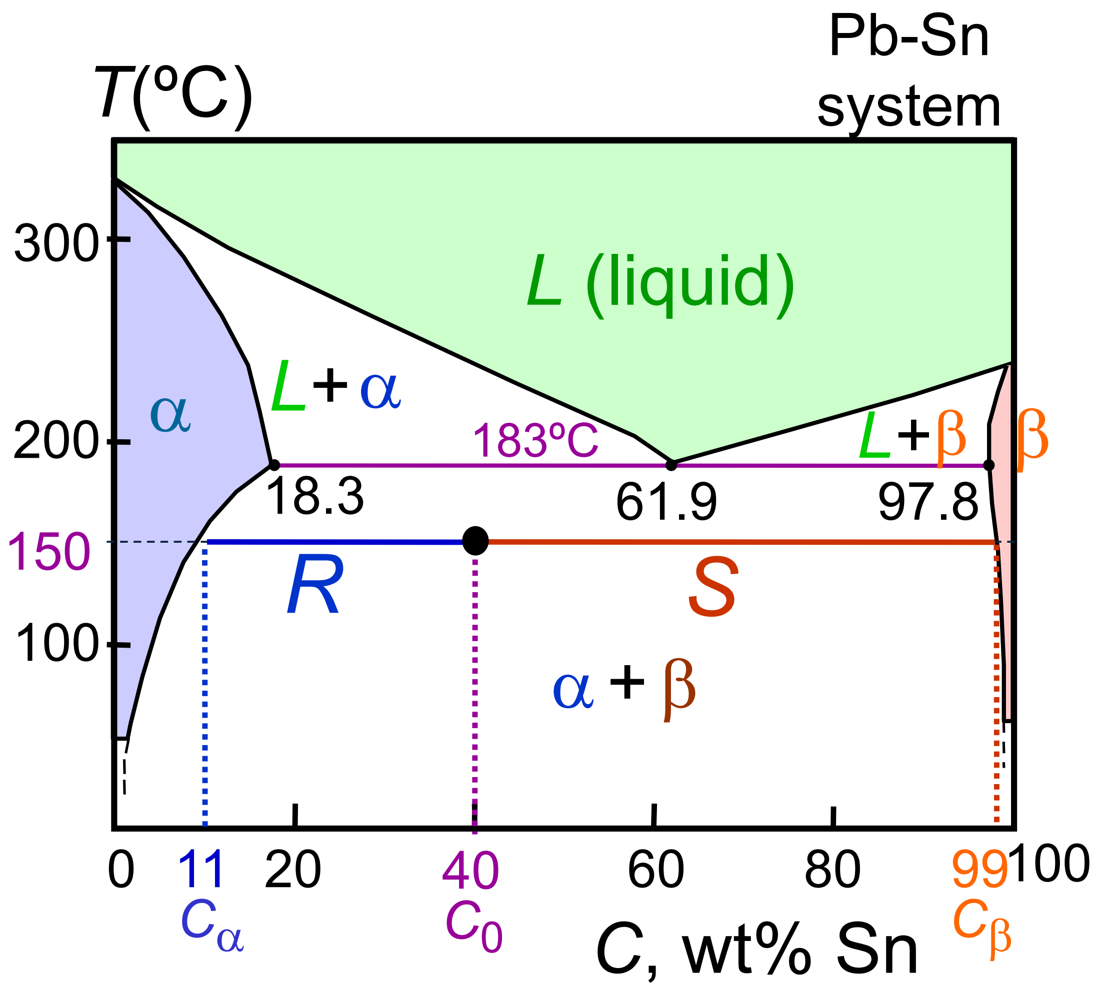
    Answer: $\alpha + \beta$
  - -- the phase compositions

    Answer: C_α = 11 wt% Sn
    C_β = 99 wt% Sn
  - -- the relative amount of each phase

    Answer:

$$W_\alpha = \frac{S}{R+S} = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = \frac{99 - 40}{99 - 11} = \frac{59}{88} = 0.67$$

$$W_\beta = \frac{R}{R+S} = \frac{C_0 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 11}{99 - 11} = \frac{29}{88} = 0.33$$



Adapted from Fig. 9.8, *Callister & Rethwisch 8e.*

EX 2: Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 220ºC, determine:
  - -- the phases present:

    Answer: α + L
  - -- the phase compositions

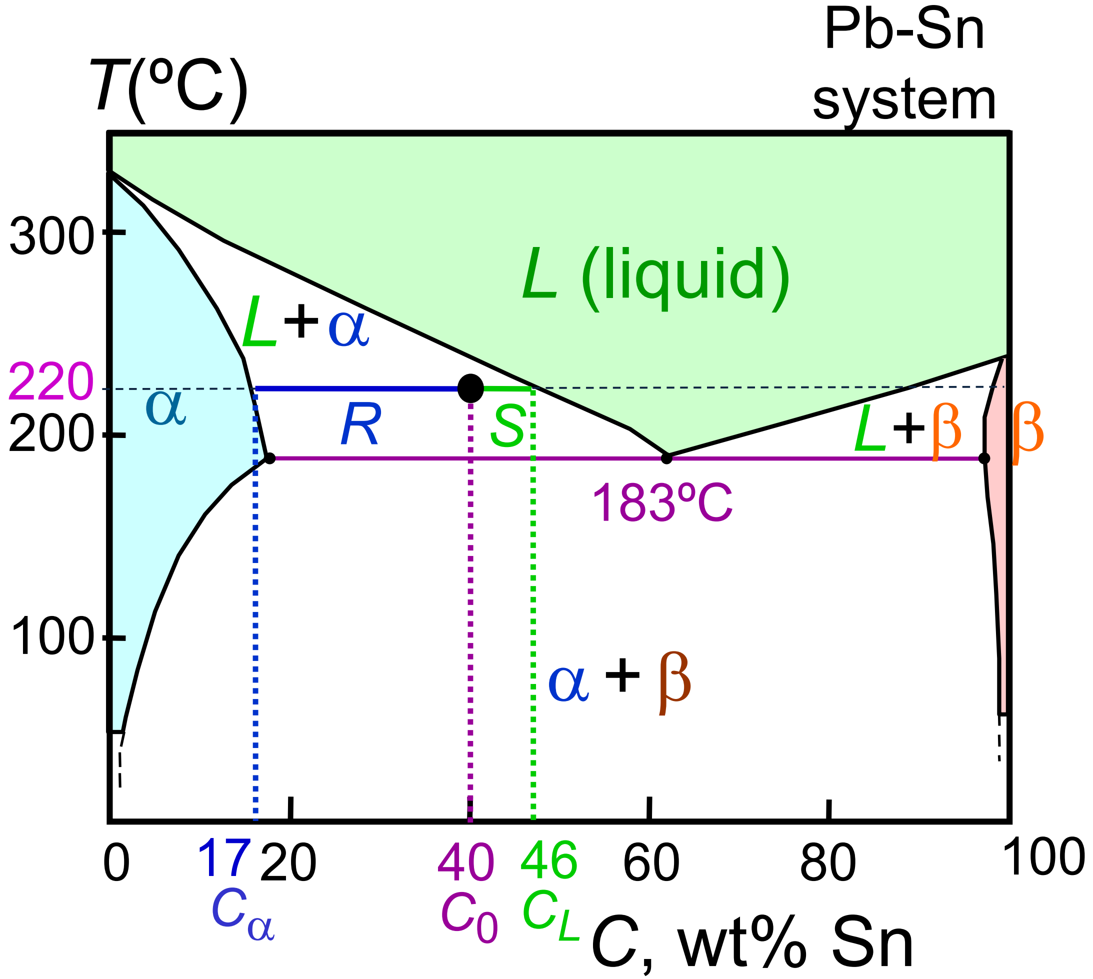
    Answer: C_α = 17 wt% Sn
    C_L = 46 wt% Sn
  - -- the relative amount of each phase

    Answer:

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17}$$

$$= \frac{6}{29} = 0.21$$

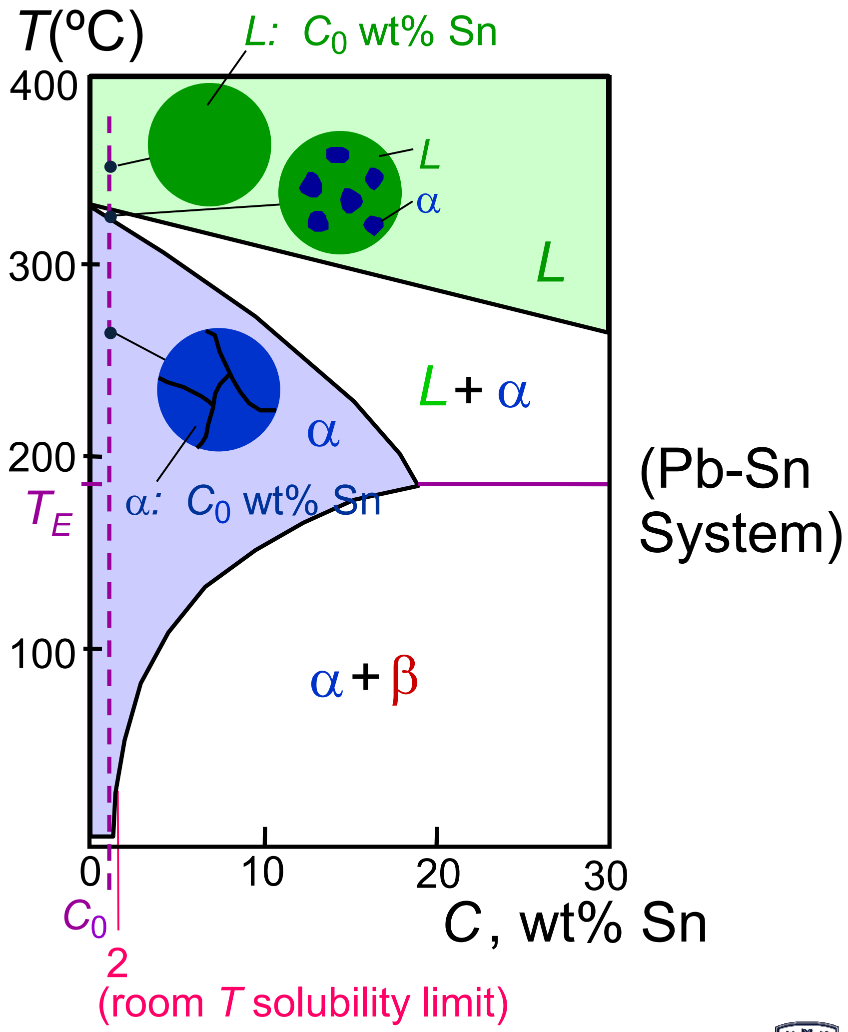
$$W_L = \frac{C_0 - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 0.79$$



