Introduction of Materials Science and Engineering

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Chapter 9: Phase Diagrams

Text book:

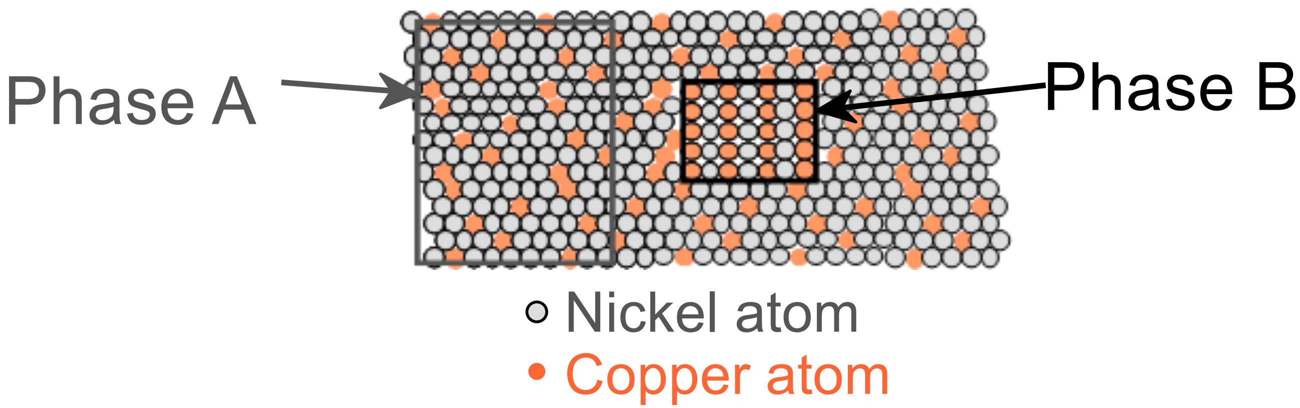
Callister's **Materials Science and Engineering, 10th edition,** Wiley

Chapter 9: Phase Diagrams

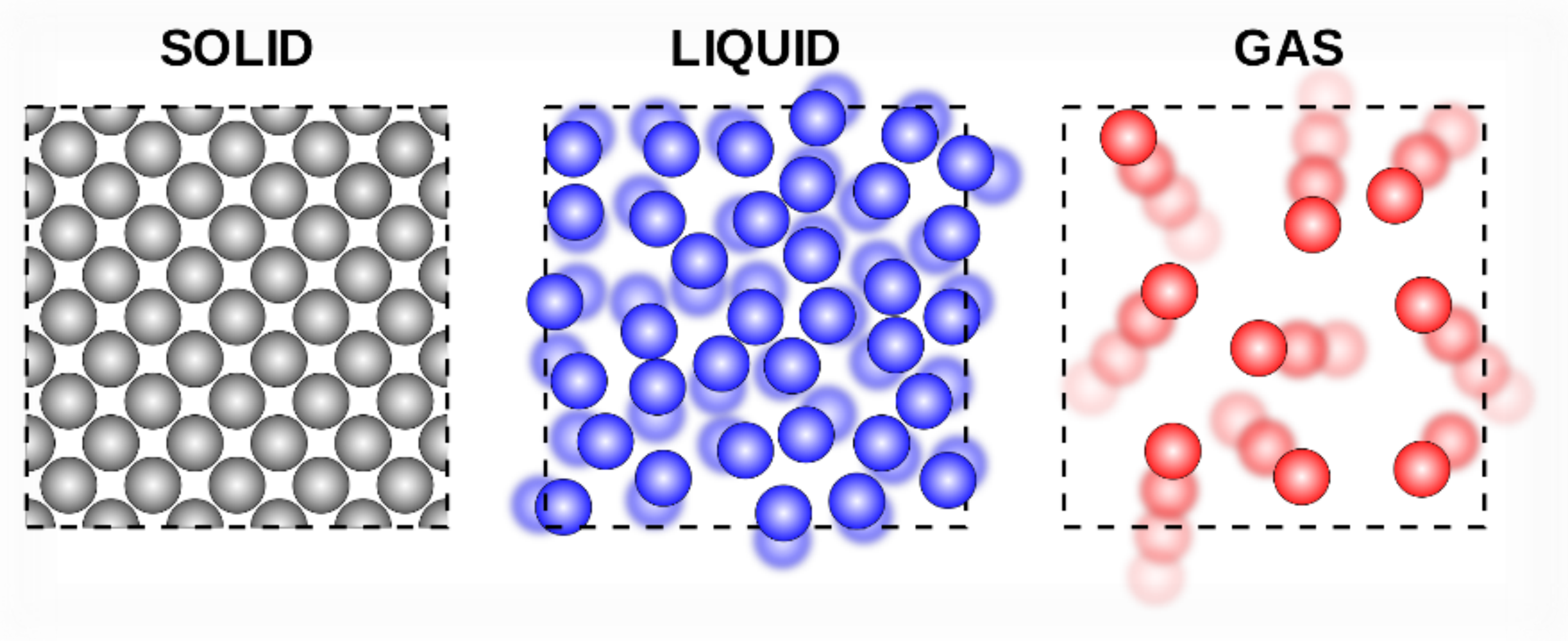
ISSUES TO ADDRESS...

- 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*)

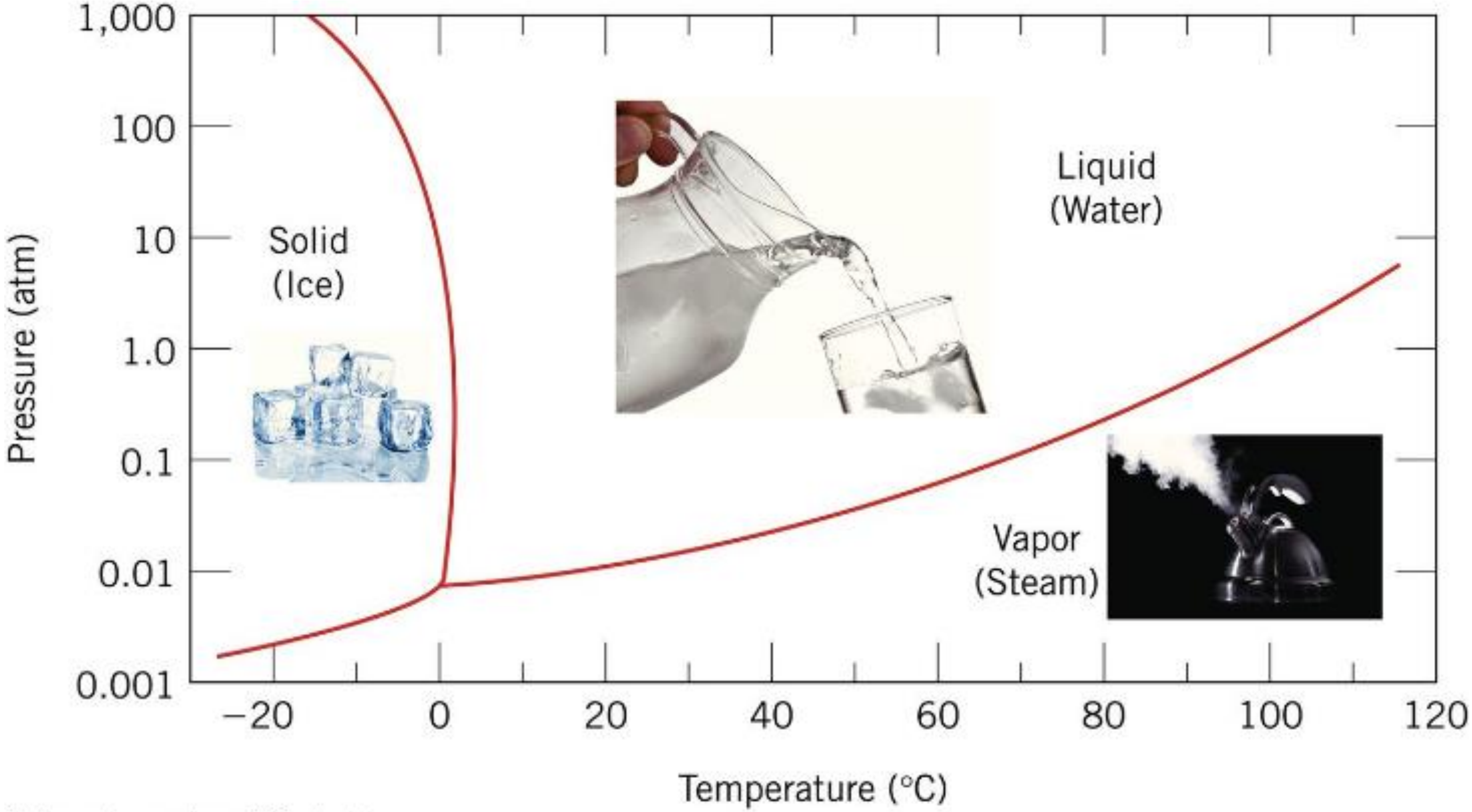
  then...
  How many phases form?
  What is the composition of each phase?
  What is the amount of each phase?



Phase



Phases of water



Photographs courtesy of iStockphoto.

What can phase diagram tell us?

Much of the information about the control of the phase structure of a particular system is conveniently and concisely displayed in what is called a **phase diagram,** also often termed an *equilibrium diagram.* Three externally controllable parameters that affect phase structure—temperature, pressure, and composition—and phase diagrams are constructed when various combinations of these parameters are plotted against one another.

The equilibrium property of a System composed of a pure component or mixing components, as function of temperature, pressure and composition.

Definitions and basic concepts

- **Component :** pure metals/compounds of which an alloy is composed.

- **System** : alloy or compound consisting of the same components but without regard to the composition.

- **Solid solution :** consisted of atoms at least two different types; the solute atoms occupy either substitutional or interstitial positions in the solvent lattice. 有溶解力 The crystal structure of the solvent is maintained.

Phase Equilibria: Solubility Limit

- Solution – solid, liquid, or gas solutions

- Solubility Limit:

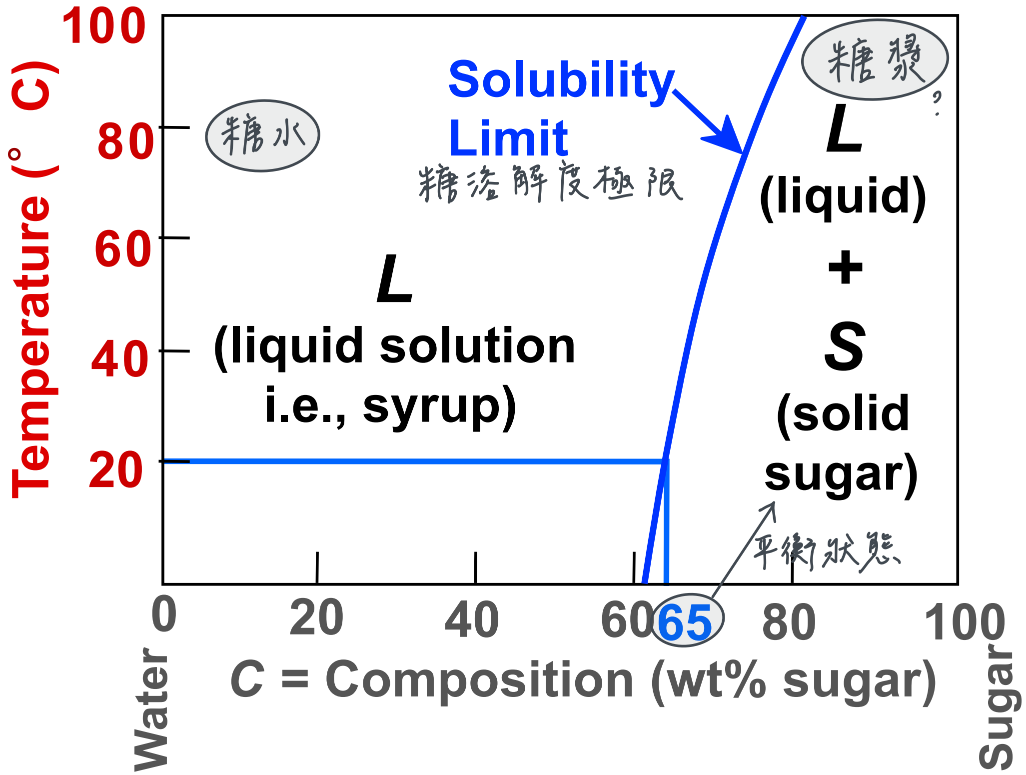
Maximum concentration of solute atoms that may dissolve in the solvent for form a solid solution. (only a single phase solution exists.)

- excess of solute

formation of another solid solution or compound that has a different composition.

Phase Equilibria: Solubility Limit

Sugar/Water Phase Diagram



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

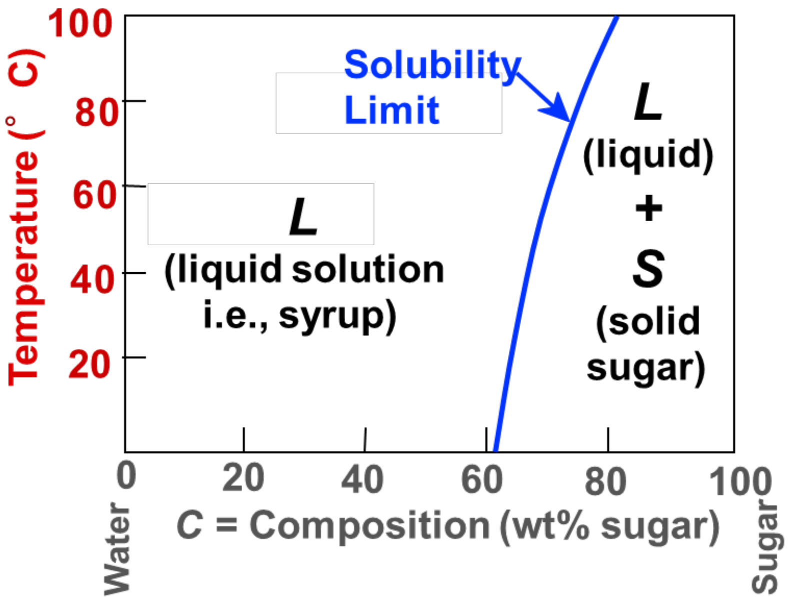
Answer: 65 wt% sugar.

At 20° C, if C < 65 wt% sugar: syrup

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

Components and Phases

Sugar/Water Phase Diagram



Syrup : one phase, (single physical and chemical property)
Water+sugar : two phases, mixture

Components and Phases

- Components:
  The elements or compounds which are present in the alloy
  (e.g., Al and Cu)

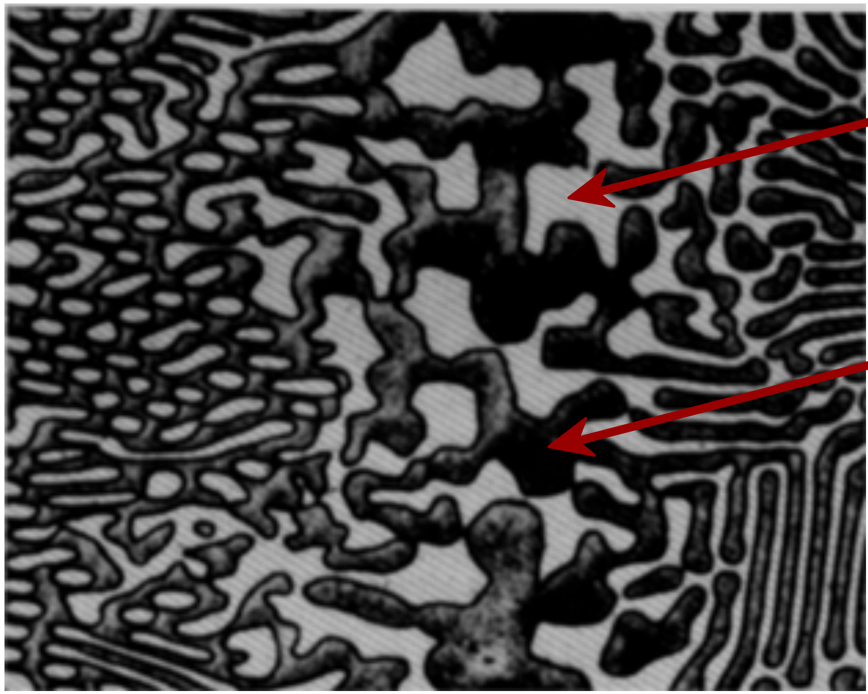
- Phases:
  Homogeneous system that has uniform physical and chemical characteristics.
  e.g. every pure material; solid, liquid, and gaseous solution.

- Mixture: systems composed of two or more phases

Components and Phases

- Components:
  The elements or compounds which are present in the alloy (e.g., Al and Cu)
- Phases:
  The physically and chemically distinct material regions that form (e.g., α and β).

Aluminum-Copper Alloy



β (lighter phase)

α (darker phase)

Adapted from chapter-opening photograph, Chapter 9, *Callister, Materials Science & Engineering: An Introduction, 3e.*

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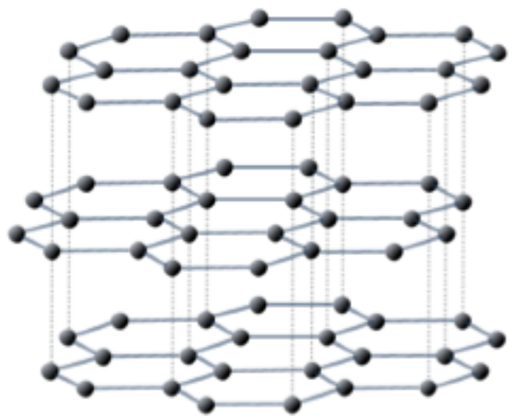
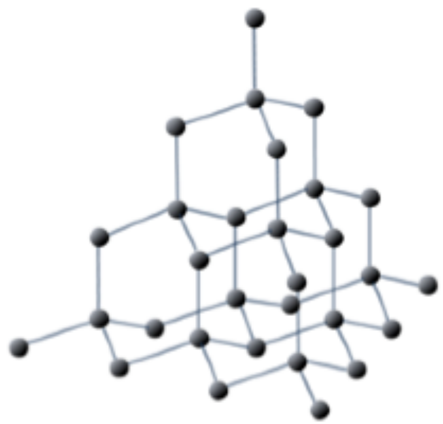
Components and Phases

Different phase: Not necessary that there are different in both physical and chemical properties.

e.g.
Water and ice
Graphite and diamond (hexagonal lattice and diamond lattice)



Graphite (solid lines are strong covalent bonds, dotted lines are weak inter-layer bonds)



Diamond (all bonds are strong covalent bonds)

Phase equilibria

- Equilibrium : stable
  - Macroscopic : characteristics of a system doesn't change with time.