Adapted from Fig. 9.8, *Callister & Rethwisch 8e.*

Microstructural Developments in Eutectic Systems I

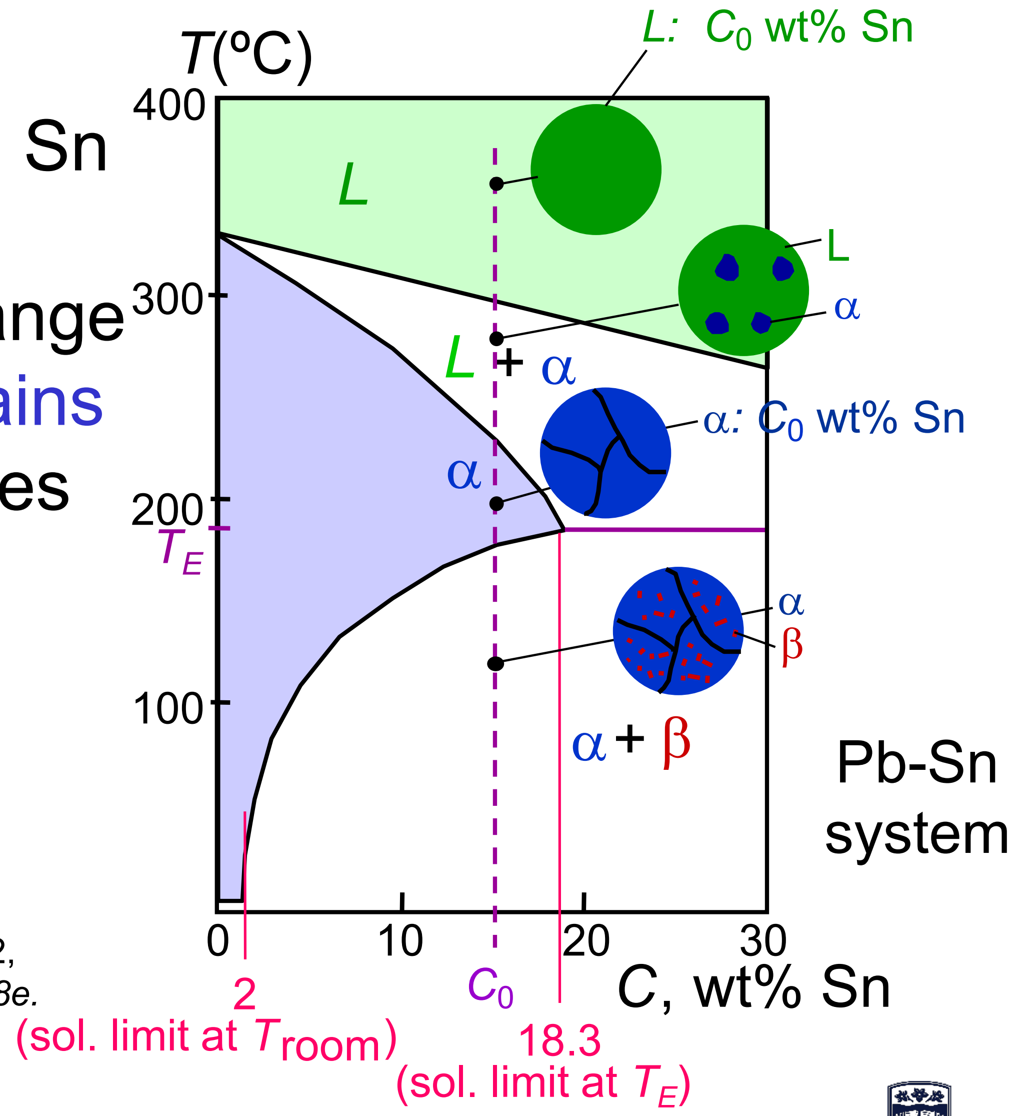
- For alloys for which
  C_0 < 2 wt% Sn
- Result: at room temperature
  -- polycrystalline with grains of
  α phase having
  composition C_0



Adapted from Fig. 9.11, *Callister & Rethwisch 8e.*

Microstructural Developments in Eutectic Systems II

- For alloys for which
  2 wt% Sn < C_0 < 18.3 wt% Sn
- Result:
  at temperatures in α + β range
  -- polycrystalline with α grains
  and small β-phase particles

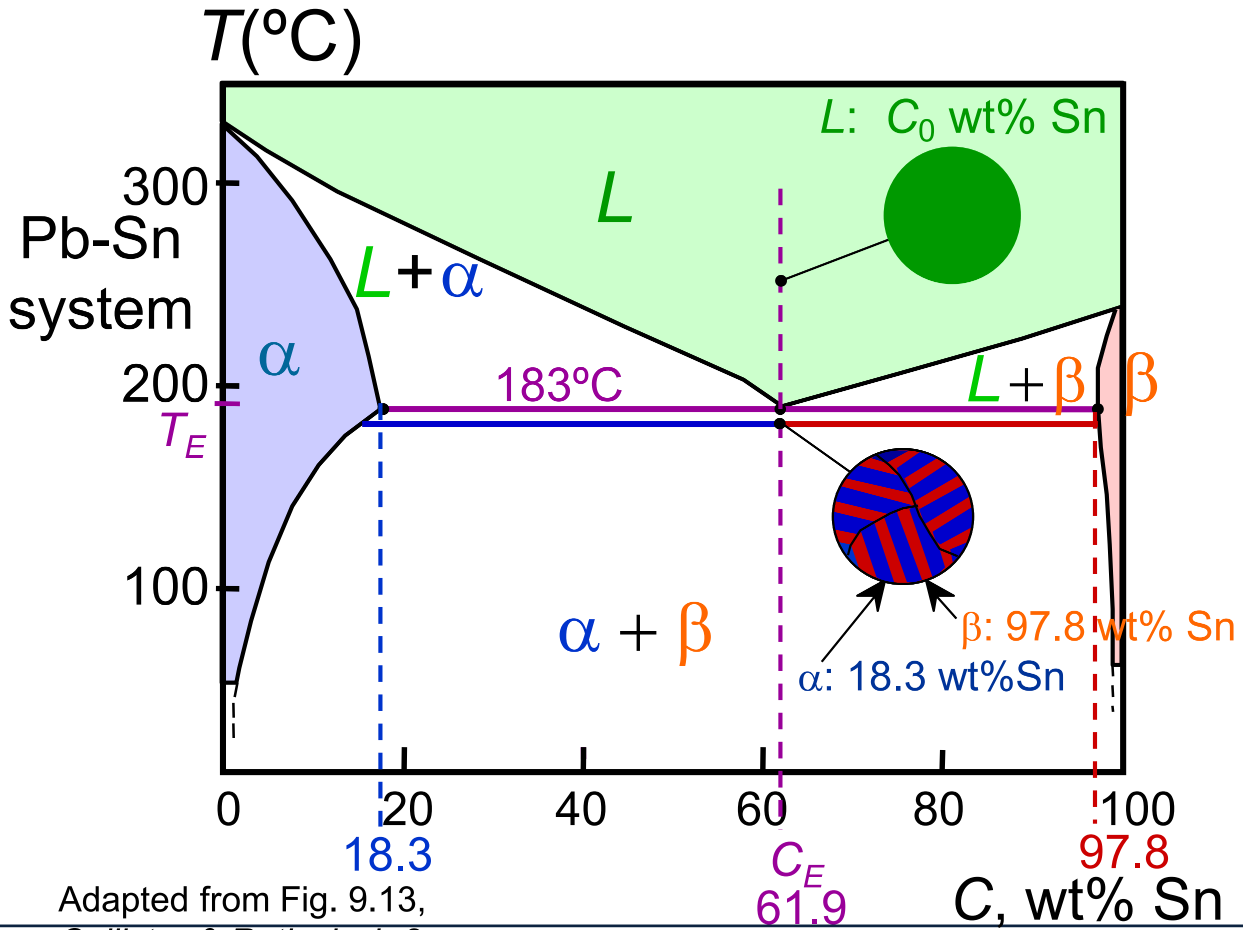


Adapted from Fig. 9.12, *Callister & Rethwisch 8e.*

Microstructural Developments in Eutectic Systems III

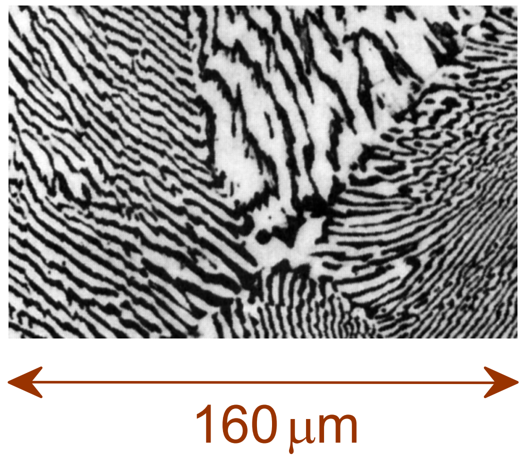
- For alloy of composition $C_0 = C_E$
- Result: Eutectic microstructure (lamellar structure)

  -- alternating layers (lamellae) of α and β phases.