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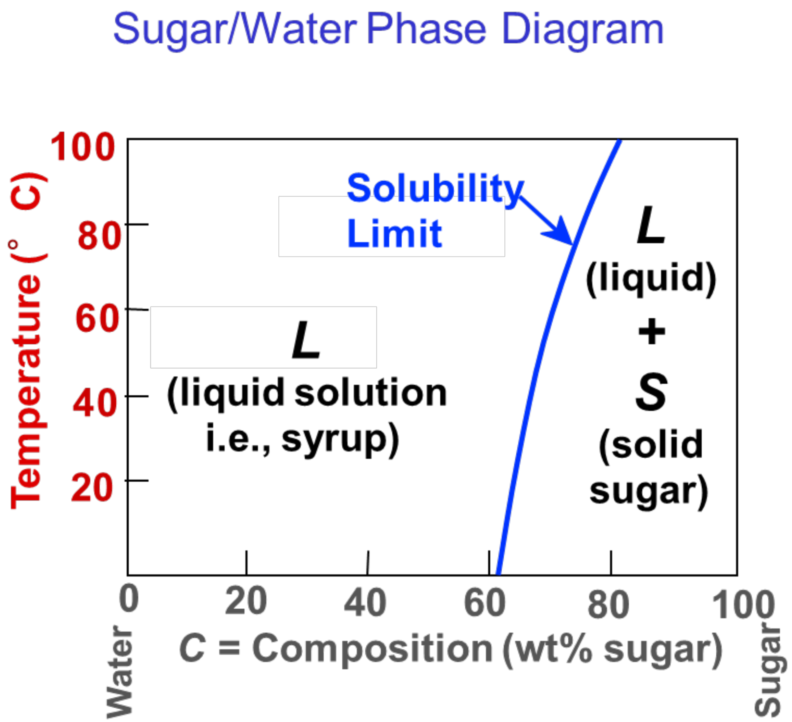
  - Energetic：system has minimum free energy at the specified environment. (temperature, pressure, composition)

- Phase equilibrium : stable system consisting of more than one phase.

Phase equilibria



Below solubility limit: syrup
Beyond : mixture of sugar and syrup

Environment changes equilibrium phase

Ex.: in sugar/water mixture, at 20C, equilibrium phase is 65% sugar + 35% water
At 100C, 80% sugar + 20% water

Phase equilibria

- From a phase diagram, equilibrium characteristics of a system are provided.
- Phase diagram doesn't indicate the time period necessary for the attainment of a new equilibrium.

- In solid solution, due to low diffusion rate of components, equilibrium rate is slow.
- Sometimes it never achieve equilibrium and the state may persist indefinitely. The system is said in a **metastable** state .

Equilibrium = 材料性質好 ？
Non-equilibrium =材料性質不好？

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

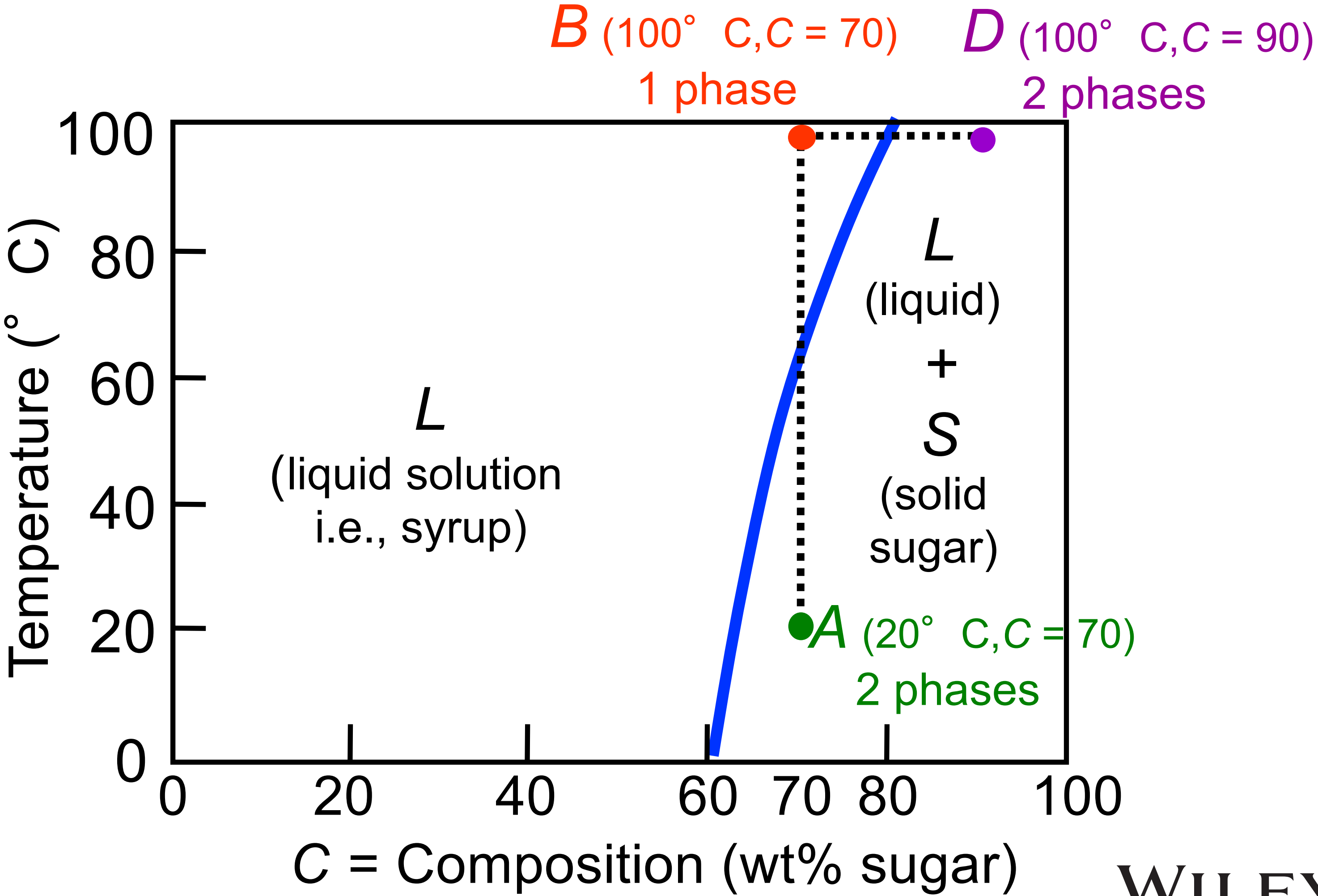
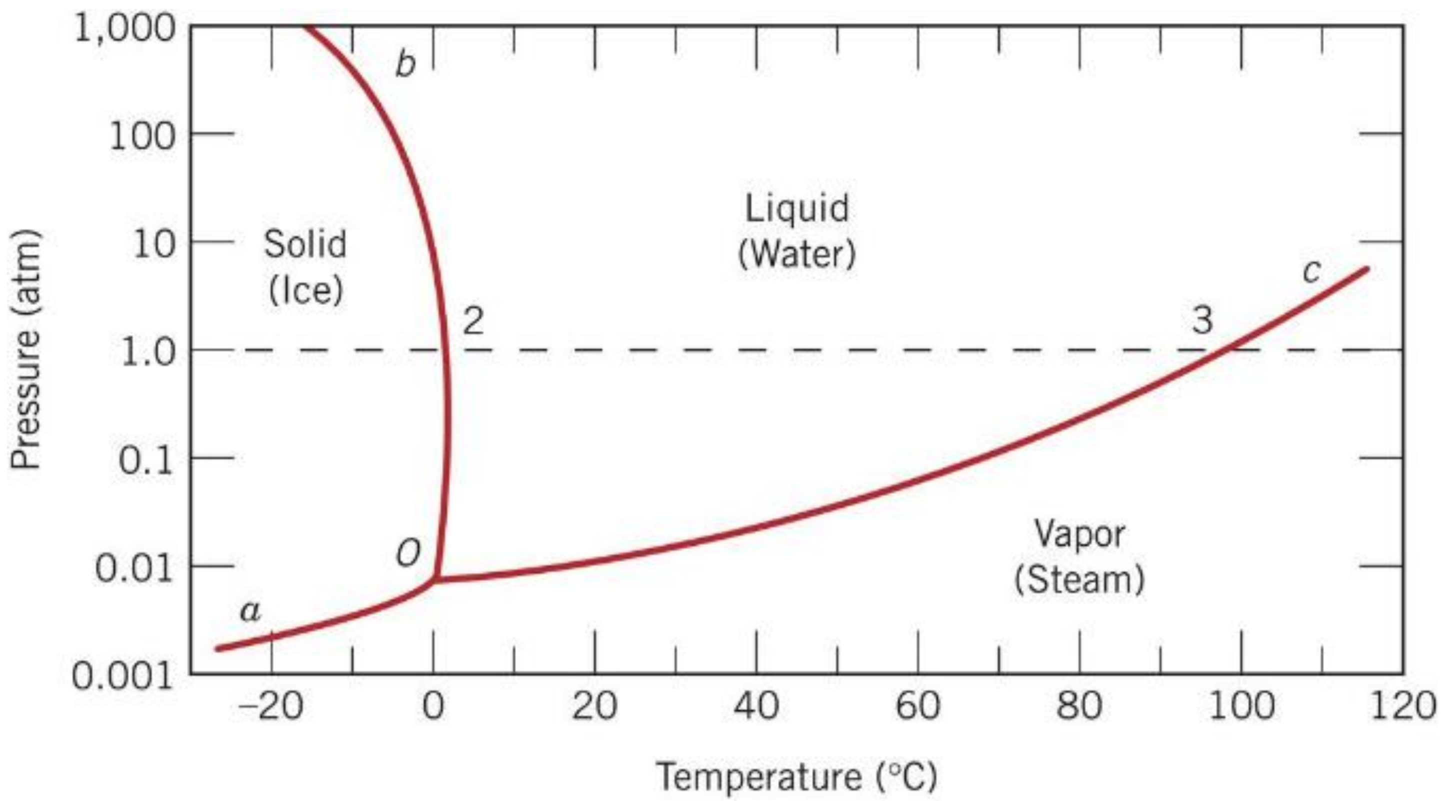


Fig. 9.1, *Callister & Rethwisch 10e.*

One-component phase diagram

- Pressure-temperature diagram.
- *aO, bO, cO* are phase boundaries and *O* is triple point, at which phases are coexist.
-



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Binary Phase Diagram: Criteria for Solid Solubility

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

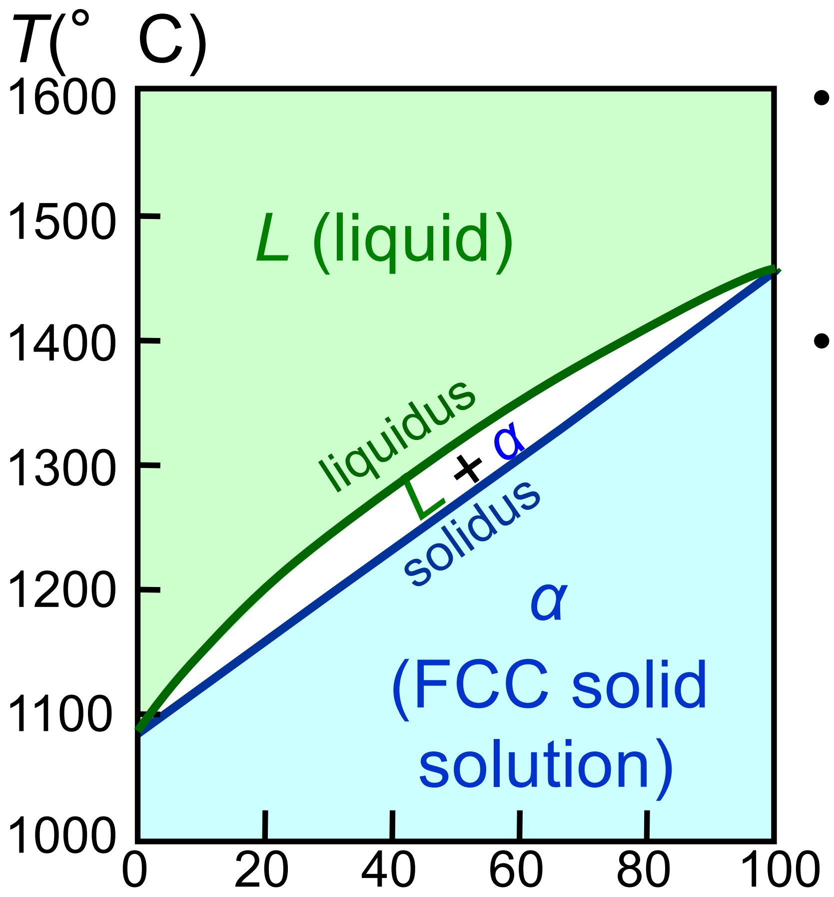
	Crystal Structure	Electroneg ativity	*r* (nm)
Ni	FCC	1.9	0.1246
Cu	FCC	1.8	0.1278

- 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.

Binary Phase Diagram

- 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*

Fig. 9.3(a), *Callister & Rethwisch 10e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

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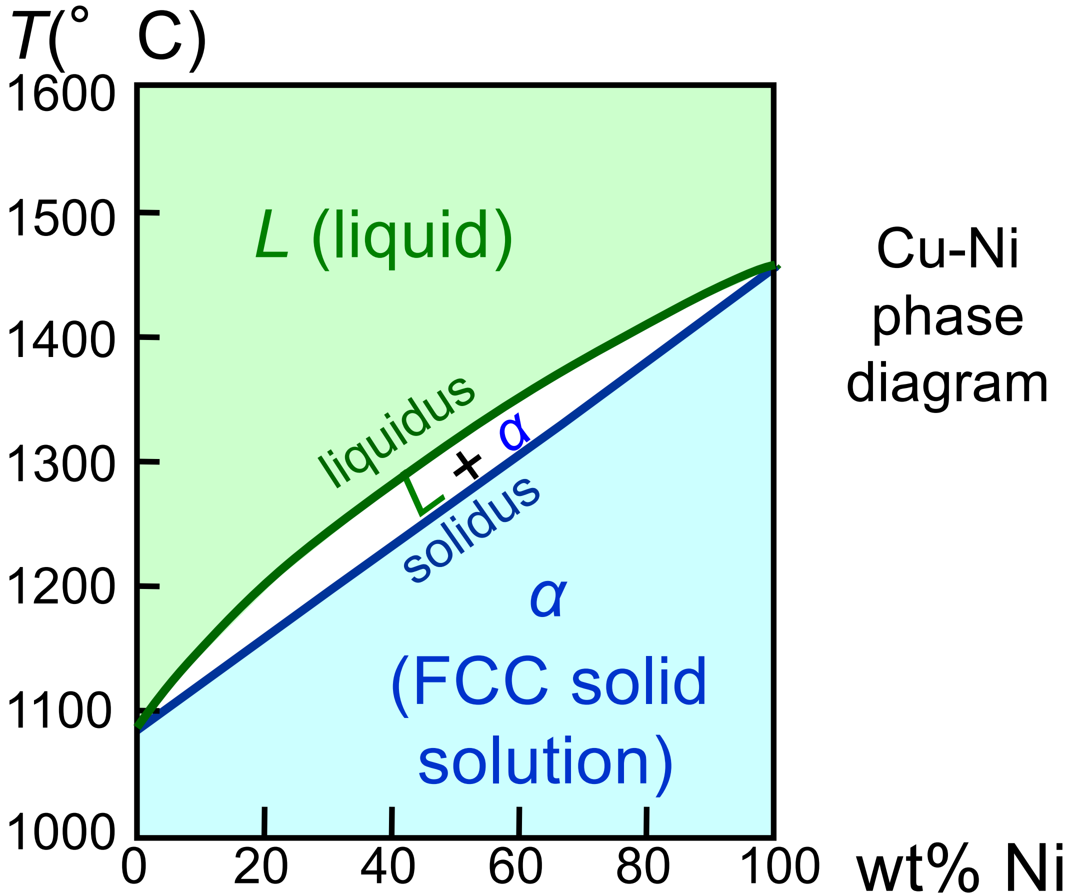
Isomorphous Binary Phase Diagram

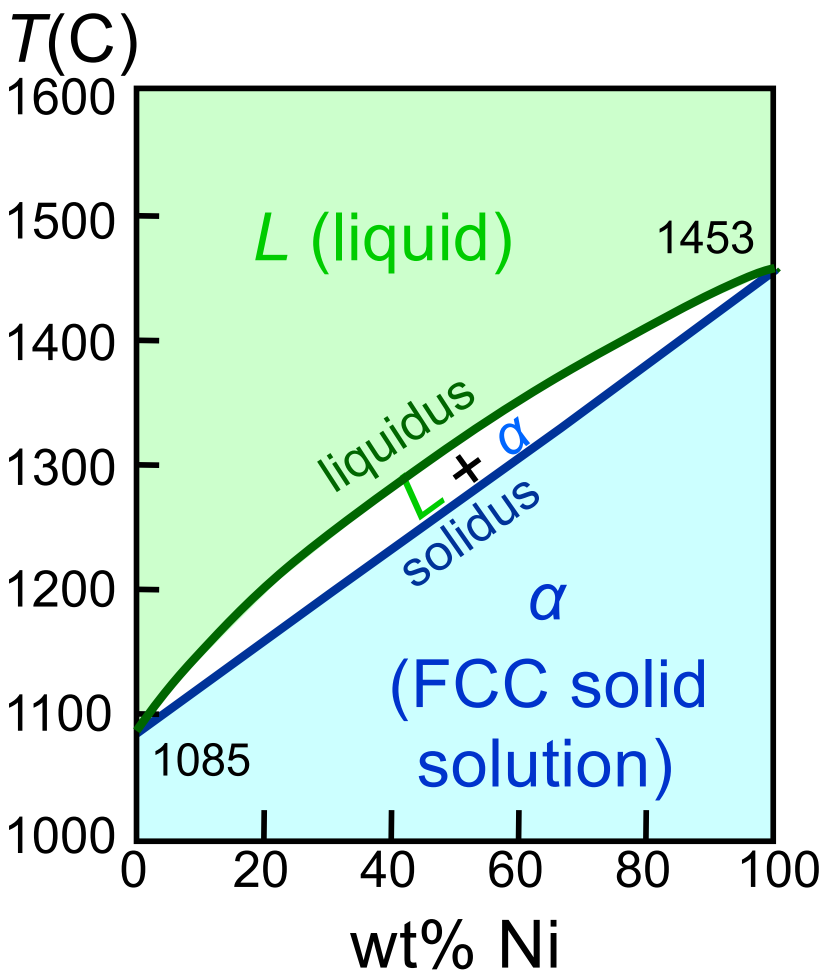
- Phase diagram:
  Cu-Ni system.
- System is:
  -- binary
  i.e., 2 components:
  Cu and Ni.
  -- isomorphous
  i.e., complete solubility of one component in another; *α* phase field extends from 0 to 100 wt% Ni.