Adapted from Fig. 9.13, *Callister & Rethwisch 8e.*

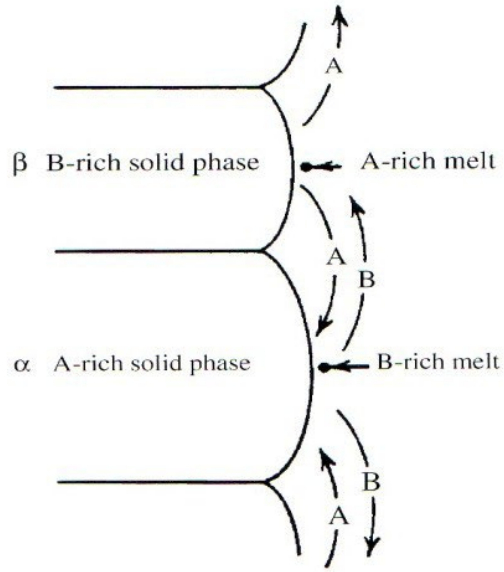
Micrograph of Pb-Sn eutectic microstructure



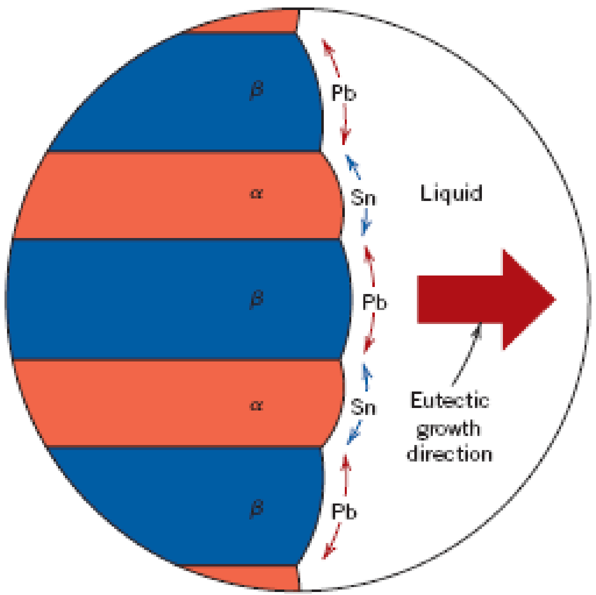
Adapted from Fig. 9.14, *Callister & Rethwisch 8e.*

Growth mechanism for a plate-like (lamellar) eutectic alloy

- Two phases grow cooperatively from the liquid
- *Normal* eutectics grow as alternate lamellae or as rods of the minor phase embedded in the other
- Both phases grow simultaneously **behind** a planar solid/liquid interface



A and B atoms diffuse as shown



As the A-rich α phase solidifies, excess B atoms diffuse a short distance in the liquid laterally where it is incorporated into the B-rich β-phase

The A atoms rejected ahead of the β -lamellae diffuse **in the liquid** to the tips of the adjacent α-lamellae

https://www.youtube.com/watch?v=K9pZZ3DjvCU

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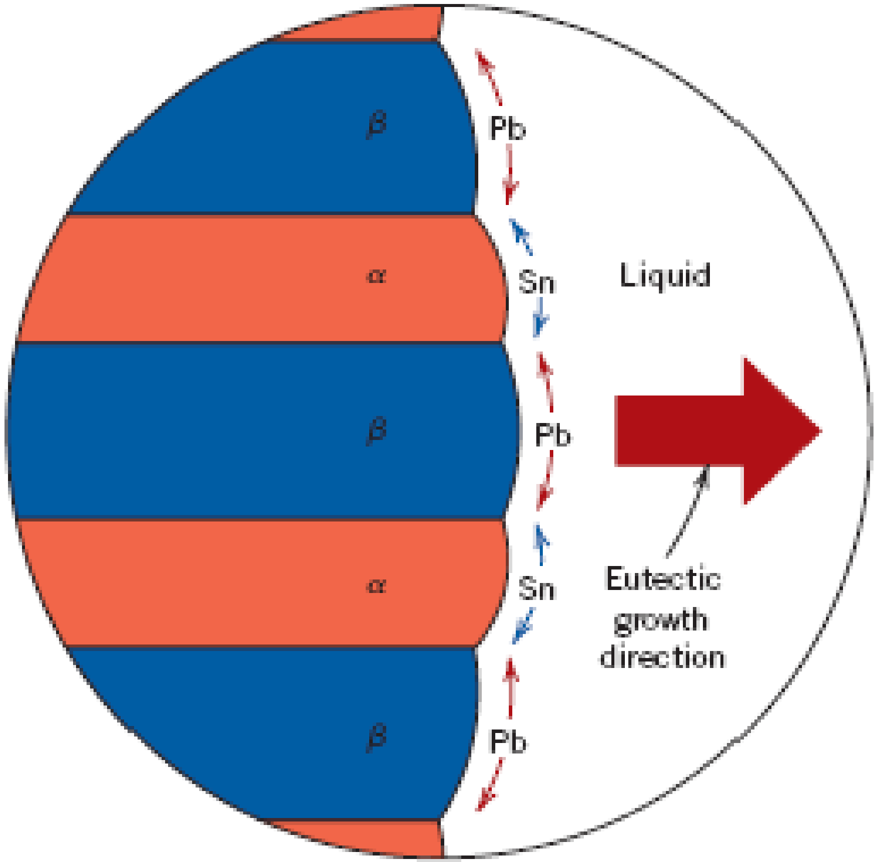
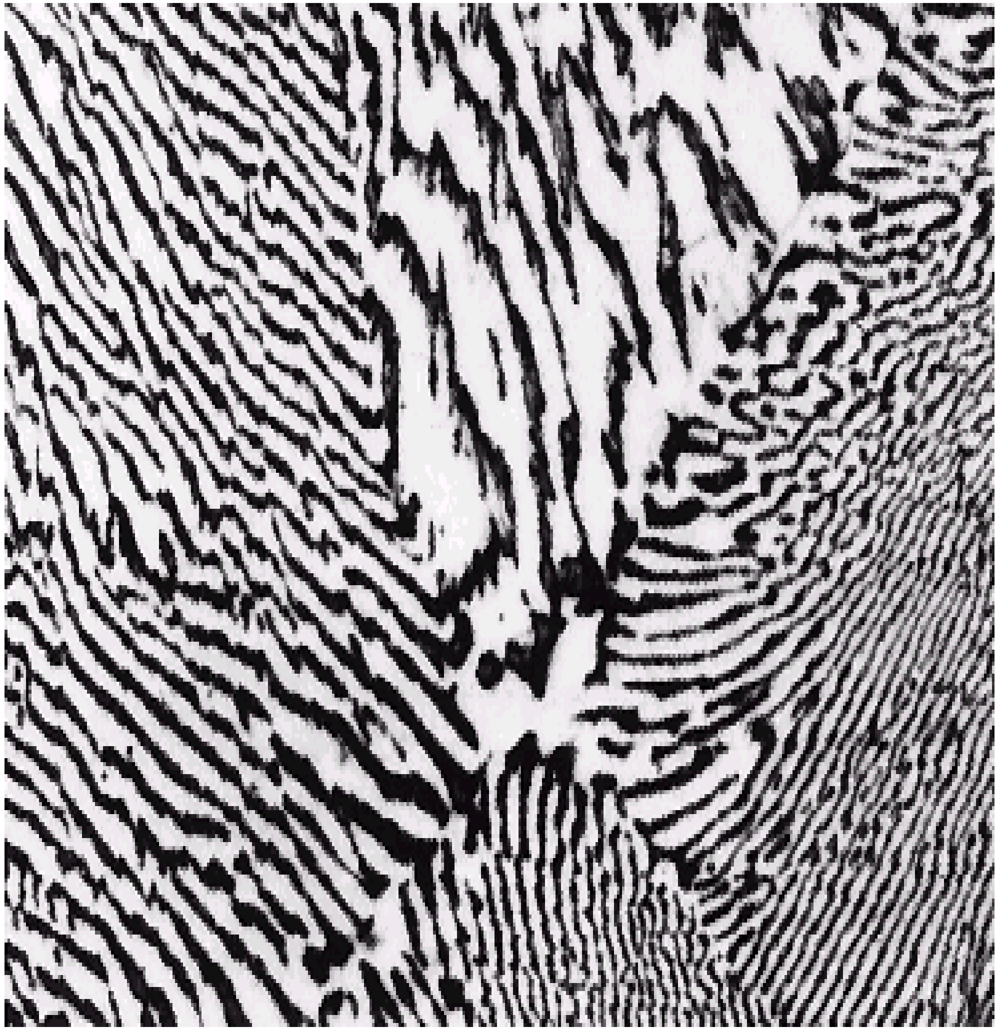
Lamellar Eutectic Structure

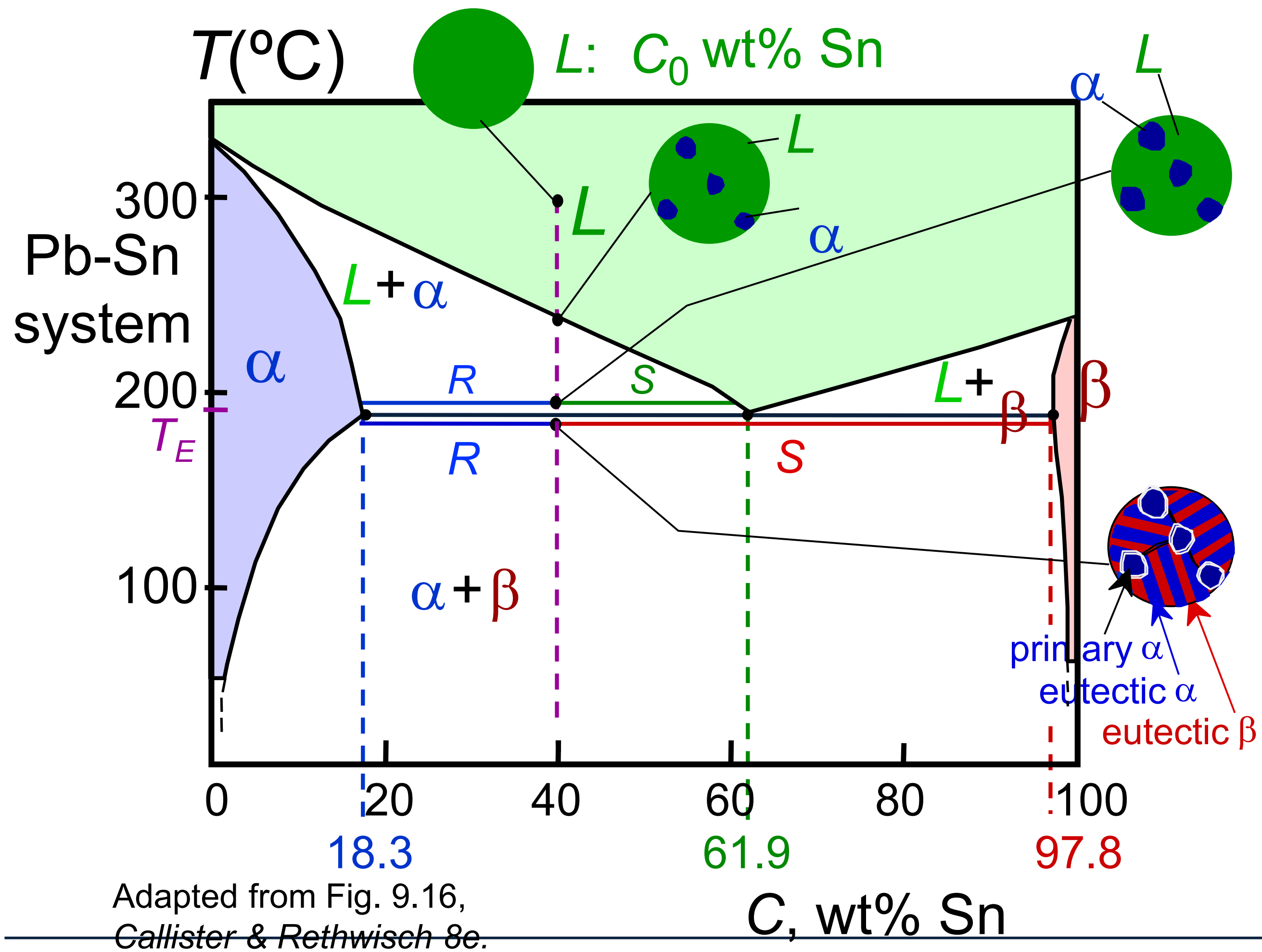


Adapted from Figs. 9.14 & 9.15, *Callister & Rethwisch 8e.*



Microstructural Developments in Eutectic Systems IV

- For alloys for which 18.3 wt% Sn < C_0 < 61.9 wt% Sn
- Result: α phase particles and a eutectic microconstituent



Adapted from Fig. 9.16, *Callister & Rethwisch 8e.*

- Just above T_E:

C_α = 18.3 wt% Sn

C_L = 61.9 wt% Sn

$$W_\alpha = \frac{S}{R+S} = 0.50$$

$$W_L = (1 - W_\alpha) = 0.50$$

- Just below T_E:

C_α = 18.3 wt% Sn

C_β = 97.8 wt% Sn

$$W_\alpha = \frac{S}{R+S} = 0.73$$

$$W_\beta = 0.27$$

Eutectic, Eutectoid, & Peritectic

- Eutectic - liquid transforms to two solid phases

$$L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$$ (For Pb-Sn, 183ºC, 61.9 wt% Sn)

- Eutectoid – one solid phase transforms to two other solid phases

$$S_2 \rightleftharpoons S_1 + S_3$$

intermetallic compound - cementite

$$\gamma \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + Fe_3C$$ (For Fe-C, 727ºC, 0.76 wt% C)

- Peritectic - liquid and one solid phase transform to a second solid phase

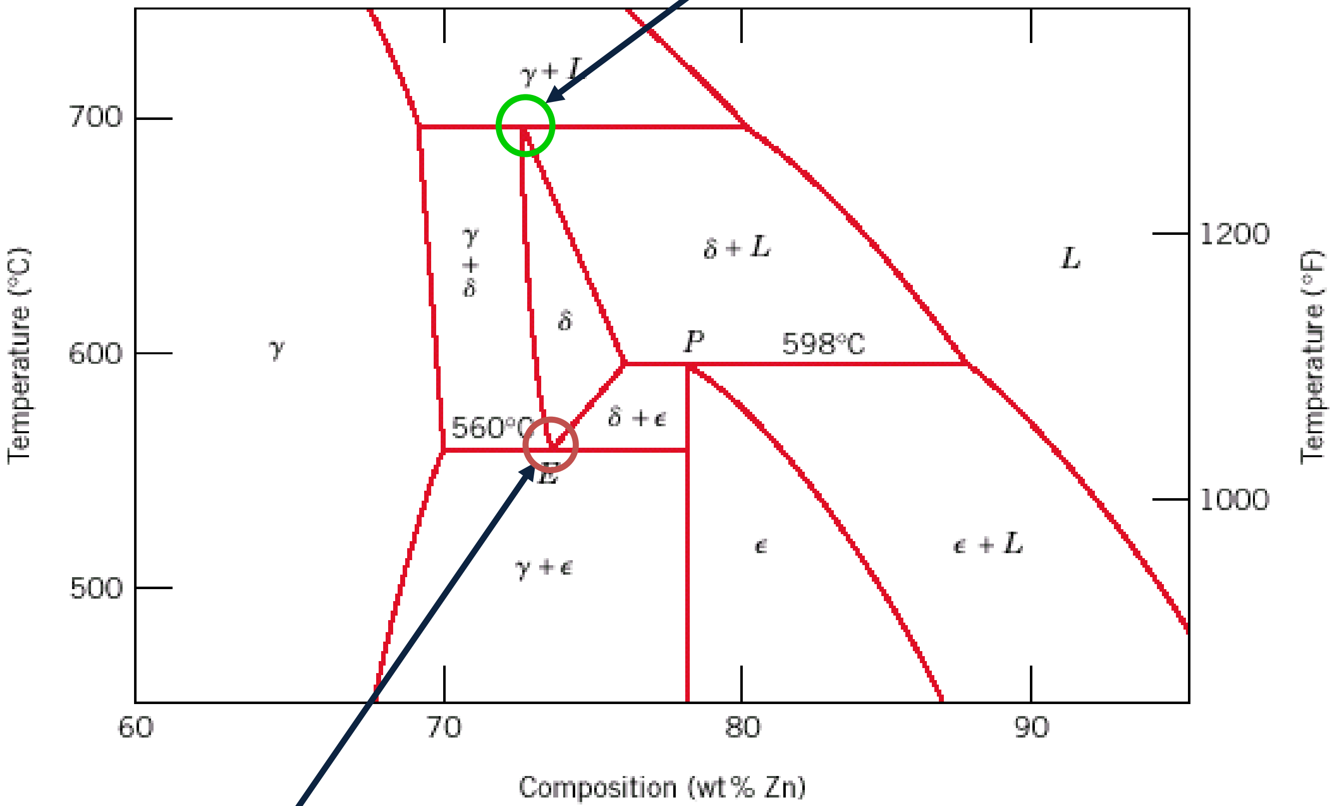
$$S_1 + L \rightleftharpoons S_2$$

$$\delta + L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \gamma$$ (For Fe-C, 1493ºC, 0.16 wt% C)