Cu-Ni phase diagram

Fig. 9.3(a), *Callister & Rethwisch 10e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams



Information available

1. Phases that are present
2. Composition of phases
3. Percentage or fractions of the phases

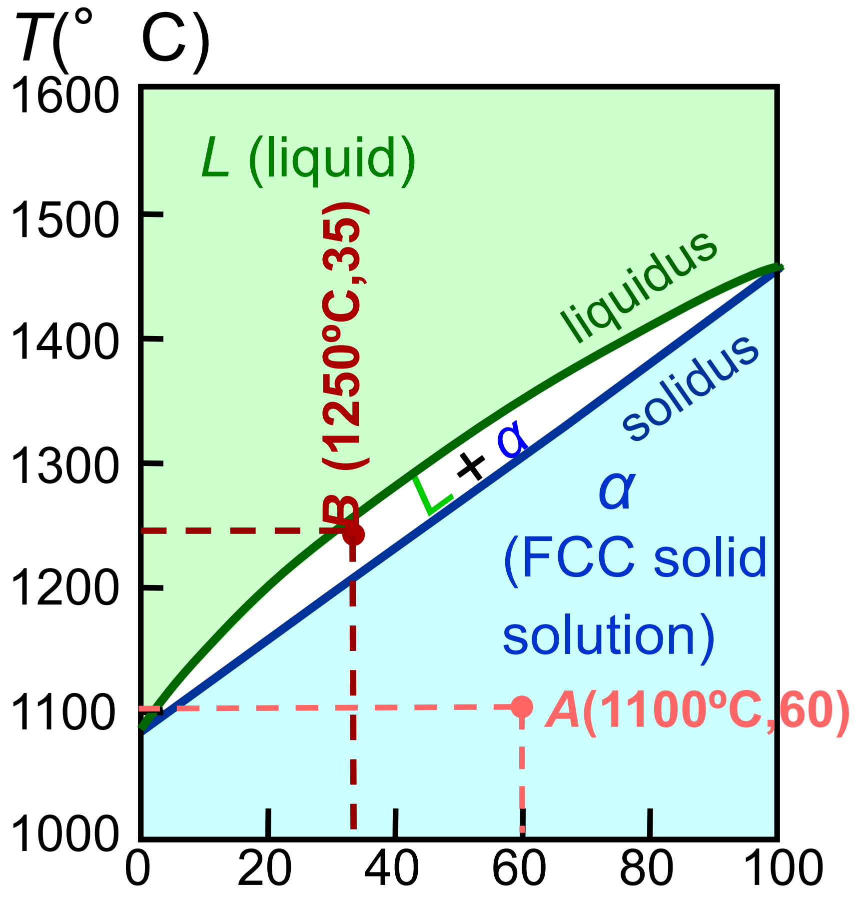
Phase Diagrams:
Determination of phase(s) present

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

- Examples:

  A(1100°C, 60 wt% Ni):
  1 phase: α

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



Cu-Ni phase diagram

Fig. 9.3(a), *Callister & Rethwisch 10e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

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 = 1320° C:

Only Liquid (L) present

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

At T_D = 1190° C:

Only Solid (α) present

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

At T_B = 1250° C:

Both α and L present

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

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

Cu-Ni system

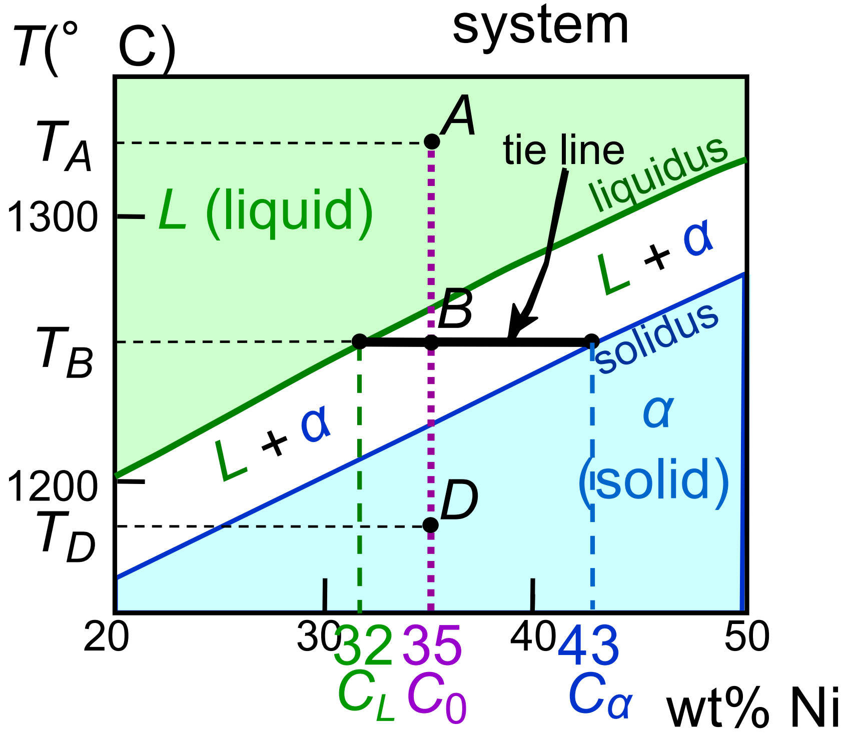


Fig. 9.3(b), *Callister & Rethwisch 10e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams:
Determination of phase weight fractions

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

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

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

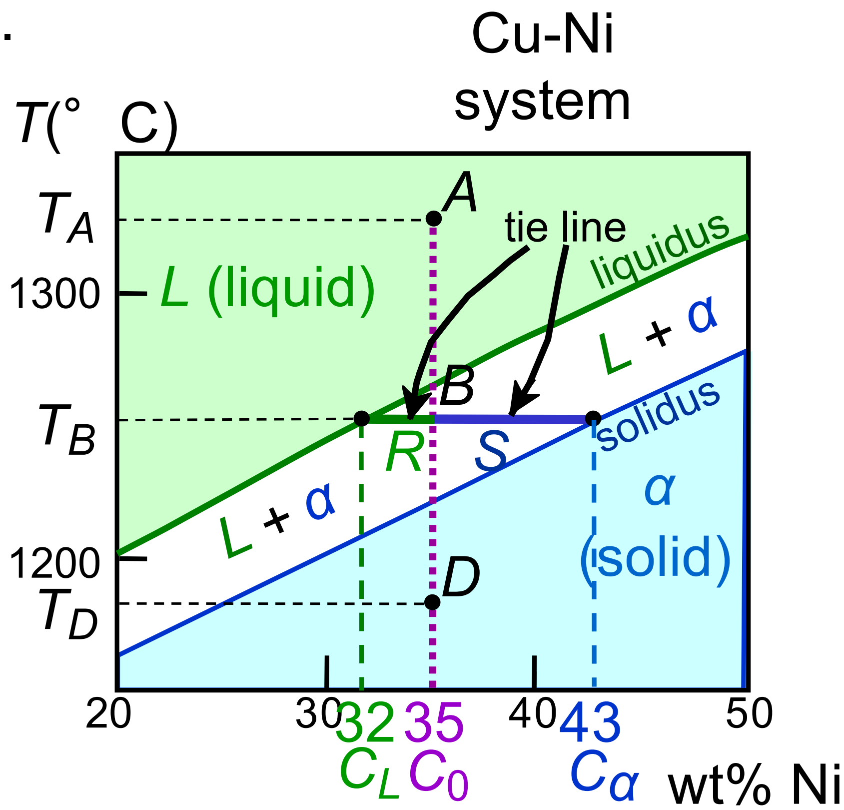
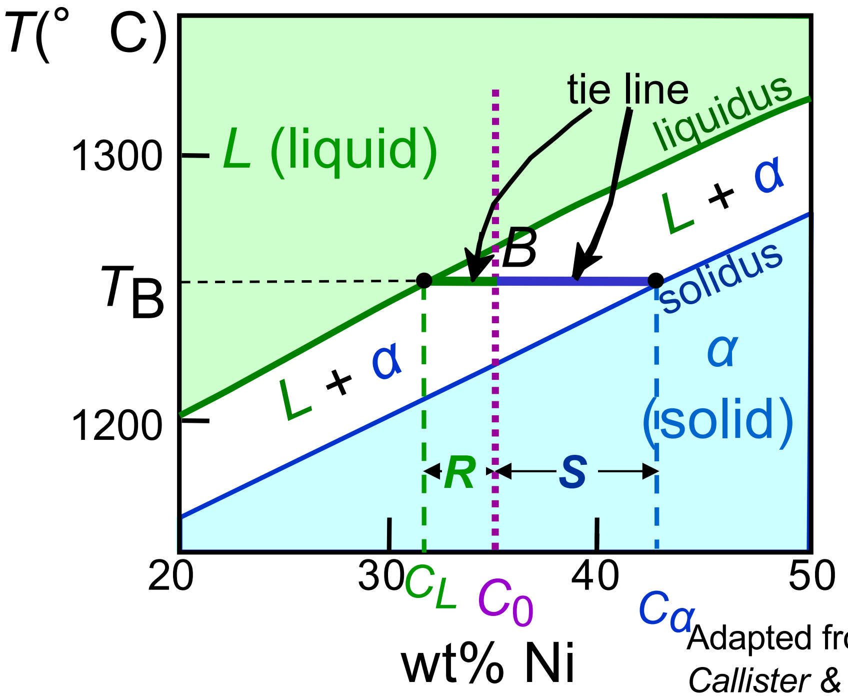


Fig. 9.3(b), *Callister & Rethwisch 10e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

The Lever Rule

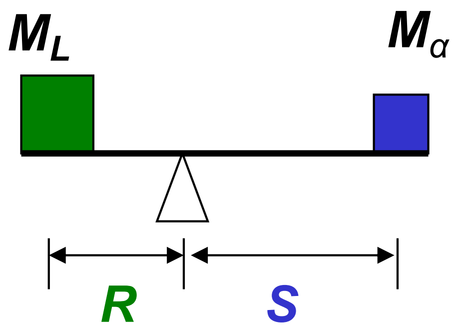
- Tie line – connects the phases in equilibrium with each other – also sometimes called an isotherm



Adapted from Fig. 9.3(b), *Callister & Rethwisch 10e.*

What fraction of each phase?

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



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

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

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

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EXAMPLE PROBLEM 9.1

Lever Rule Derivation

Derive the lever rule.

Solution

The Lever Rule: volume fraction

- It is often more convenient to specify relative phase amount in terms of volume fraction (rather than weight fraction)
- Because they may be determined from examination of the microstructure.
- The properties of a multiphase alloy may be estimated on the basis of volume fraction.

The Lever Rule: volume fraction

$$V_\alpha = \frac{v_\alpha}{v_\alpha + v_\beta}$$

Conversion between mass fraction and volume fraction

$$V_\alpha = \frac{\dfrac{W_\alpha}{\rho_\alpha}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}}$$

$$W_\alpha = \frac{V_\alpha \rho_\alpha}{V_\alpha \rho_\alpha + V_\beta \rho_\beta}$$

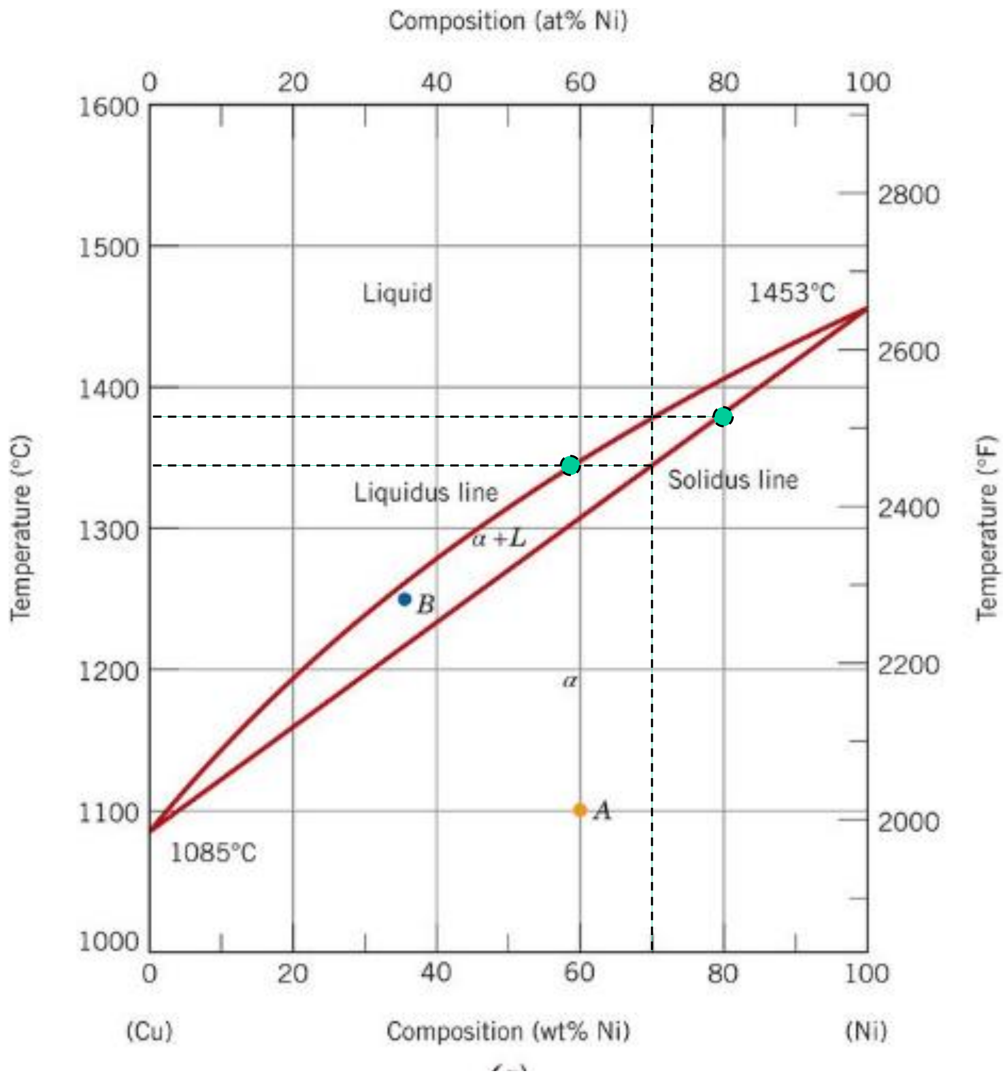
Concept Check 9.3 A copper–nickel alloy of composition 70 wt% Ni–30 wt% Cu is slowly heated from a temperature of 1300°C (2370°F).

(a) At what temperature does the first liquid phase form?

(b) What is the composition of this liquid phase?

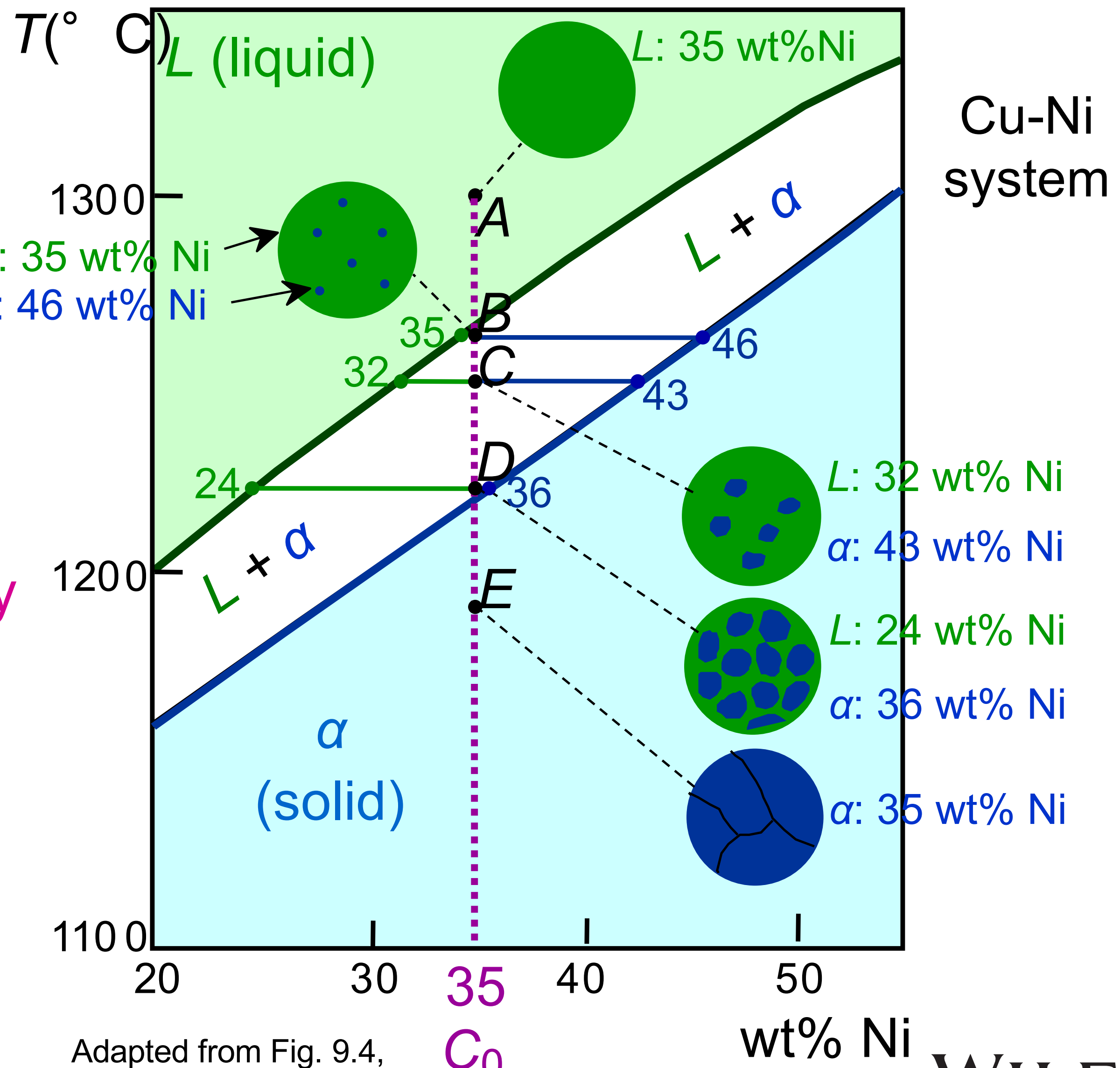
(c) At what temperature does complete melting of the alloy occur?

(d) What is the composition of the last solid remaining prior to complete melting?