Eutectoid & Peritectic

Cu-Zn Phase diagram

Peritectic transformation $\gamma + L \rightleftharpoons \delta$

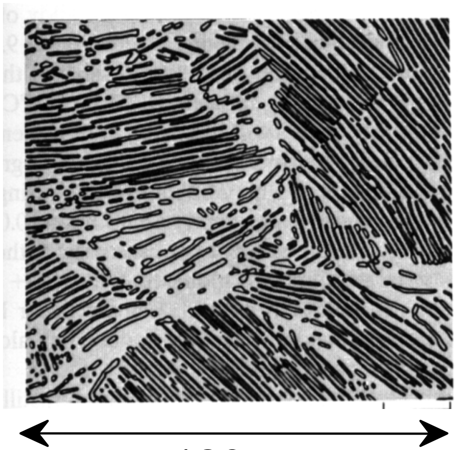


Adapted from Fig. 9.21, *Callister & Rethwisch 8e.*

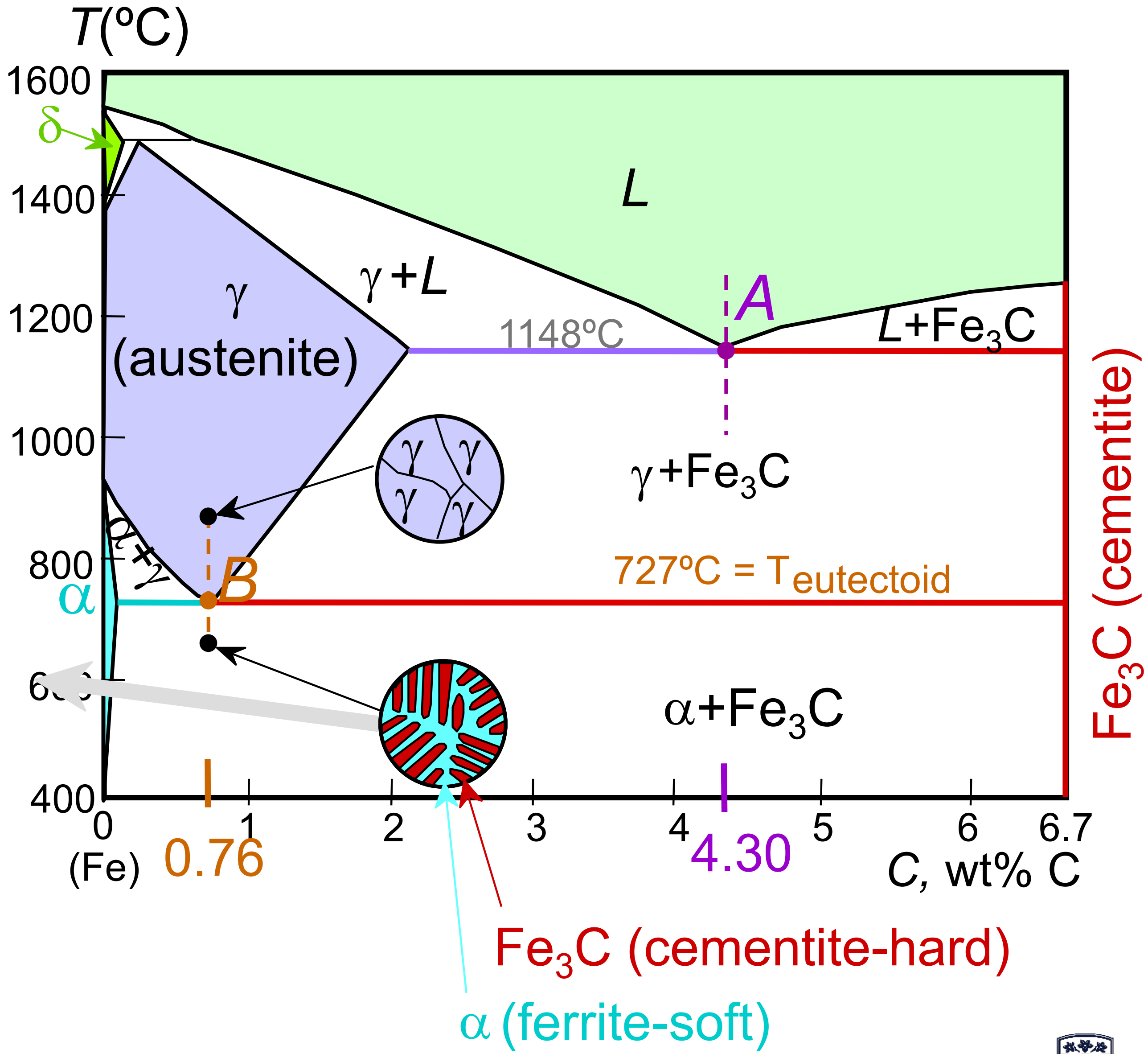
Eutectoid transformation $\delta \rightleftharpoons \gamma + \varepsilon$

Iron-Carbon (Fe-C) Phase Diagram

- 2 important points
  - Eutectic (*A*): $L \Rightarrow \gamma + Fe_3C$
  - Eutectoid (*B*): $\gamma \Rightarrow \alpha + Fe_3C$



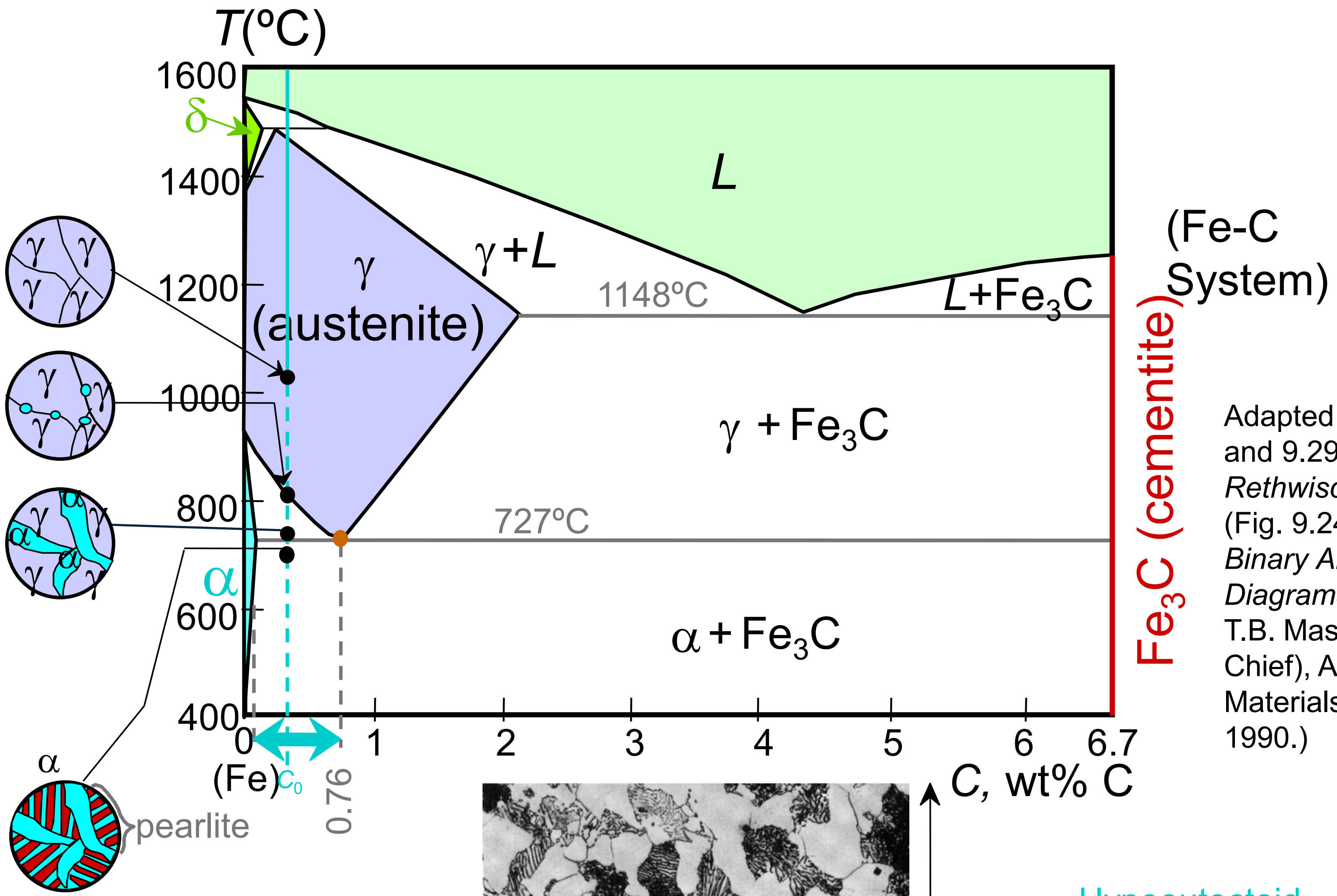
Result: Pearlite = alternating layers of α and Fe_3C phases



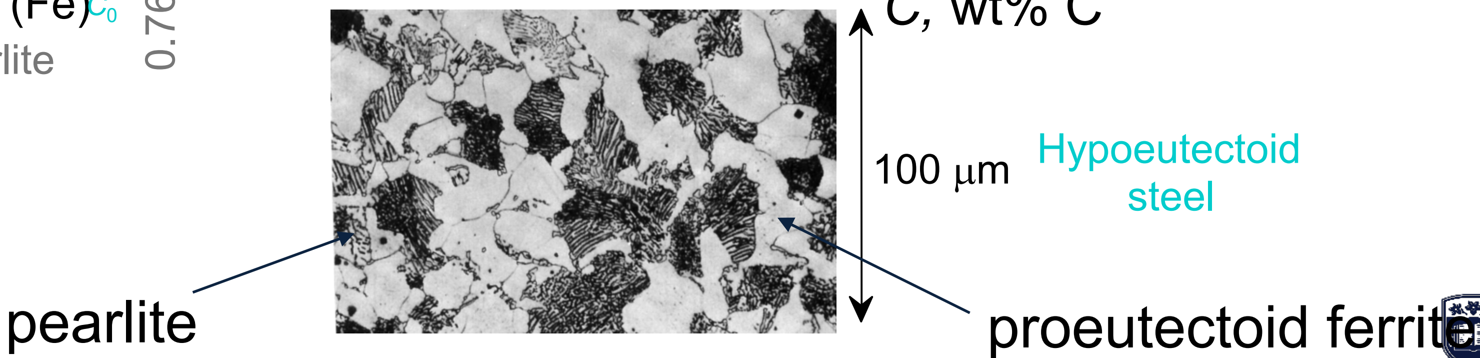
(Adapted from Fig. 9.27, *Callister & Rethwisch 8e.*)

Adapted from Fig. 9.24, *Callister & Rethwisch 8e.*

Hypoeutectoid Steel



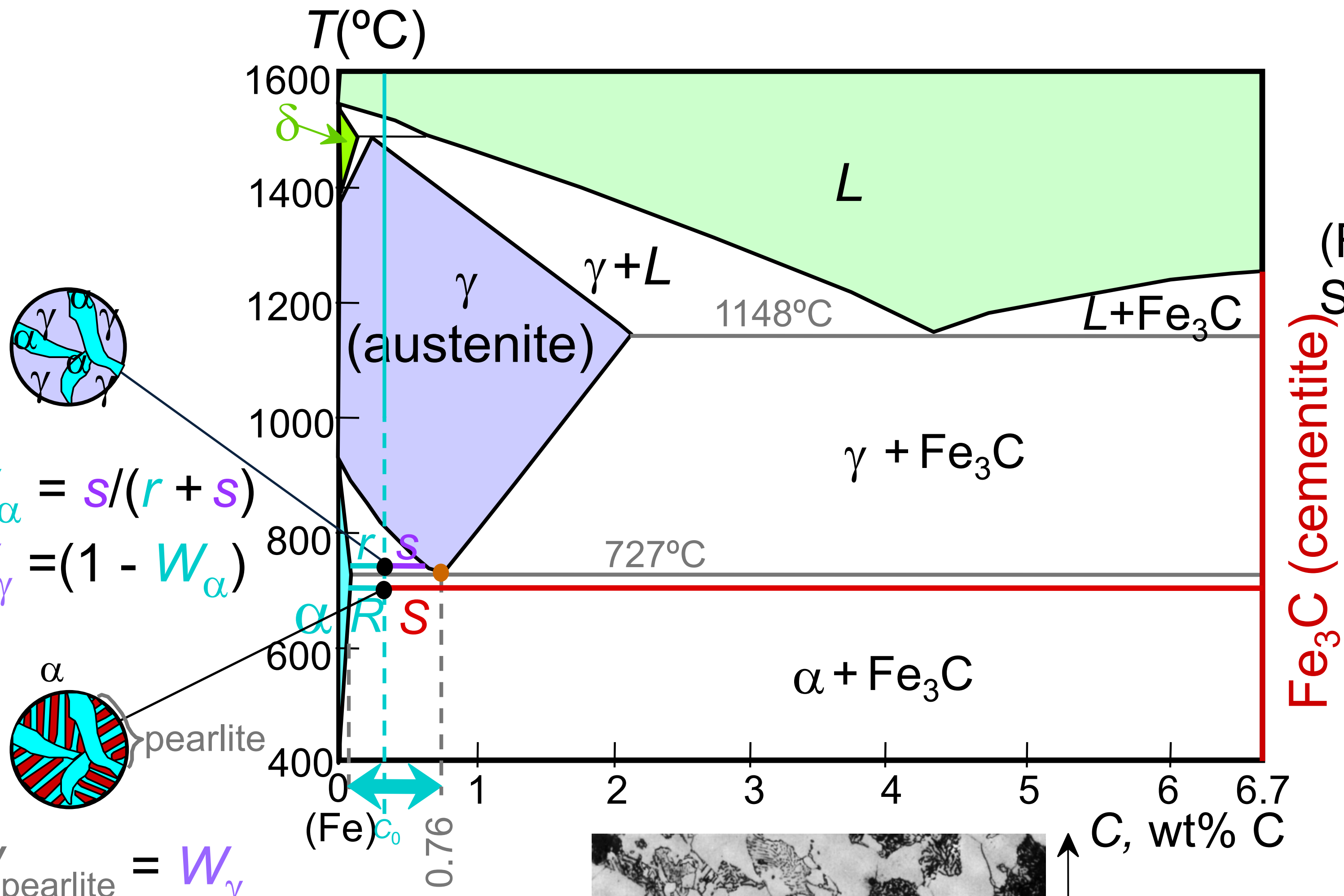
Adapted from Figs. 9.24 and 9.29, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)



Hypoeutectoid steel

Adapted from Fig. 9.30, *Callister & Rethwisch 8e.*

Hypoeutectoid Steel



$W_\alpha = s/(r + s)$

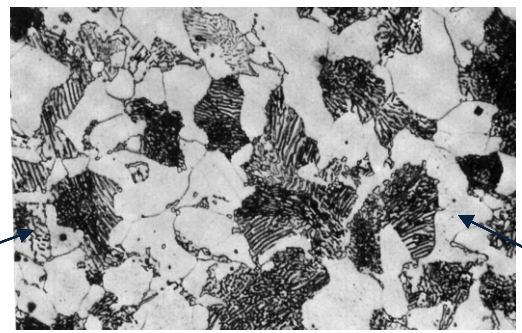
$W_\gamma = (1 - W_\alpha)$

$W_{pearlite} = W_\gamma$

$W_{\alpha'} = S/(R + S)$

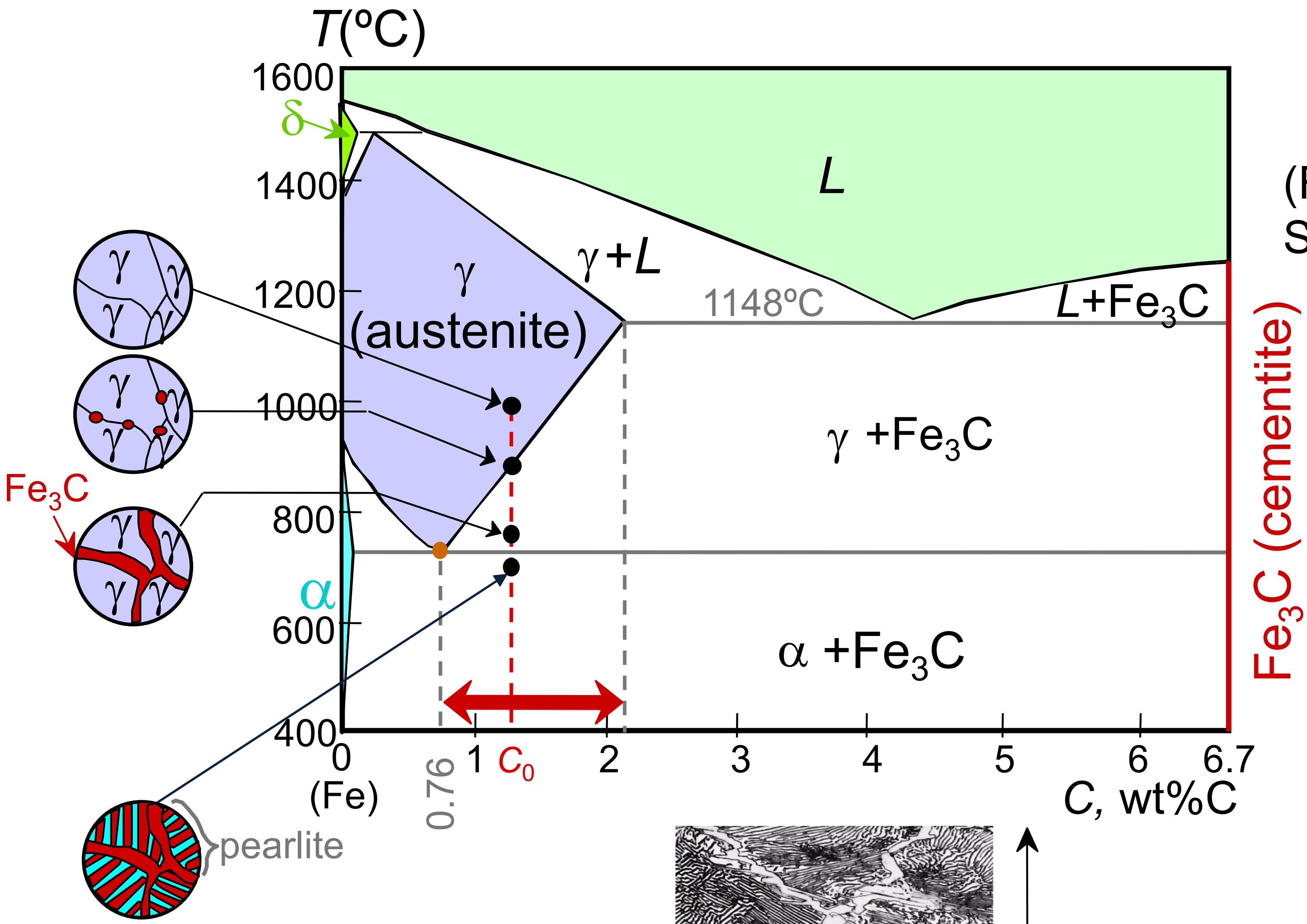
$W_{Fe_3C} = (1 - W_{\alpha'})$

Adapted from Figs. 9.24 and 9.29, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)