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

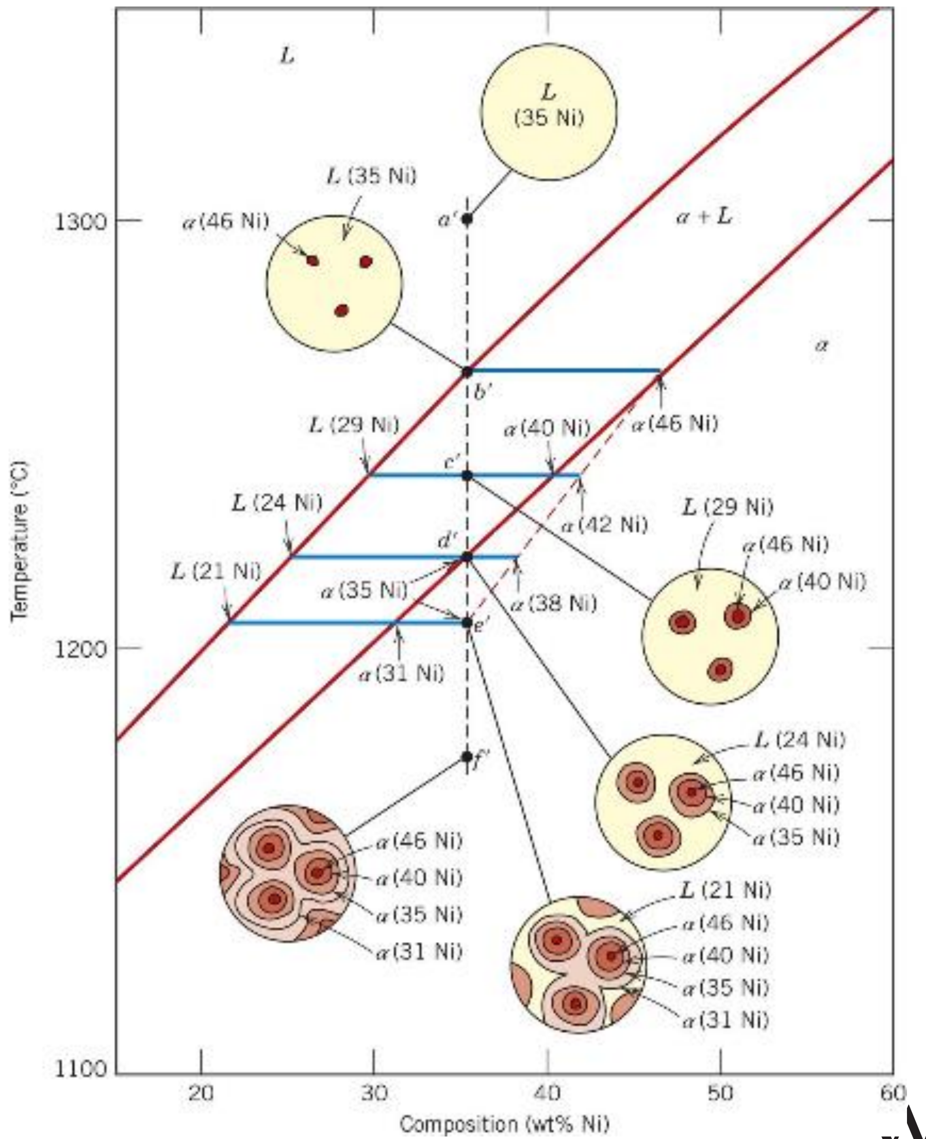


Adapted from Fig. 9.4, *Callister & Rethwisch 10e.*

Non-equilibrium cooling process

Fast diffusion in liquid,
slow diffusion in solid.

a': L(35Ni)
b': L(35Ni), α(46Ni)
c': L(29Ni), α(40Ni), average Ni=42
**No composition change for previously formed solid phase*
d': L(24Ni), α(35Ni), average Ni=38
e': L(21Ni), α(31Ni), average Ni=35
f': α(35Ni)



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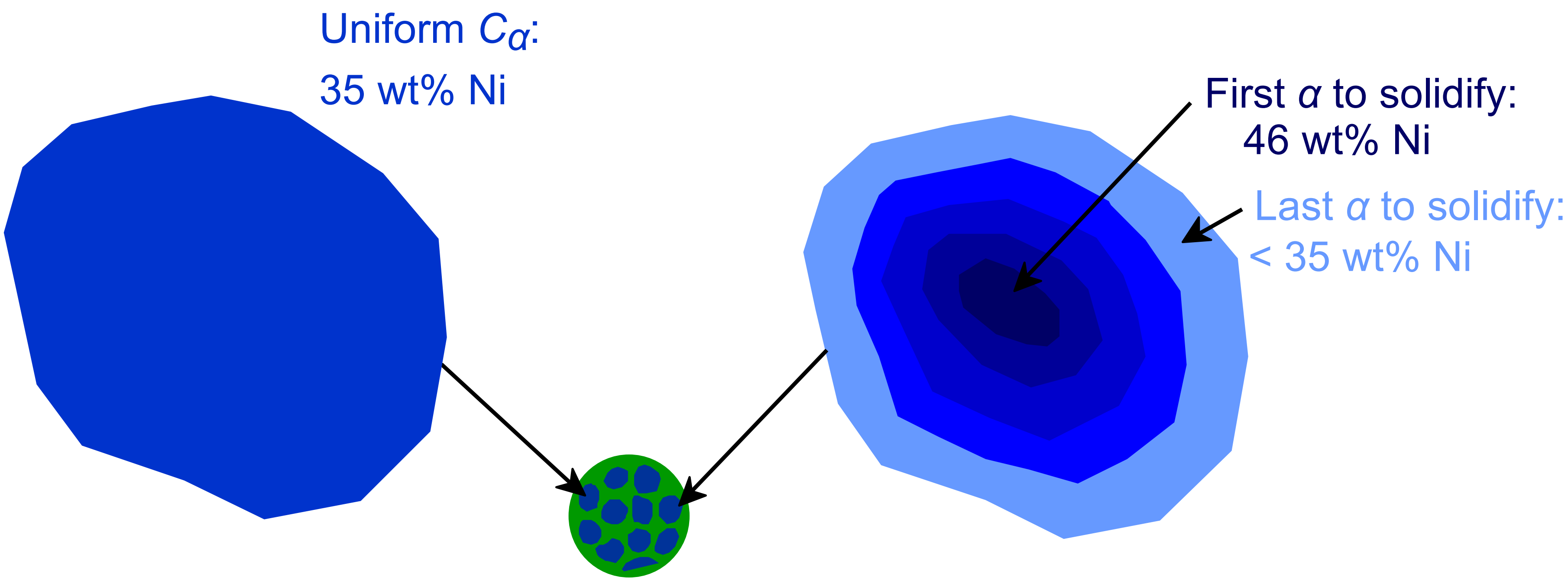
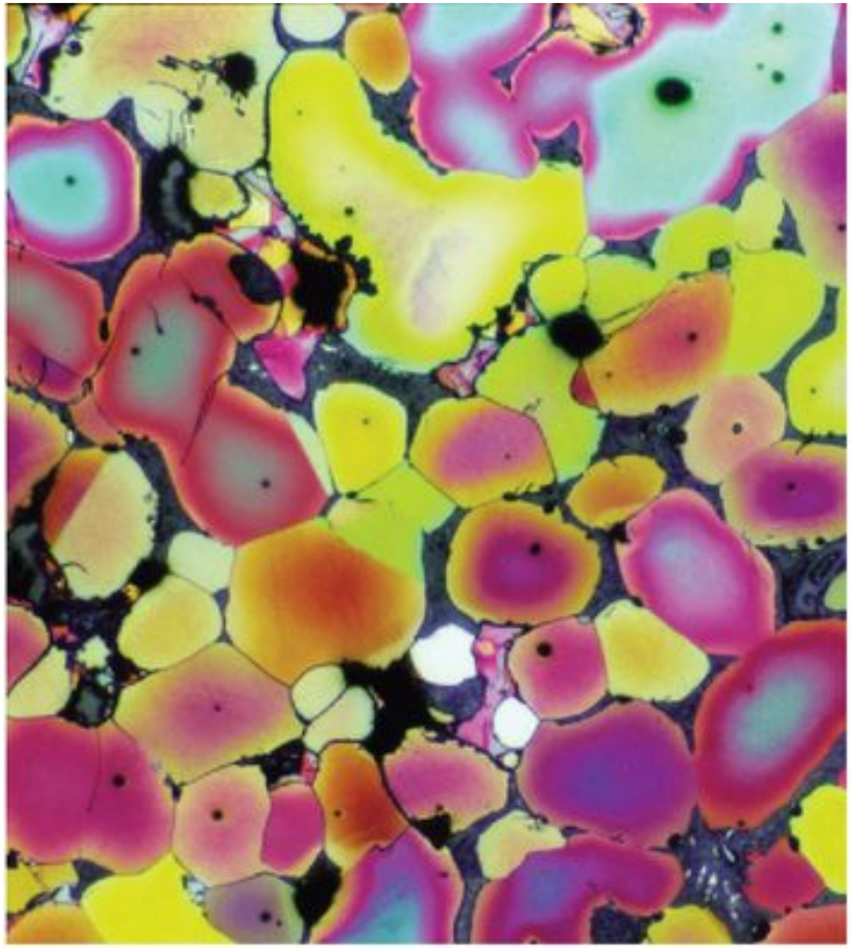
Cored vs Equilibrium Structures

- C_α changes as we solidify.
- Cu-Ni case: First α to solidify has C_α = 46 wt% Ni.
  Last α to solidify has C_α = 35 wt% Ni.

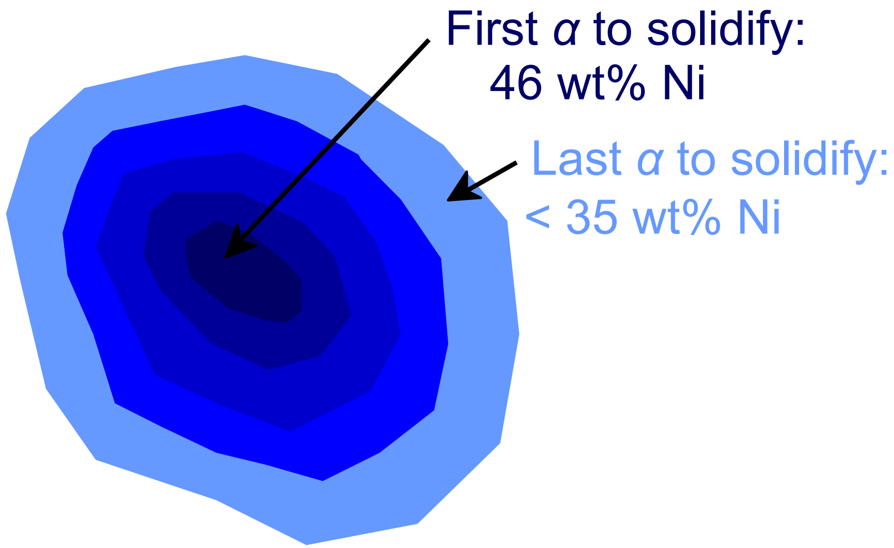
- Slow rate of cooling:
  Equilibrium structure
- Fast rate of cooling:
  Cored structure



Cored Structures



Courtesy of George F. Vander Voort, Struers Inc.



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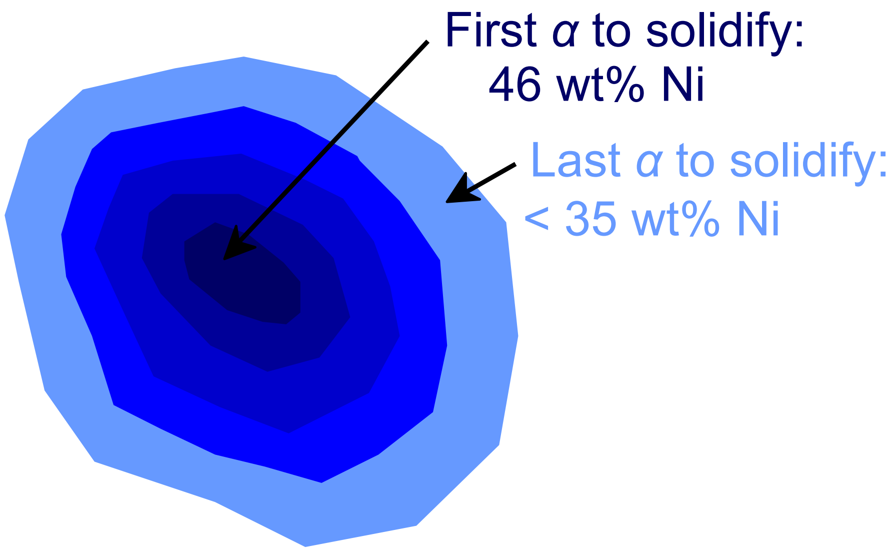
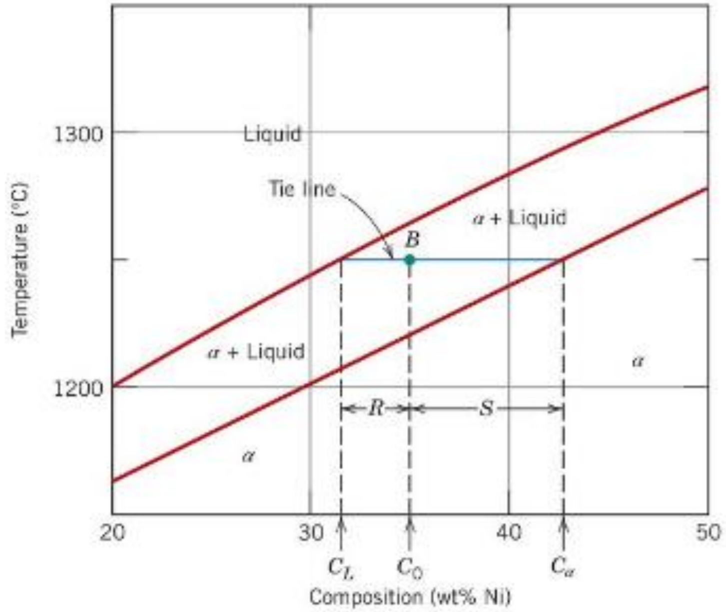
Cored Structures



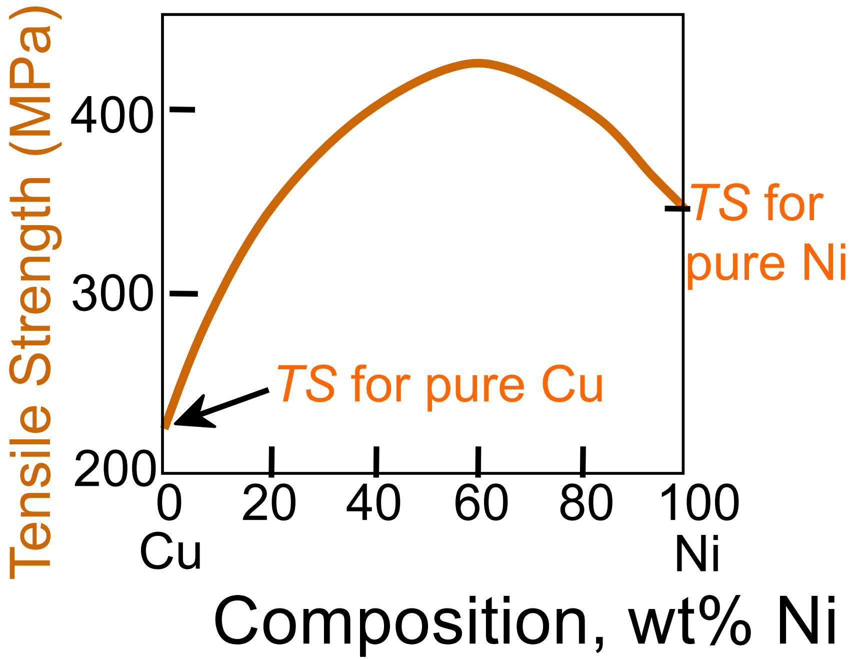


- For each grain, outer ring (grain boundary) has lower melting T, sudden loss of mechanical integrity when casting.
- Melting may begin at T below equilibrium solidus T of alloy.
- May be eliminated by heat treatment at T below solidus point. (homogenization)

Mechanical Properties: Cu-Ni System

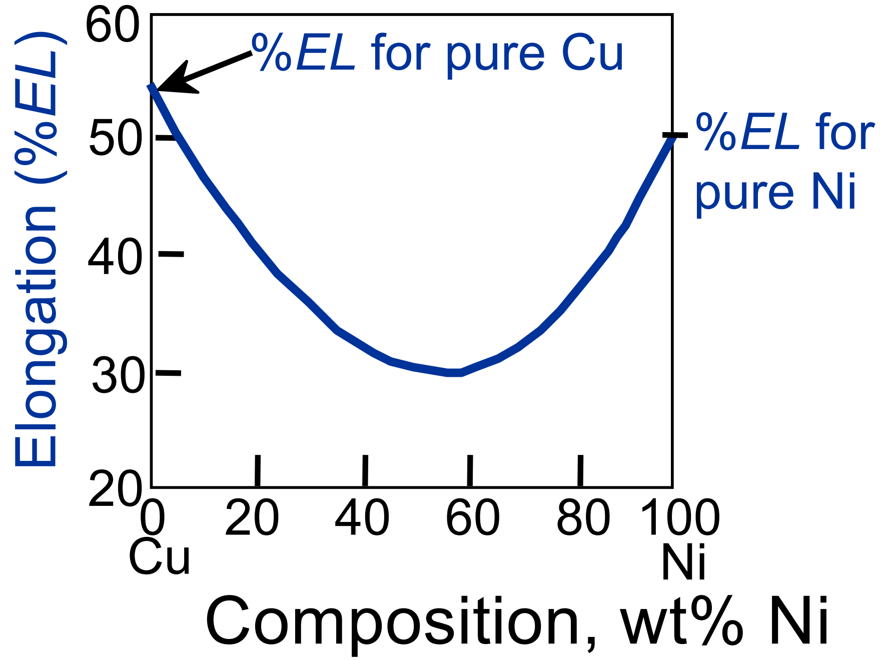
- Effect of solid solution strengthening on:

-- Tensile strength (*TS*)



Adapted from Fig. 9.6(a), *Callister & Rethwisch 10e.*

-- Ductility (%*EL*)