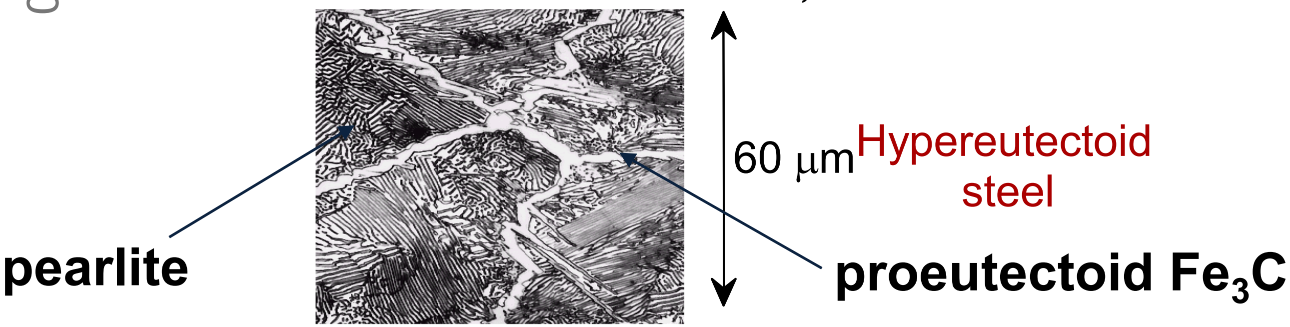
Adapted from Fig. 9.30, *Callister & Rethwisch 8e.*

Hypereutectoid Steel



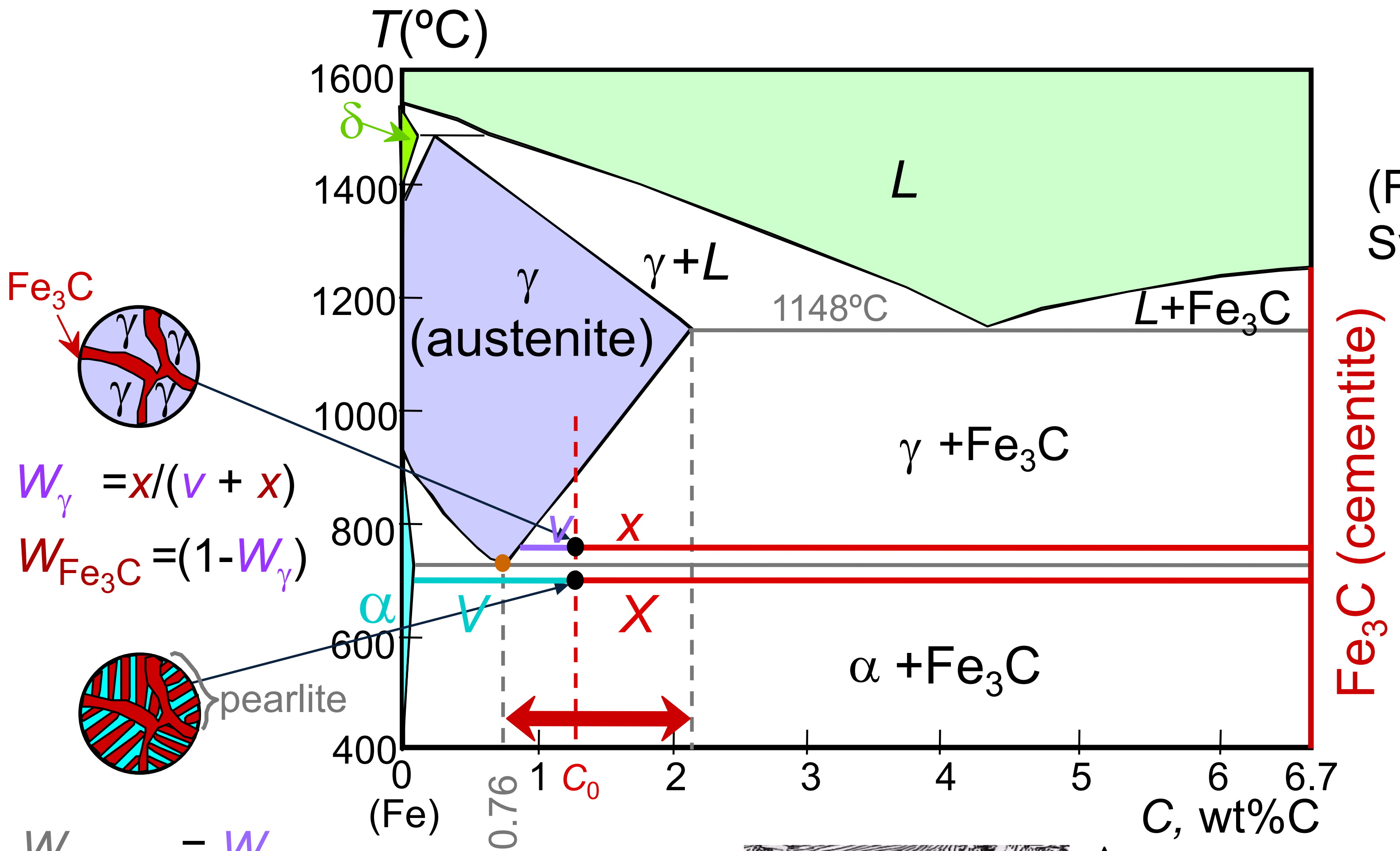
(Fe-C System)

Adapted from Figs. 9.24 and 9.32, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)



Adapted from Fig. 9.33, *Callister & Rethwisch 8e.*

Hypereutectoid Steel



$W_\gamma = x/(v + x)$

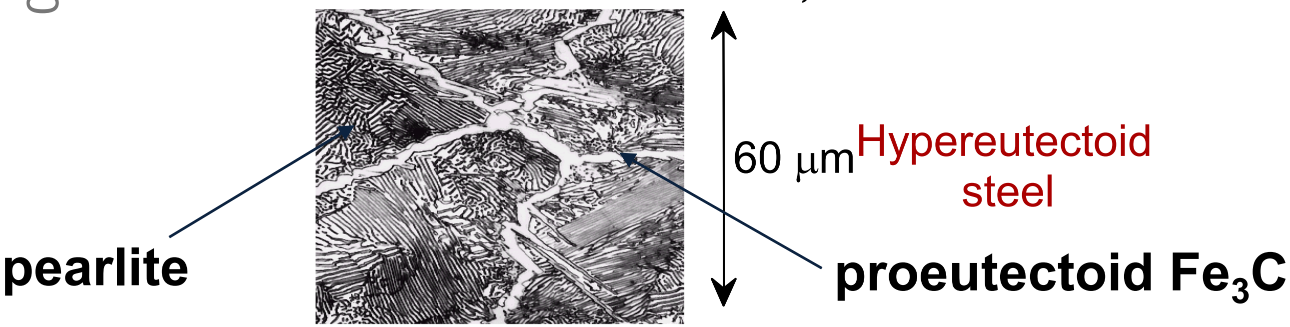
$W_{Fe_3C} = (1 - W_\gamma)$

$W_{pearlite} = W_\gamma$

$W_\alpha = X/(V + X)$

$W_{Fe_3C'} = (1 - W_\alpha)$

Adapted from Figs. 9.24 and 9.32, *Callister & Rethwisch 8e.* (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)



Adapted from Fig. 9.33, *Callister & Rethwisch 8e.*

Example Problem

For a 99.6 wt% Fe-0.40 wt% C steel at a temperature just below the eutectoid, determine the following:

a) The compositions of Fe_3C and ferrite (α).

b) The amount of cementite (in grams) that forms in 100 g of steel.

c) The amounts of pearlite and proeutectoid ferrite (α) in the 100 g.

Solution to Example Problem

a) Using the *RS* tie line just below the eutectoid

C_α = 0.022 wt% C
C_{Fe_3C} = 6.70 wt% C

b) Using the lever rule with the tie line shown

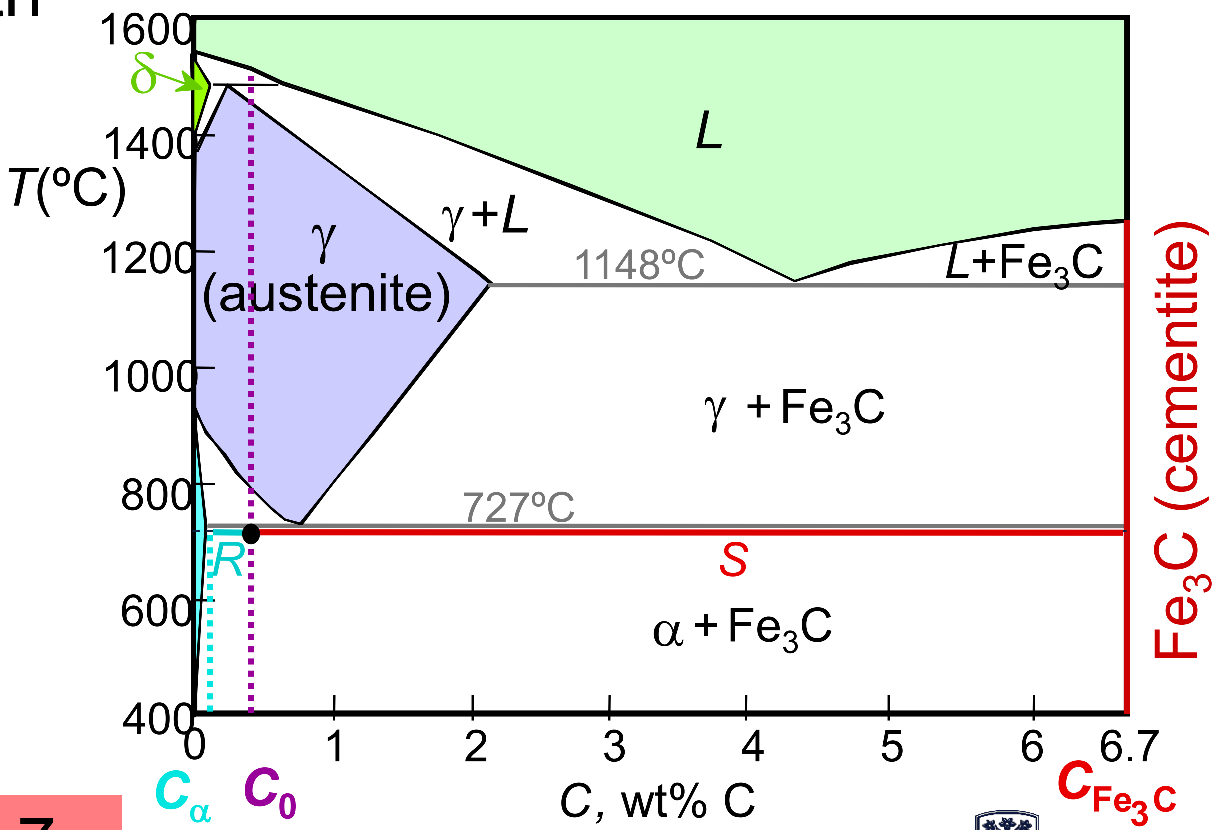
$$W_{Fe_3C} = \frac{R}{R+S} = \frac{C_0 - C_\alpha}{C_{Fe_3C} - C_\alpha}$$

$$= \frac{0.40 - 0.022}{6.70 - 0.022} = 0.057$$

Amount of Fe_3C in 100 g

= (100 g)W_{Fe_3C}

= (100 g)(0.057) = 5.7 g



Solution to Example Problem (cont.)

c) Using the *VX* tie line just above the eutectoid and realizing that

$C_0 = 0.40$ wt% C
$C_\alpha = 0.022$ wt% C
$C_{pearlite} = C_\gamma = 0.76$ wt% C

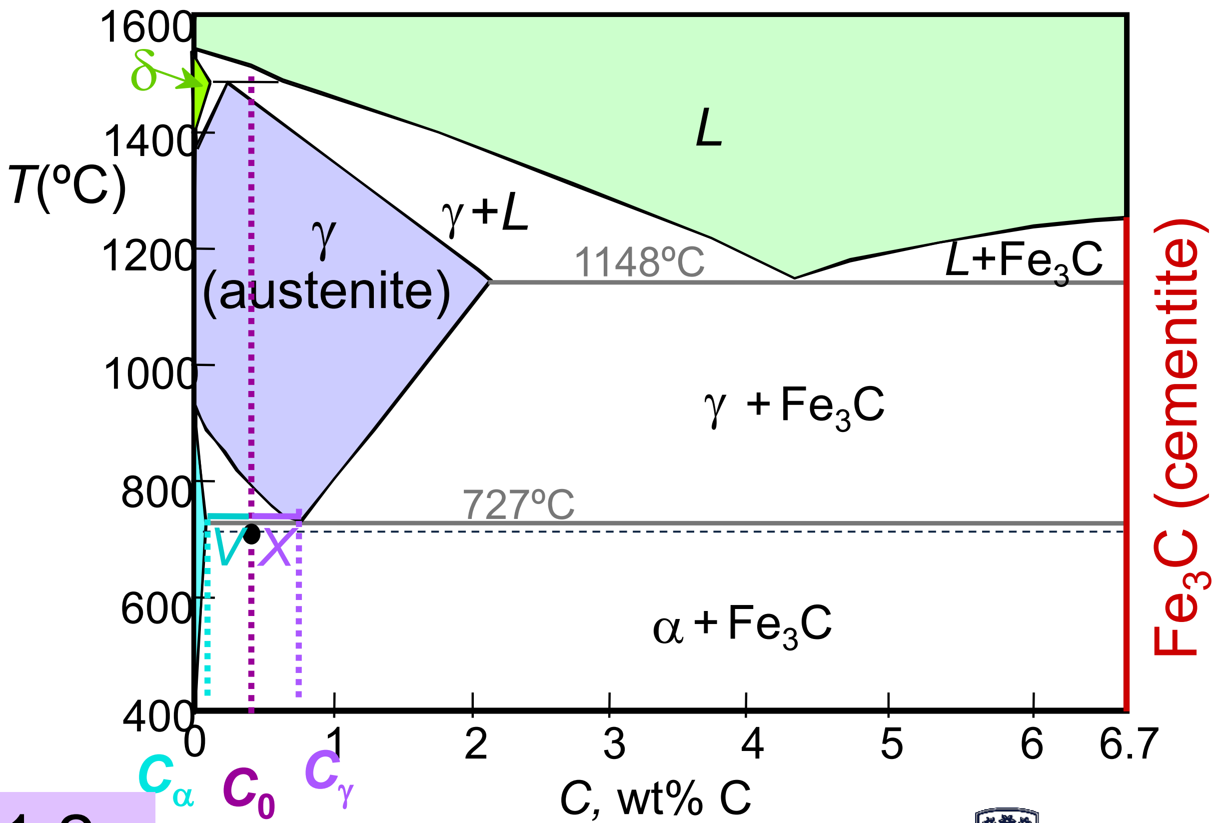
$$W_{pearlite} = \frac{V}{V+X} = \frac{C_0 - C_\alpha}{C_\gamma - C_\alpha}$$

$$= \frac{0.40 - 0.022}{0.76 - 0.022} = 0.512$$

Amount of pearlite in 100 g

$= (100\text{ g})W_{pearlite}$

$= (100\text{ g})(0.512) = 51.2\text{ g}$



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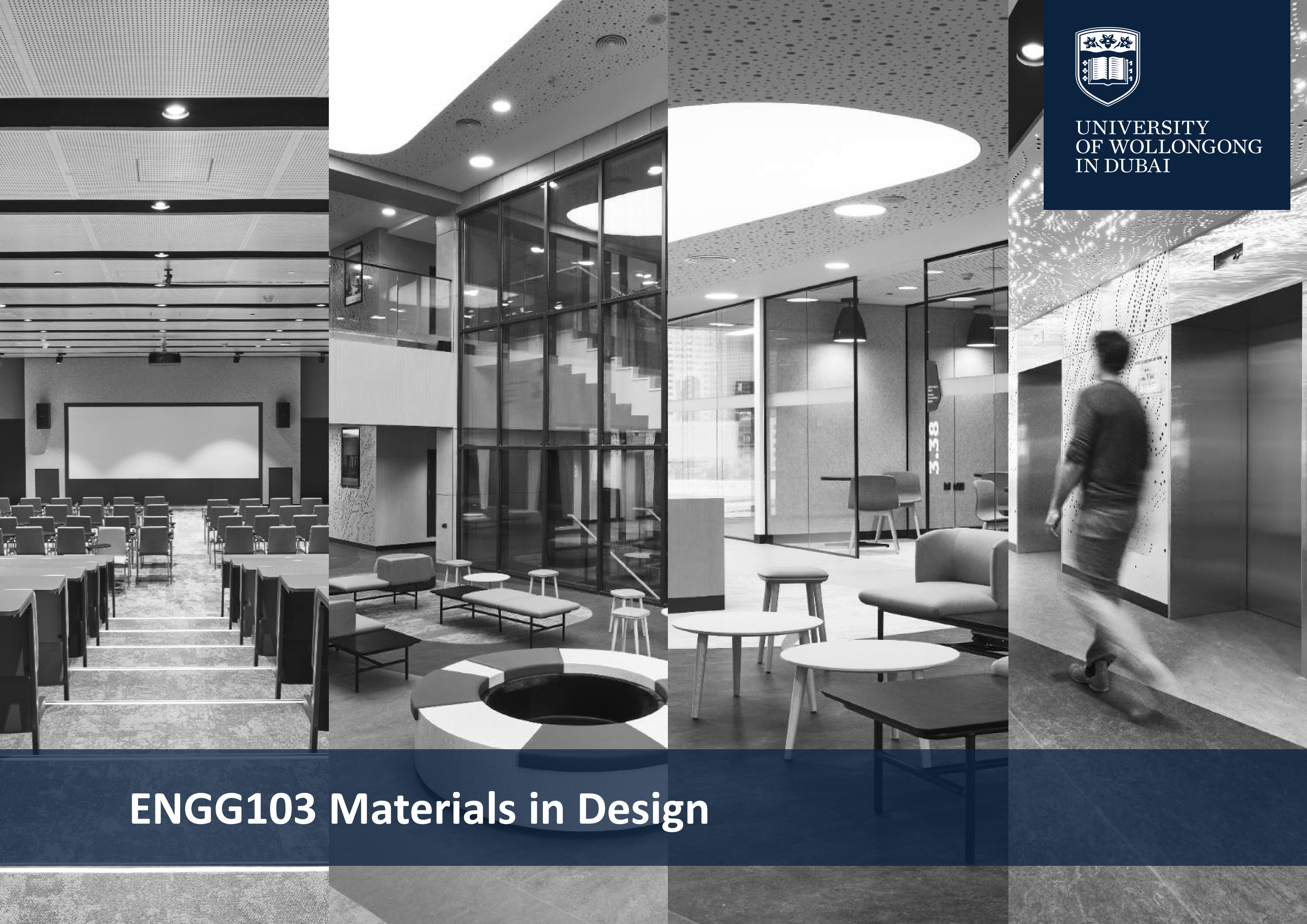
Summary

- Phase diagrams are useful tools to determine:
  - -- the number and types of phases present,
  - -- the composition of each phase,
  - -- and the weight fraction of each phase

  given the temperature and composition of the system.
- The microstructure of an alloy depends on
  - -- its composition, and
  - -- whether or not cooling rate allows for maintenance of equilibrium.
- Important phase diagram phase transformations include eutectic, eutectoid, and peritectic.



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