Adapted from Fig. 9.6(b), *Callister & Rethwisch 10e.*

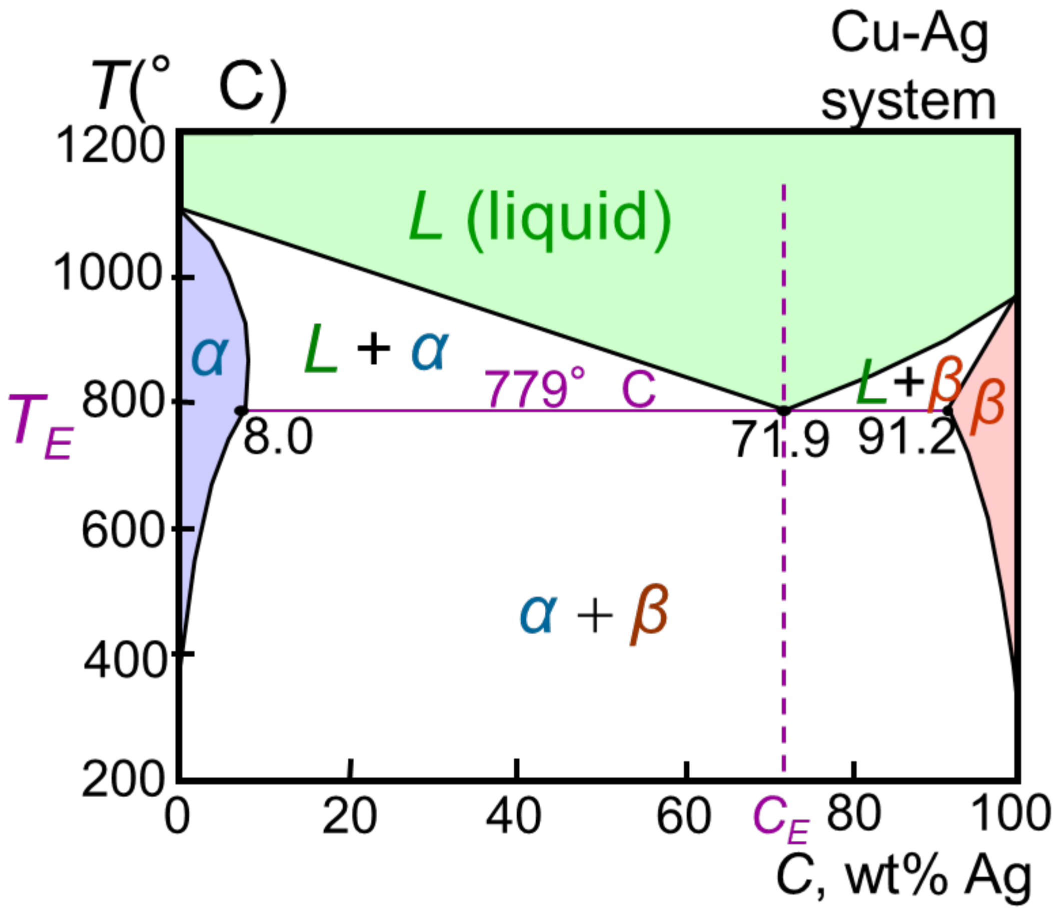
Binary-Eutectic（共晶）Systems

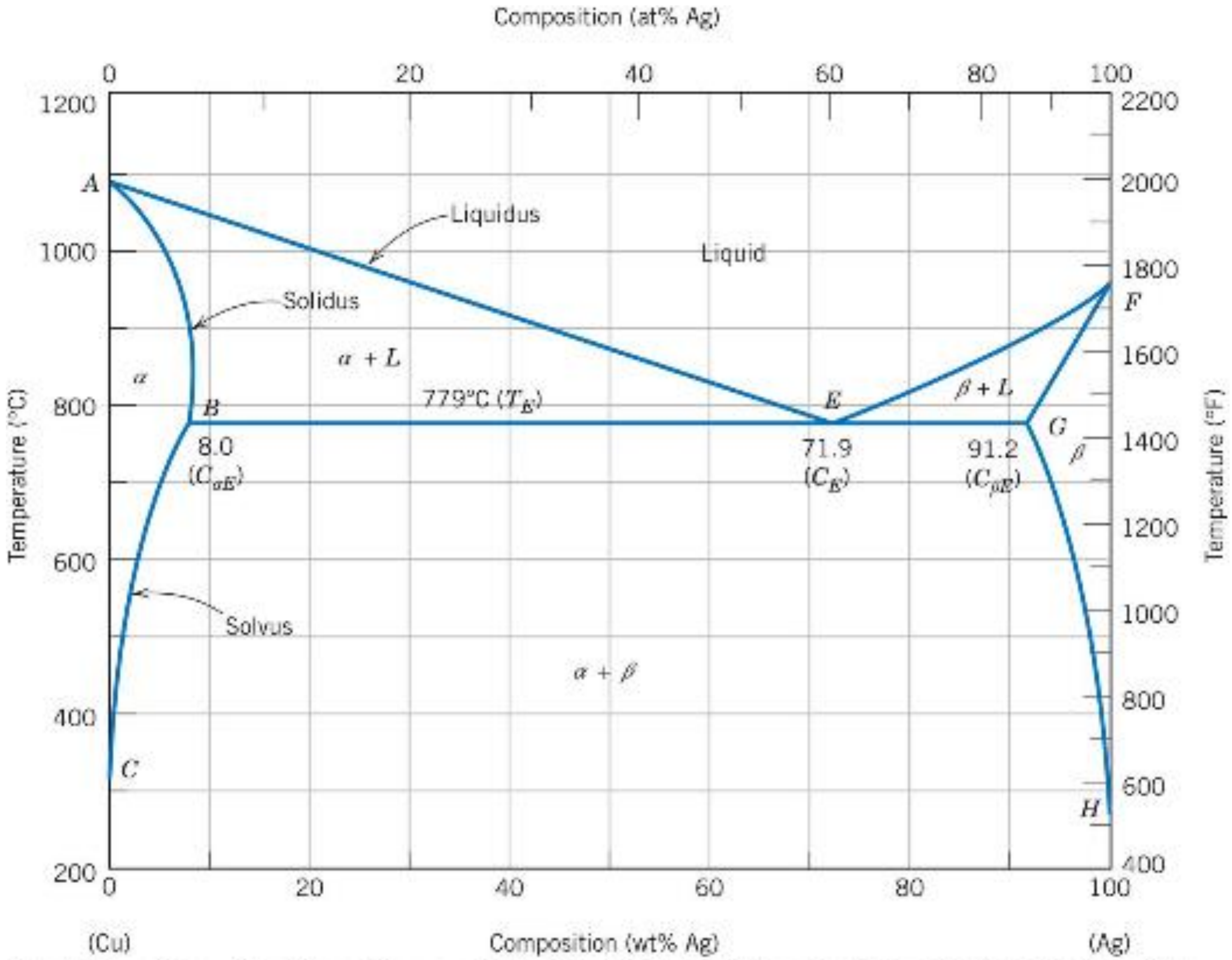
2 components

has a special composition with a min. melting T.

- 3 single phase regions (L, α, β)
- Limited solubility:
  α: mostly Cu
  β: mostly Ag
- 3 two-phase regions
- separated by *solvus line, solidus line and liquidus line*

Cu: FCC, Ag: FCC





Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.

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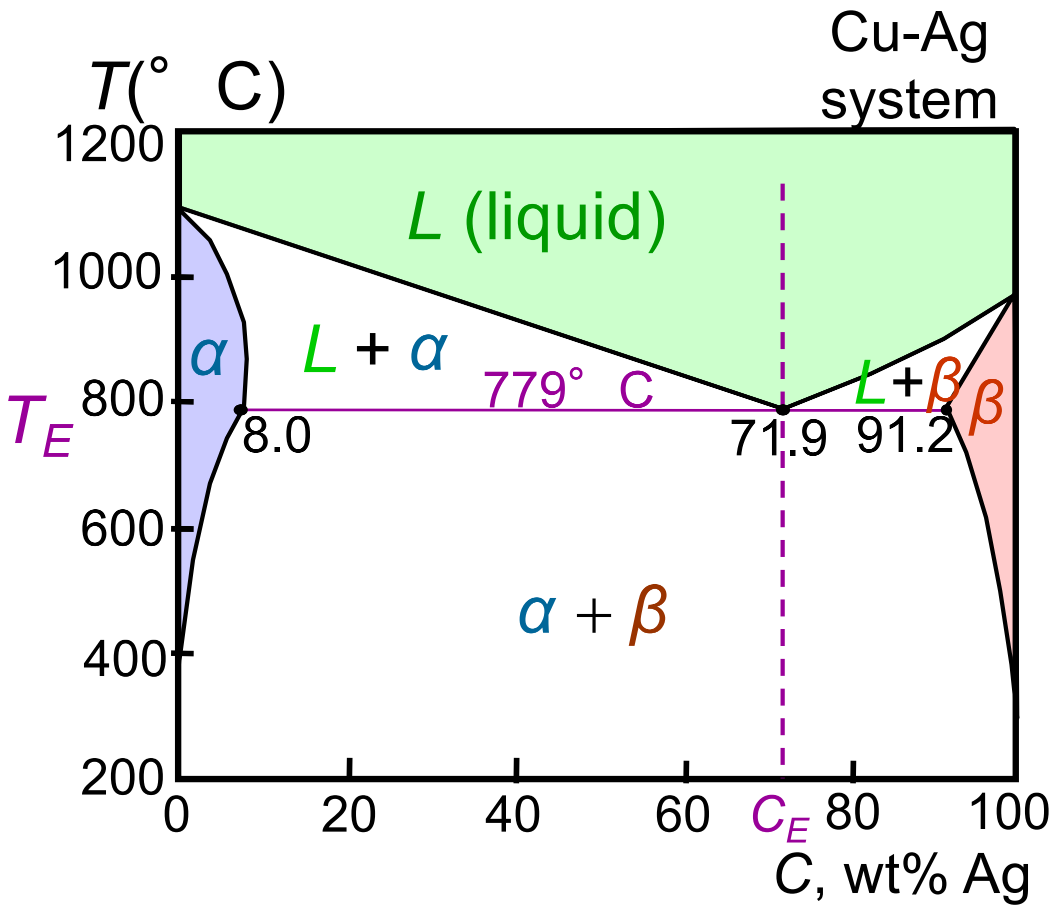
Binary-Eutectic Systems

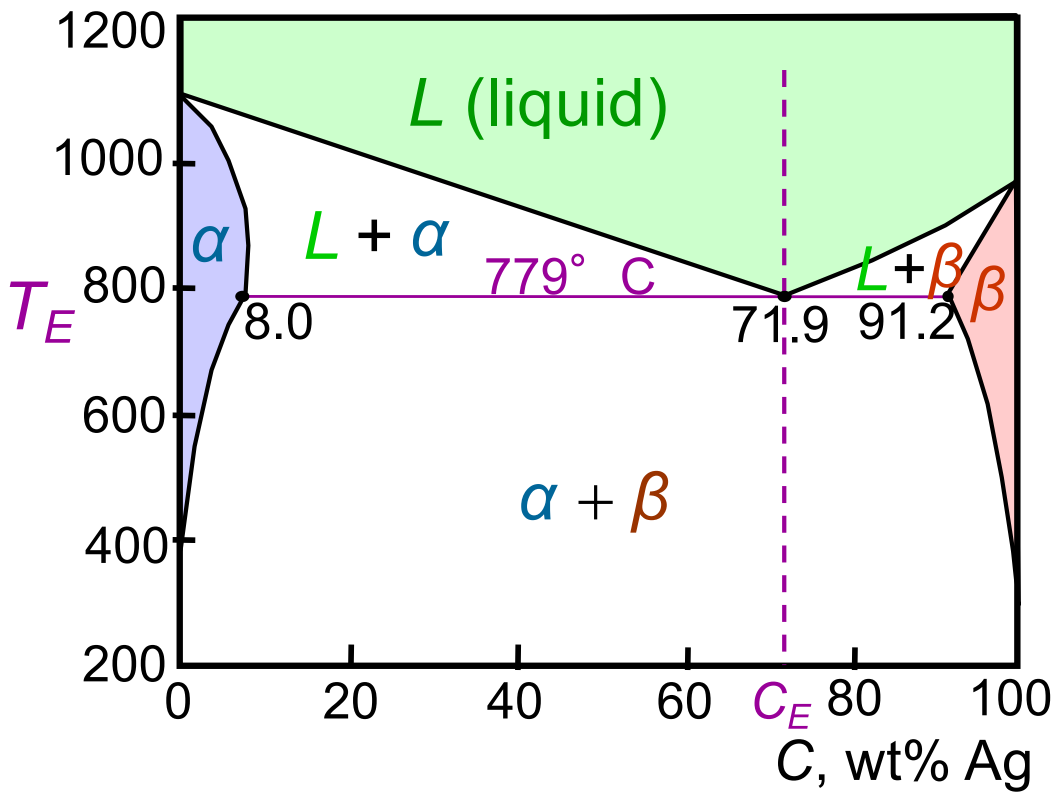
- As Ag is added to Cu, melting T decrease.
- Same as Cu is added to Ag.

- T_E : No liquid below T_E
- C_E : Composition at temperature T_E

(For Cu-Ag system, 71.9 wt% Ag at 779C)



Binary-Eutectic Systems



Eutectic Systems

has a special composition with a min. melting *T*.

**Eutectic* : easily melted*

- **Eutectic reaction**

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

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

EXAMPLE PROBLEM 9.2

Determination of Phases Present and Computation of Phase Compositions

For a 40 wt% Sn–60 wt% Pb alloy at 150°C (300°F),

(a) what phase(s) is (are) present?

(b) What is (are) the composition(s) of the phase(s)?

Solution

EX 1: Pb-Sn Eutectic System

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

  Answer: $\alpha + \beta$

  - -- the phase compositions

  Answer: $C_\alpha = 11$ wt% Sn
  $C_\beta = 99$ wt% Sn

  - -- the relative amount of each phase

  Answer:

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

$$= \frac{99 - 40}{99 - 11} = \frac{59}{88} = 0.67$$

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

$$= \frac{40 - 11}{99 - 11} = \frac{29}{88} = 0.33$$

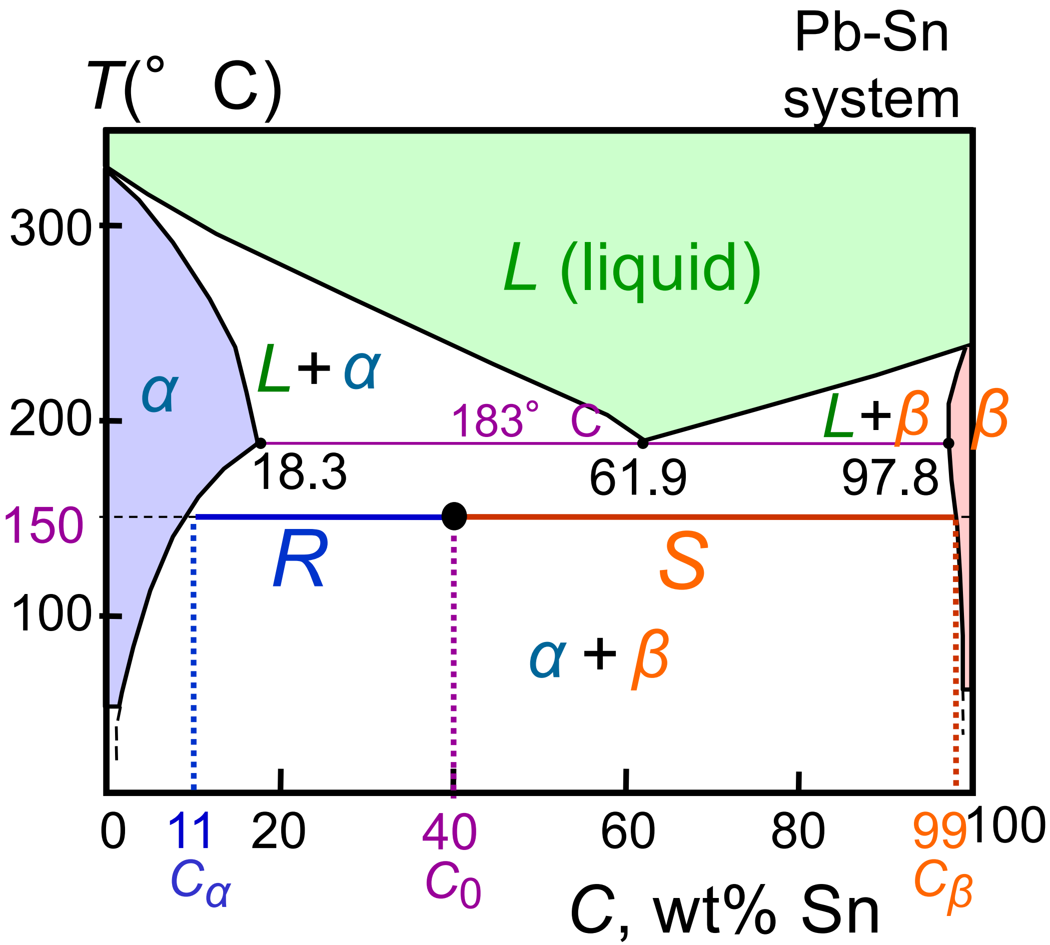


Fig. 9.8, *Callister & Rethwisch 10e.*
[Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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EXAMPLE PROBLEM 9.3

Relative Phase Amount Determinations—Mass and Volume Fractions

For the lead–tin alloy in Example Problem 9.2, calculate the relative amount of each phase present in terms of **(a)** mass fraction and **(b)** volume fraction. At 150°C, take the densities of Pb and Sn to be 11.35 and 7.29 g/cm^3, respectively.

Solution

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EX 2: Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 220° C, determine:

  -- the phases present:

  Answer: $\alpha + L$

  -- the phase compositions

  Answer: C_α = 17 wt% Sn

  C_L = 46 wt% Sn

  -- the relative amount of each phase

  Answer:

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 0.21$$

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

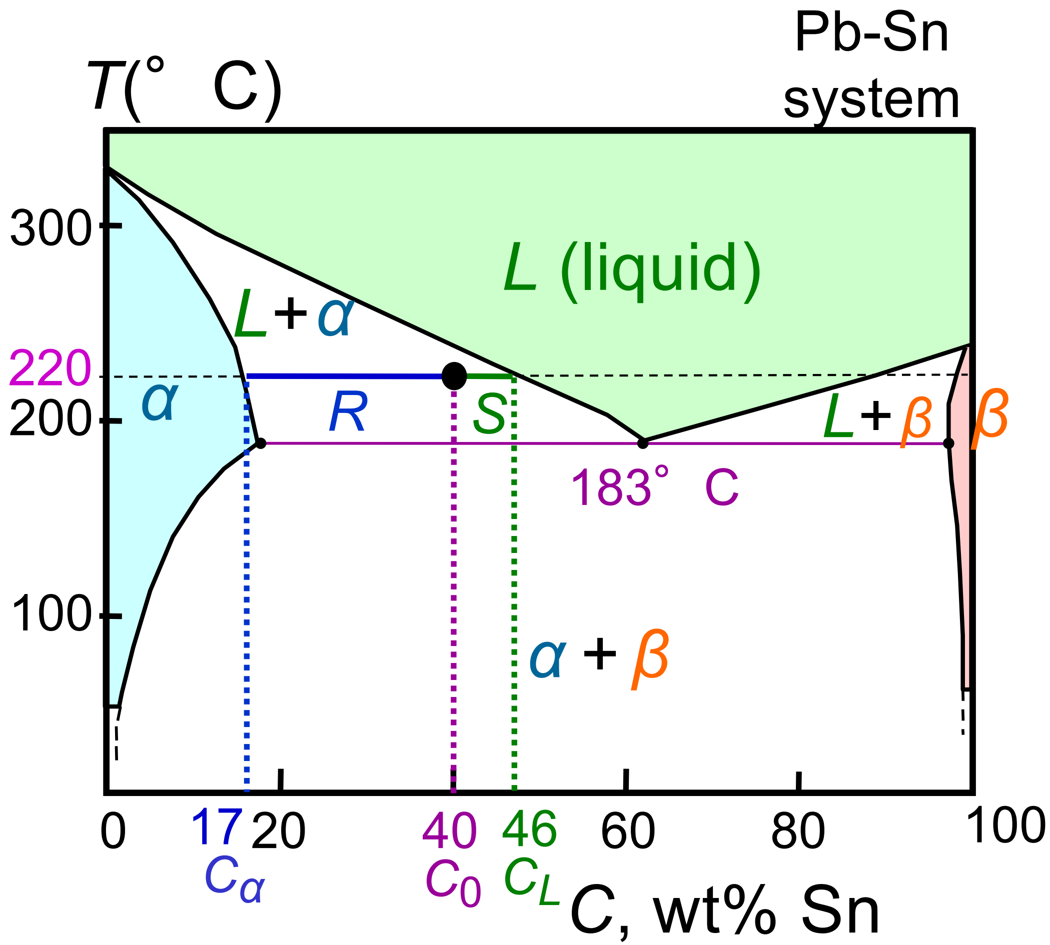


Fig. 9.8, *Callister & Rethwisch 10e.* [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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

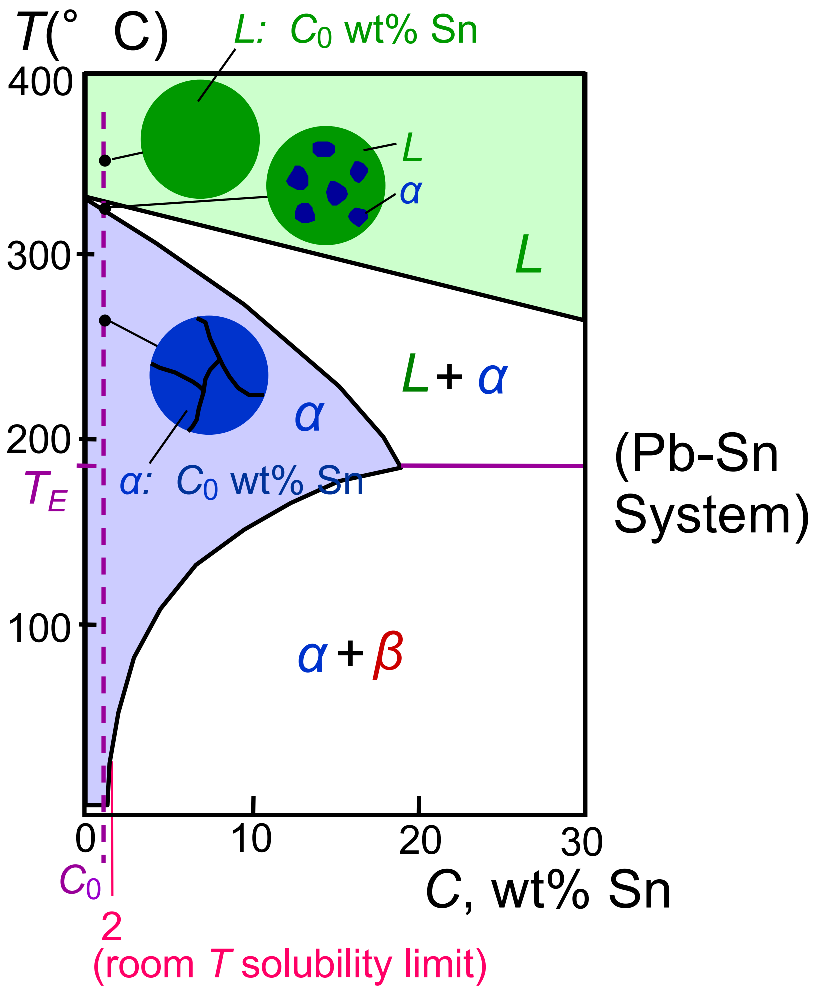


Fig. 9.11, *Callister & Rethwisch 10e.*

Microstructural Developments in Eutectic Systems II

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

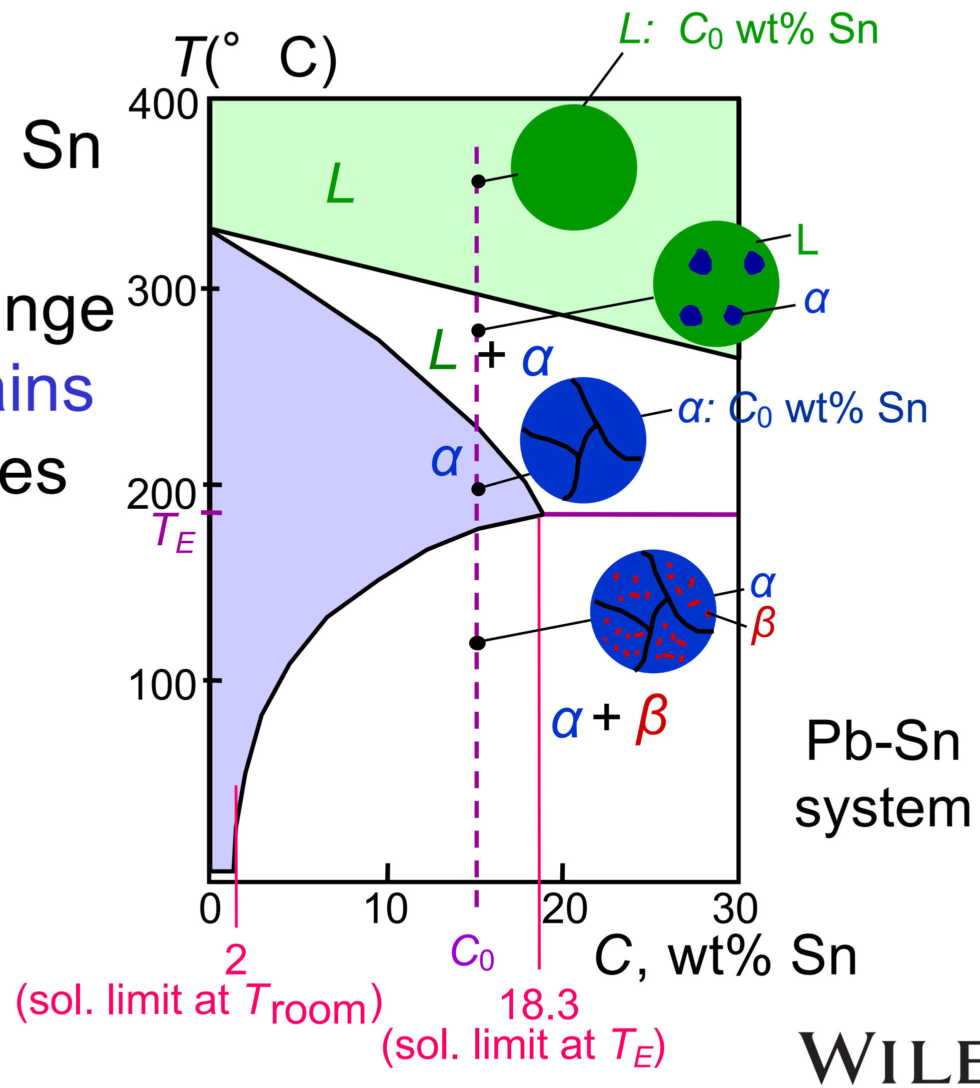


Fig. 9.12, *Callister & Rethwisch 10e.*

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.

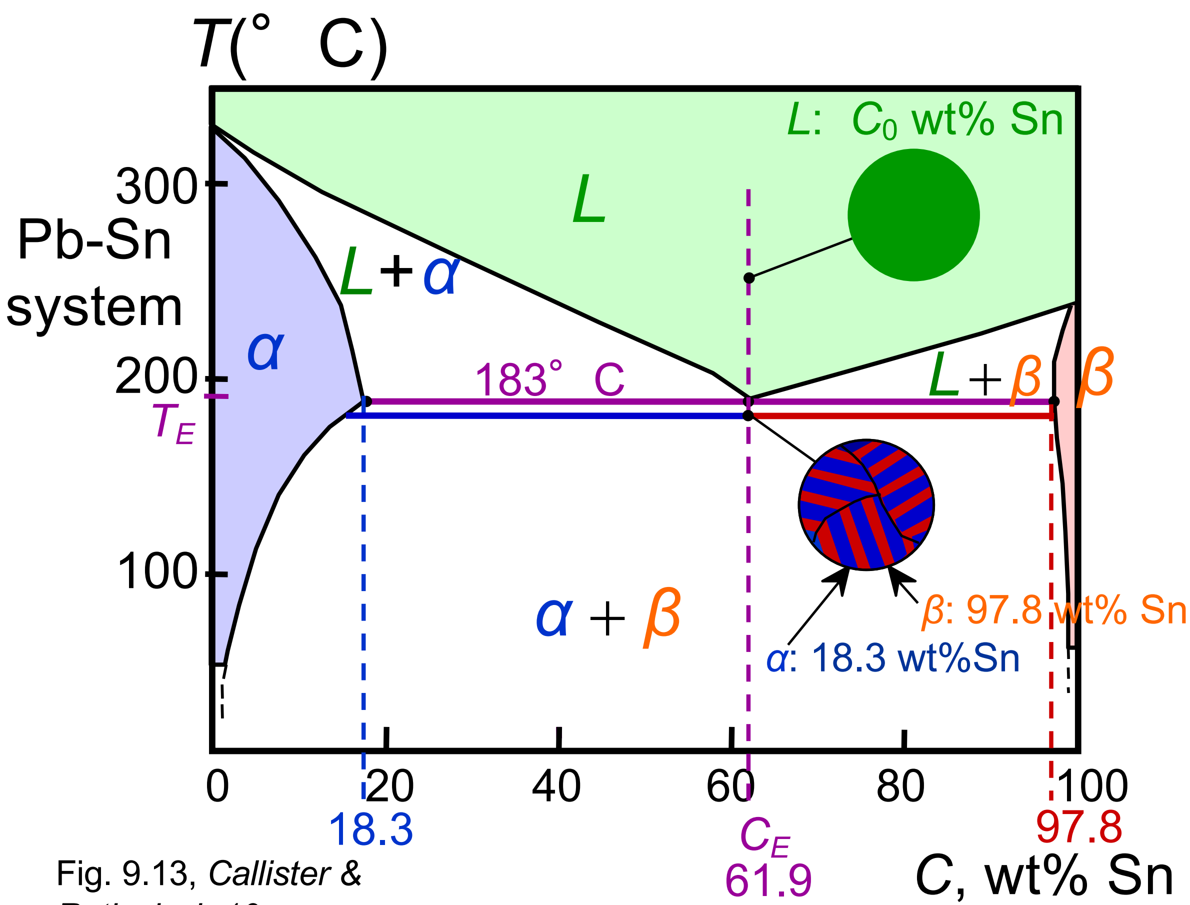


Fig. 9.13, *Callister & Rethwisch 10e.*

Micrograph of Pb-Sn eutectic microstructure

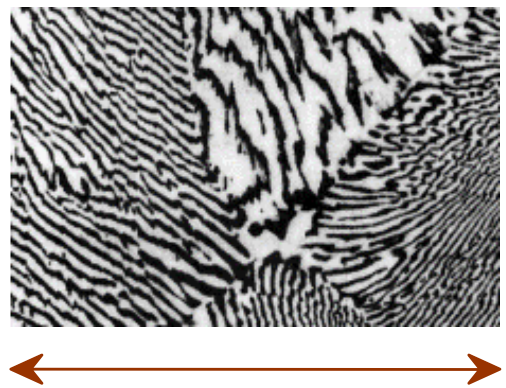
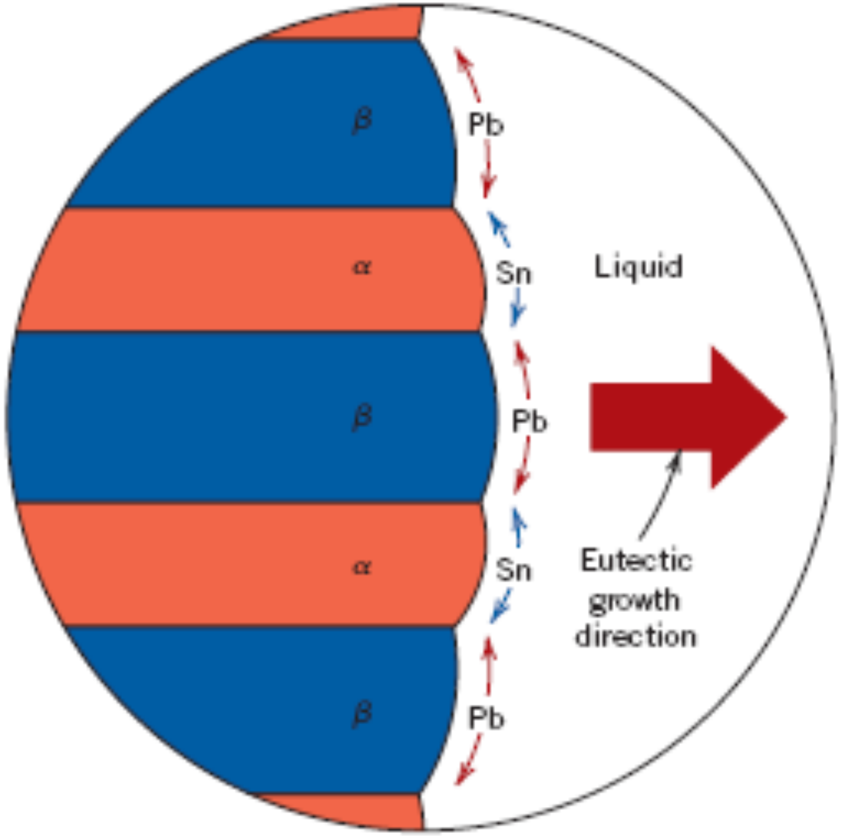
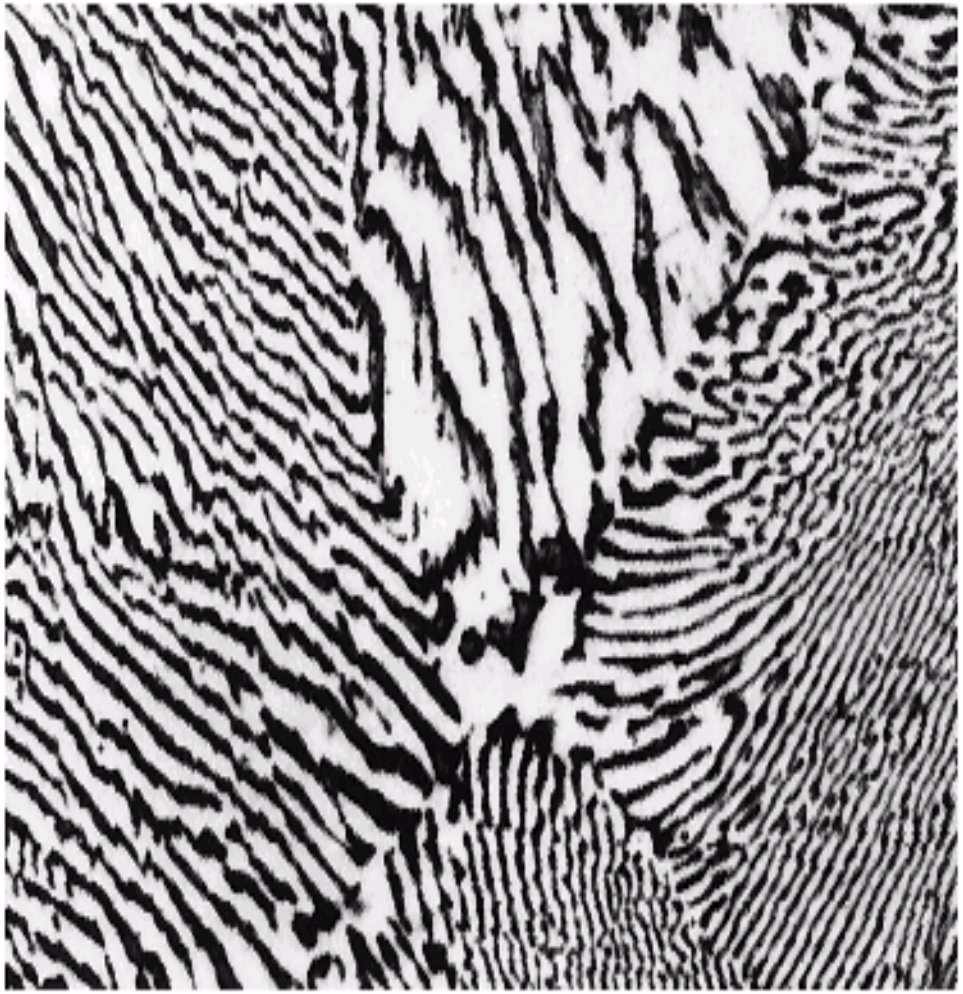


Fig. 9.14, *Callister & Rethwisch 10e.* (From *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

Lamellar Eutectic Structure





Figs. 9.14 & 9.15, *Callister & Rethwisch 10e.*
(Fig. 9.14 from *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

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

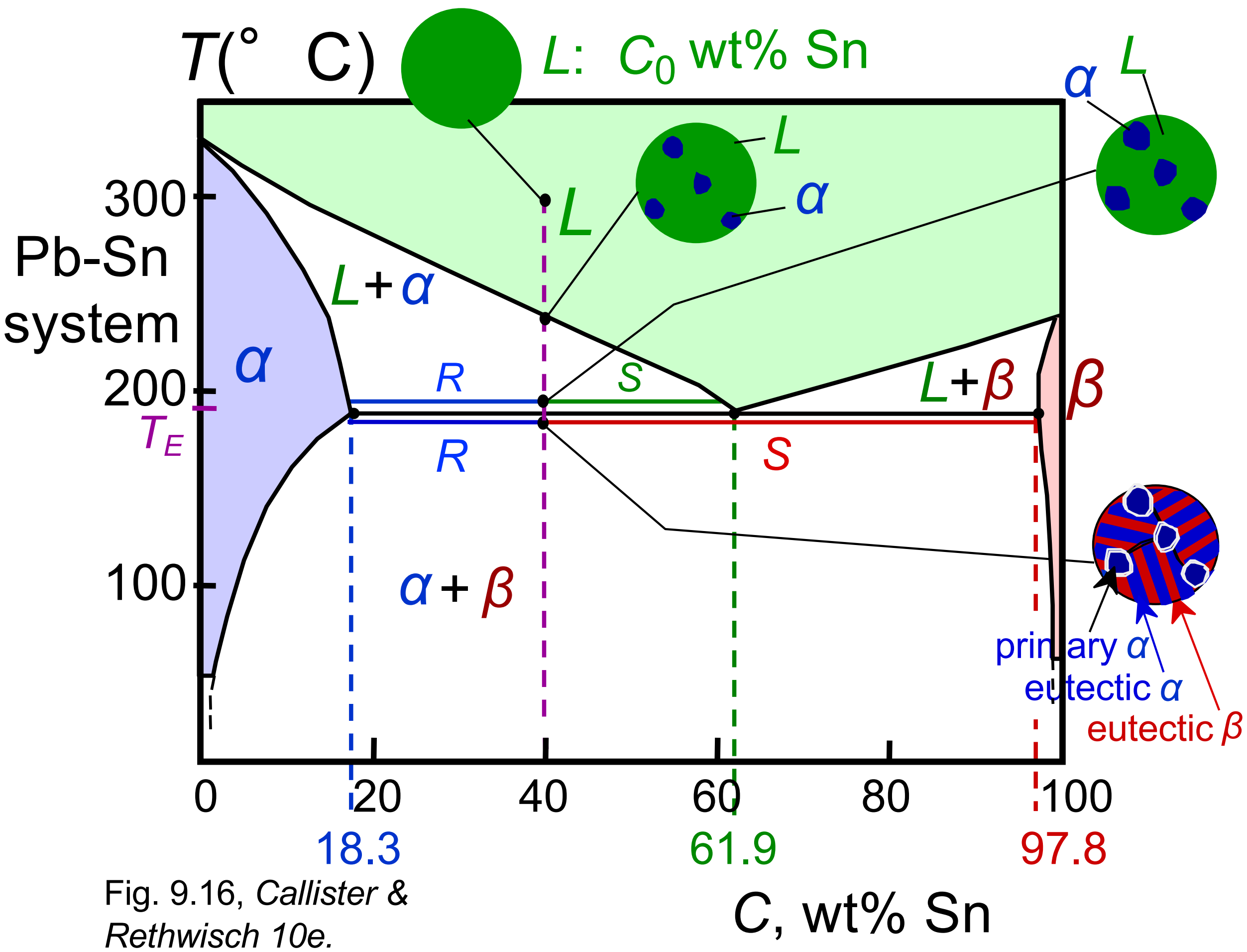


Fig. 9.16, *Callister & Rethwisch 10e.*

- Just above T_E:

  C_α = 18.3 wt% Sn

  C_L = 61.9 wt% Sn

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

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

- Just below T_E:

  C_α = 18.3 wt% Sn

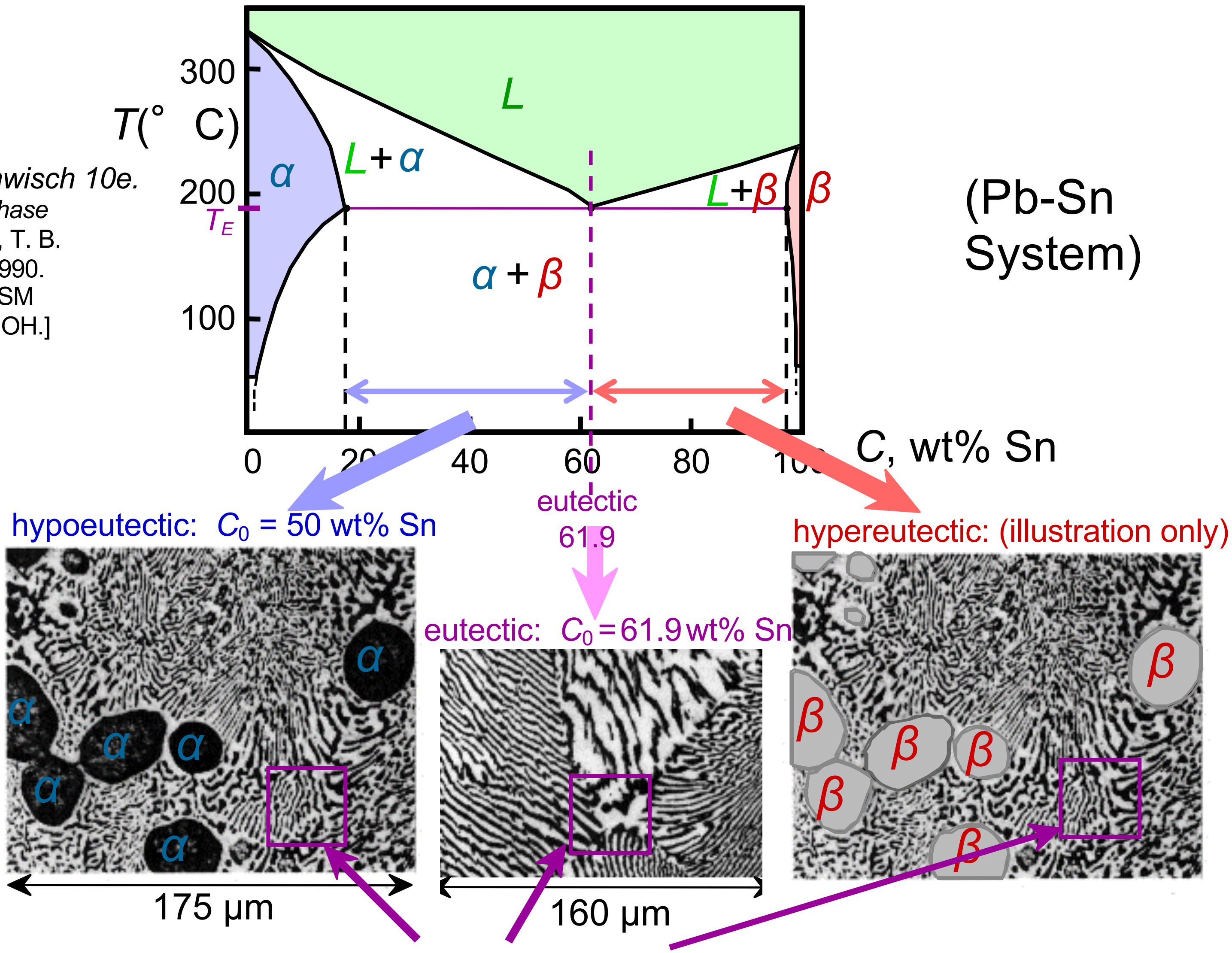
  C_β = 97.8 wt% Sn

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

  W_β = 0.27

Hypoeutectic & Hypereutectic

Fig. 9.8, *Callister & Rethwisch 10e.* [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



(Figs. 9.14 and 9.17 from *Metals Handbook*, 9th ed., Vol. 9, *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

eutectic micro-constituent

Fig. 9.17, *Callister & Rethwisch 10e.*

Fig. 9.14, *Callister & Rethwisch 10e.*

Adapted from Fig. 9.17, *Callister & Rethwisch 10e.* (Illustration only)

Intermetallic Compounds

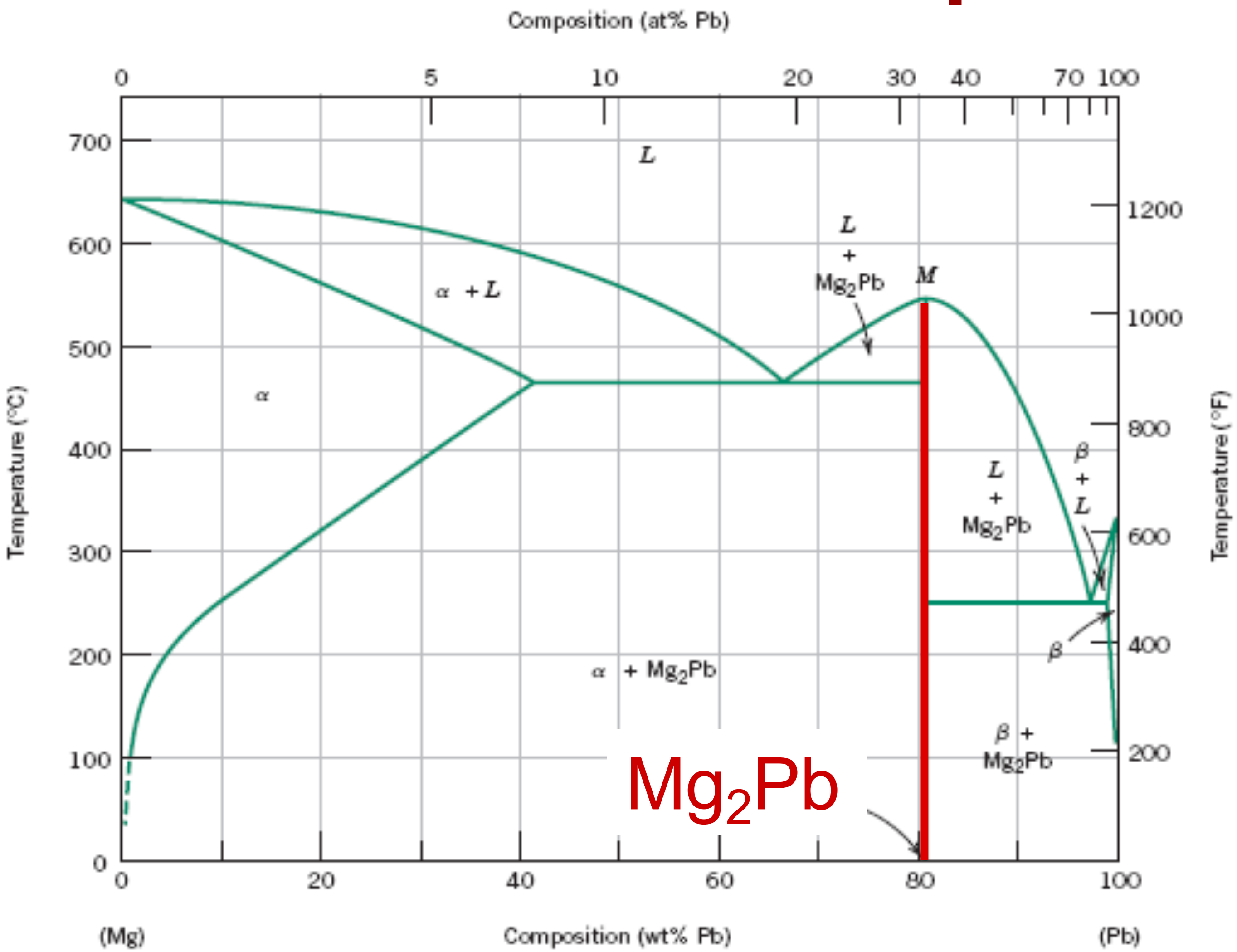


Fig. 9.20, *Callister & Rethwisch 10e.*
[Adapted from *Phase Diagrams of Binary Magnesium Alloys*, A. A. Nayeb-Hashemi and J. B. Clark (Editors), 1988. Reprinted by permission of ASM International, Materials Park, OH.]

Note: intermetallic compound exists as a line on the diagram - not an area - because of stoichiometry (i.e. composition of a compound is a fixed value).

Eutectic, Eutectoid, & Peritectic

- Eutectic - liquid transforms to two solid phases

  $L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$ (For Pb-Sn, 183° C, 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, 727° C, 0.76 wt% C)

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

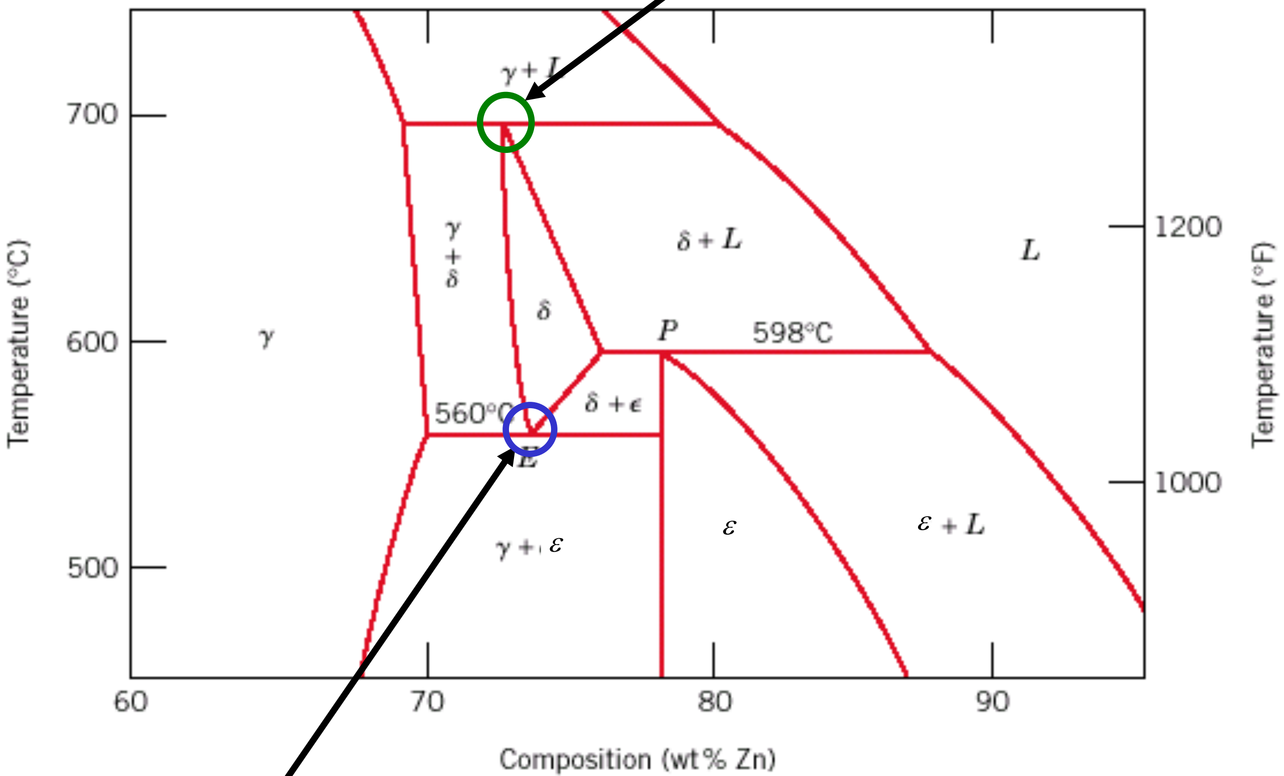
  $S_1 + L \rightleftharpoons S_2$

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

Eutectoid & Peritectic

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

Cu-Zn Phase diagram



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

Fig. 9.21, *Callister & Rethwisch 10e.* [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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Iron-Carbon (Fe-C) Phase Diagram

鐵－碳系統（The Iron-Carbon System）

- 所有二元合金中最重要的大概就是鐵－碳系統了，鋼和鑄鐵是每個技術先進的文明中首要的構造用材料，它們基本上是鐵－碳合金。本節在於學習這個系統的相圖以及幾種可能的顯微組織演變。熱處理、顯微組織和機械性質的關係將在十一章探究。

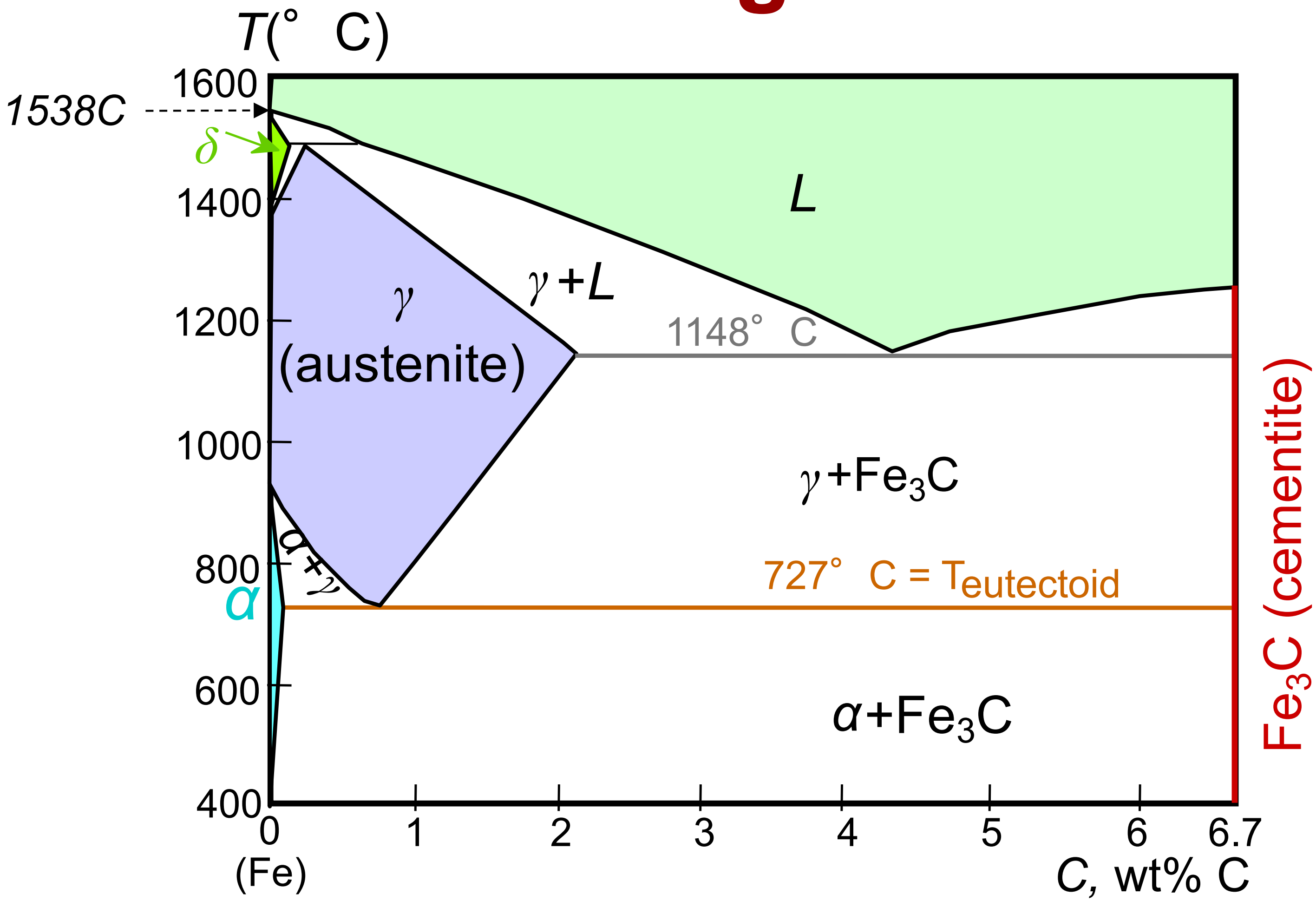
純鐵: C＜0.008wt%

鋼鐵:C＜0.008%＜C＜2.14%

鑄鐵:2.14%＜C＜6.7%

Iron-iron Carbide (Fe-Fe_3C) Phase Diagram

Iron-iron Carbide (Fe-Fe_3C) Phase Diagram



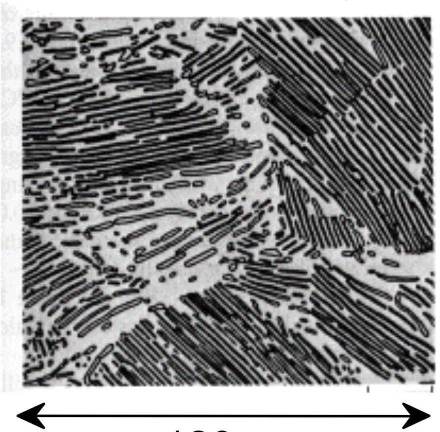
Pure iron : α(BCC), ferrite, ➔γ(FCC), austenite, ➔δ(BCC), δ-ferrite

Iron-iron Carbide (Fe-Fe_3C) Phase Diagram

- Carbon is an interstitial impurity in iron and form solid solution with α, γ and δ single phase.
- α Ferrite (肥粒鐵): BCC, low solubility of C. Because interstitial site in BCC is small. Relatively soft, can be made magnetic.
- γ Austenite (沃斯田鐵)：FCC, max solubility is 2.4%. Non-magnetic,
- δ Ferrite: BCC, similar to α Ferrite, but only stable at high temperature.
- Cementite Fe_3C(雪明碳鐵)：hard and brittle, enhance the steel strength.

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

Fig. 9.27, *Callister & Rethwisch 10e.*
(From *Metals Handbook*, Vol. 9, 9th ed., *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

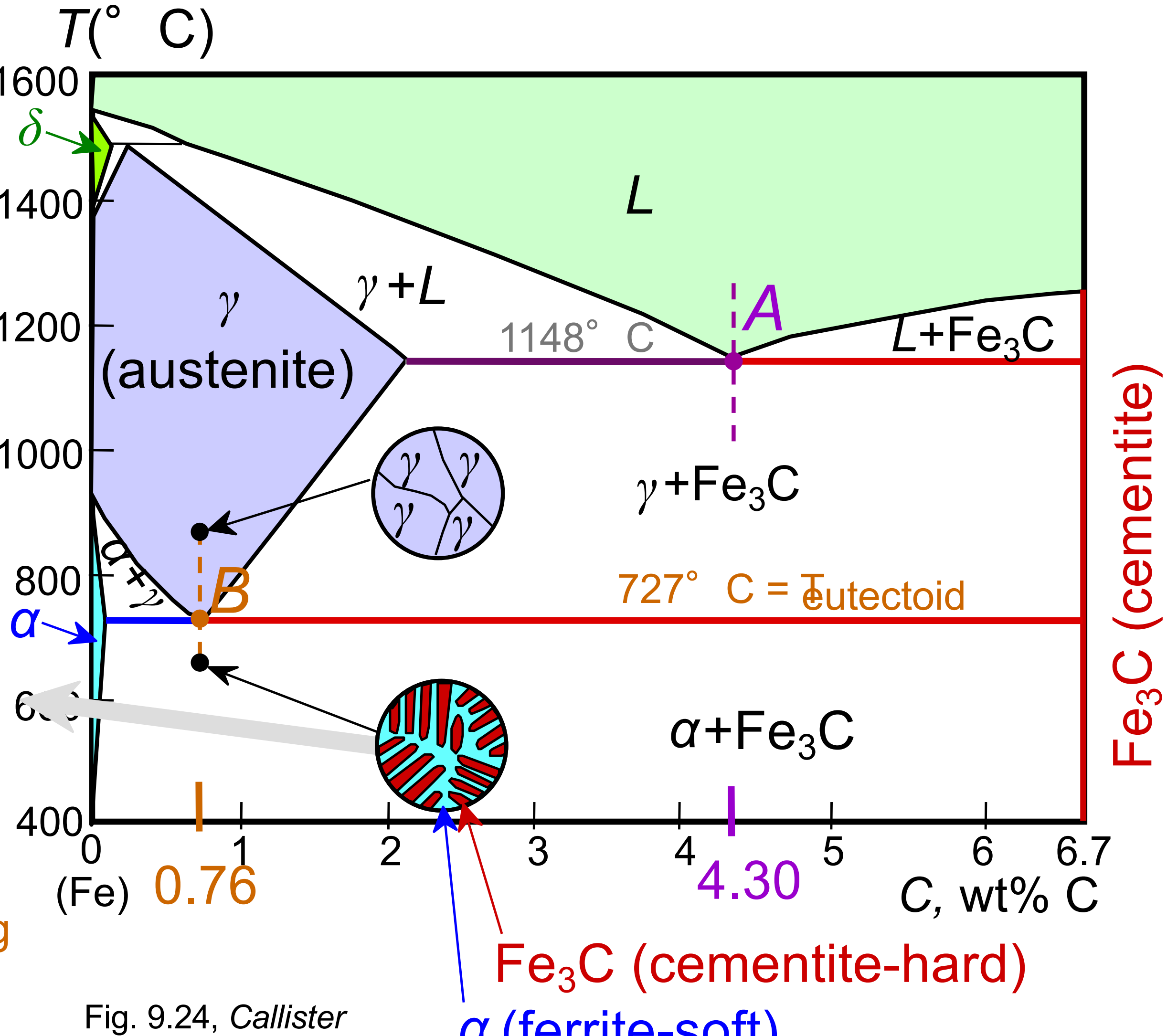
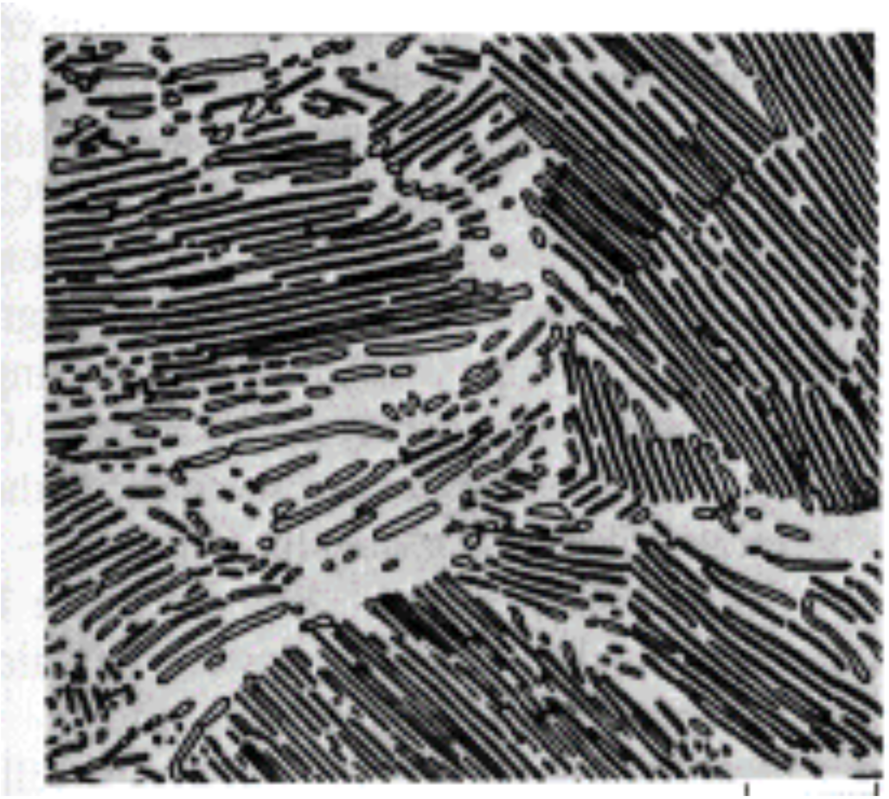
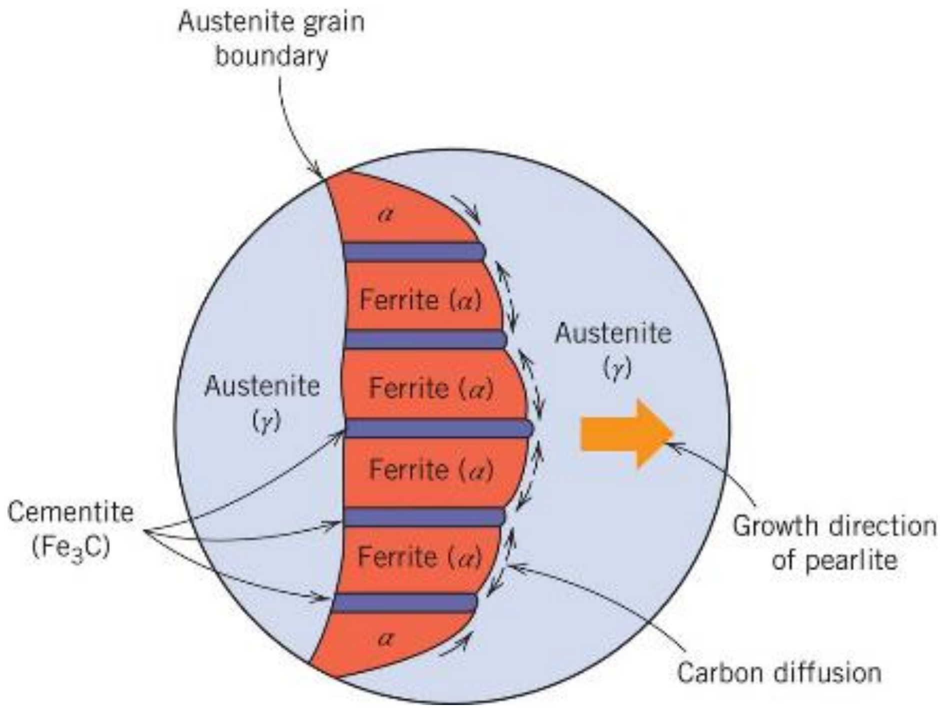


Fig. 9.24, *Callister & Rethwisch 10e.*
[Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Pearlite





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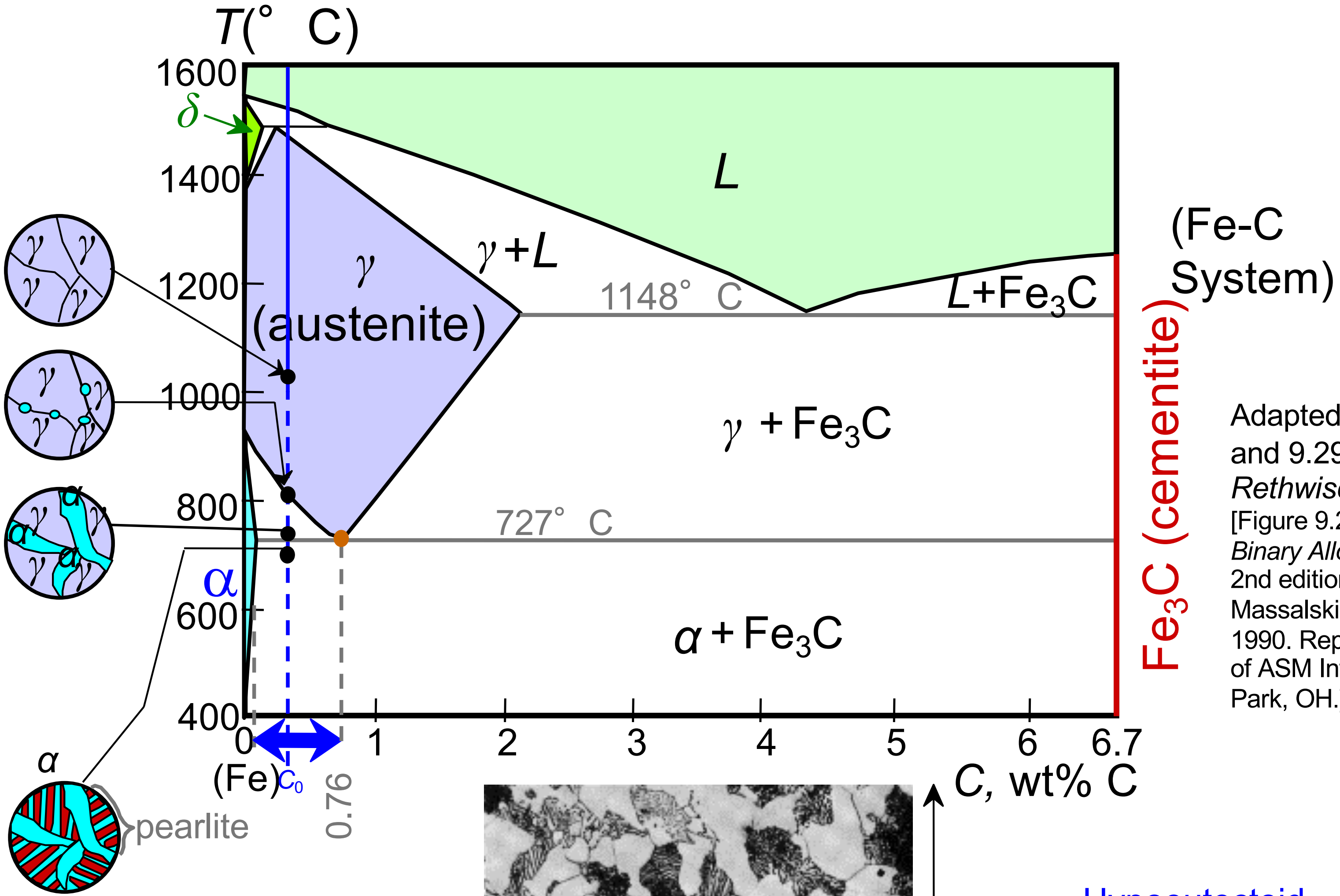
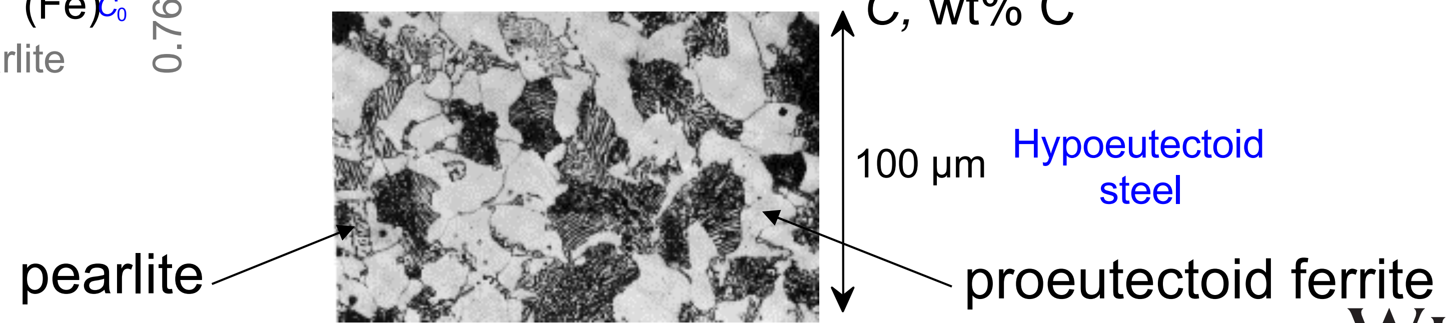
Hypoeutectoid Steel

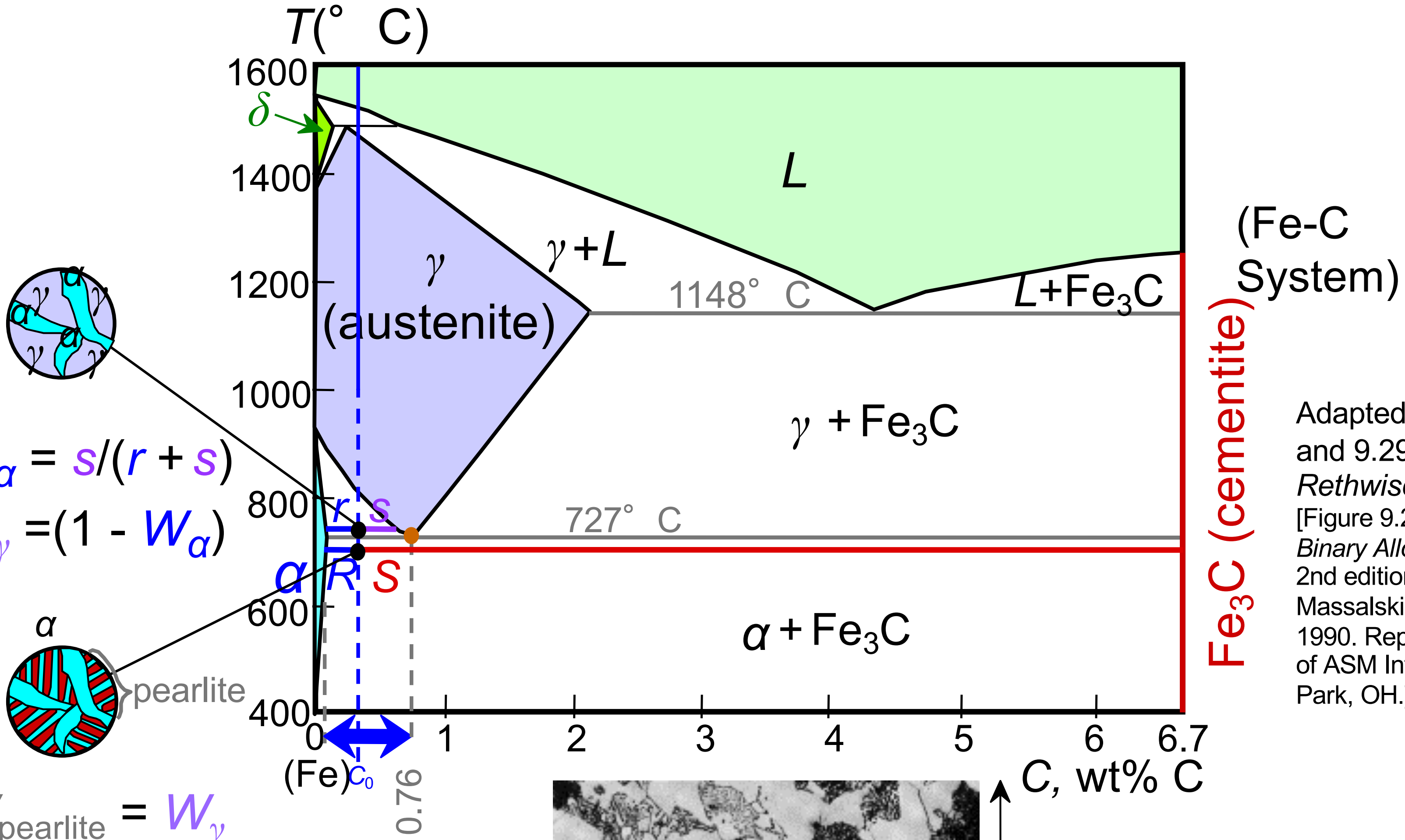


Adapted from Figs. 9.24 and 9.29, *Callister & Rethwisch 10e.*
[Figure 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



Adapted from Fig. 9.30, *Callister & Rethwisch 10e.*
(Photomicrograph courtesy of Republic Steel Corporation.)

Hypoeutectoid Steel



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

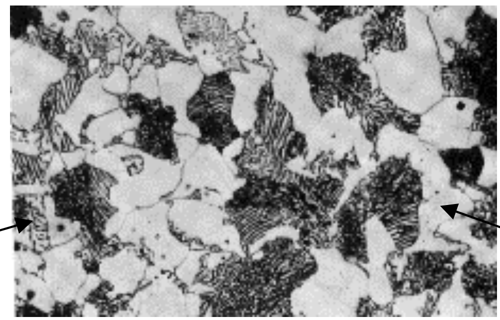
$W_\gamma = (1 - W_\alpha)$

$W_{pearlite} = W_\gamma$

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

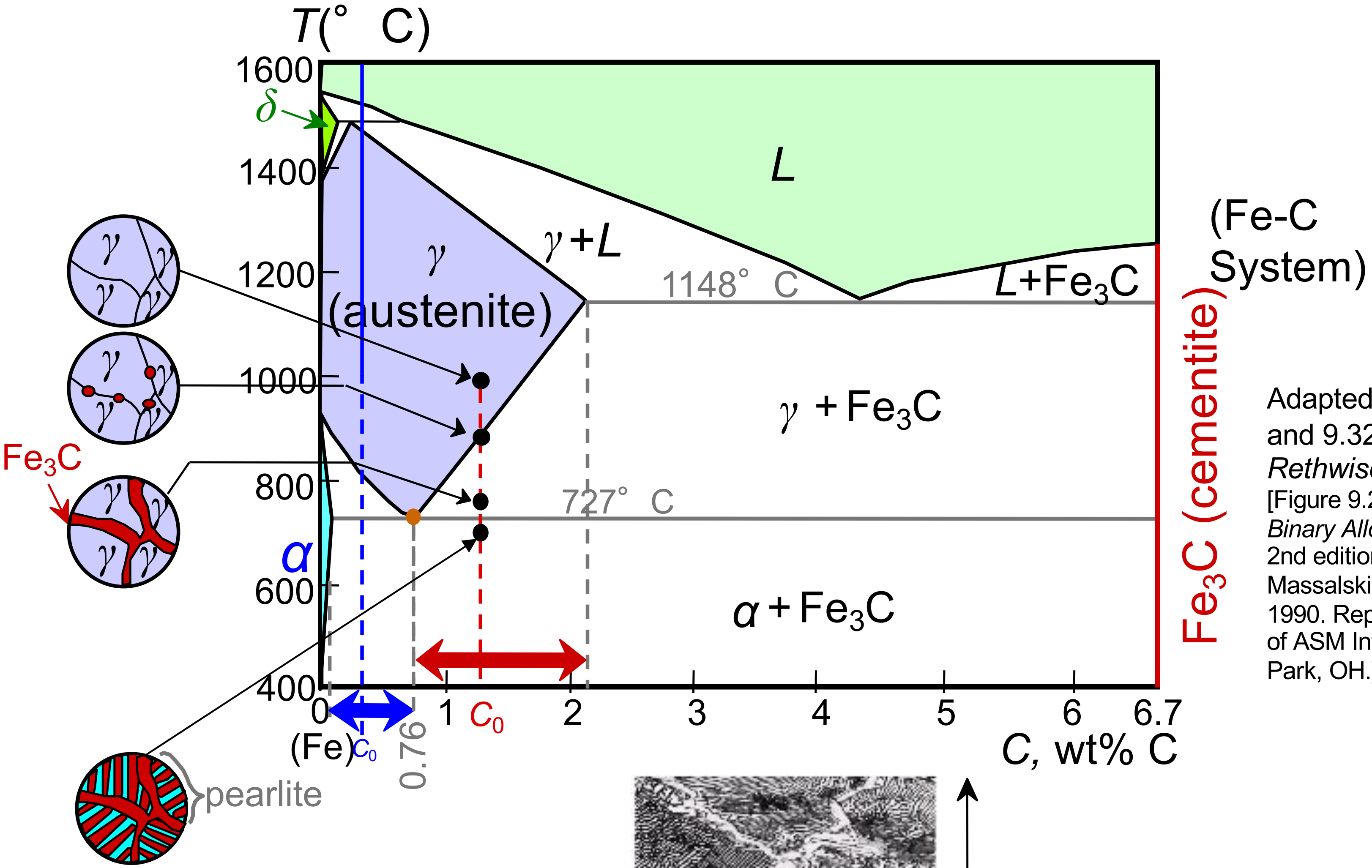
$W_{Fe_3C} = (1 - W_{\alpha'})$

Adapted from Figs. 9.24 and 9.29, *Callister & Rethwisch 10e.* [Figure 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

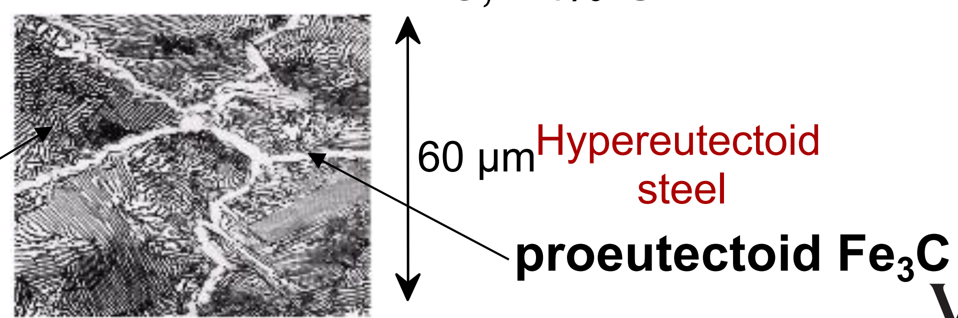


Adapted from Fig. 9.30, *Callister & Rethwisch 10e.*
(Photomicrograph courtesy of Republic Steel Corporation.)

Hypereutectoid Steel

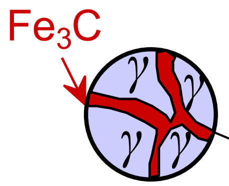


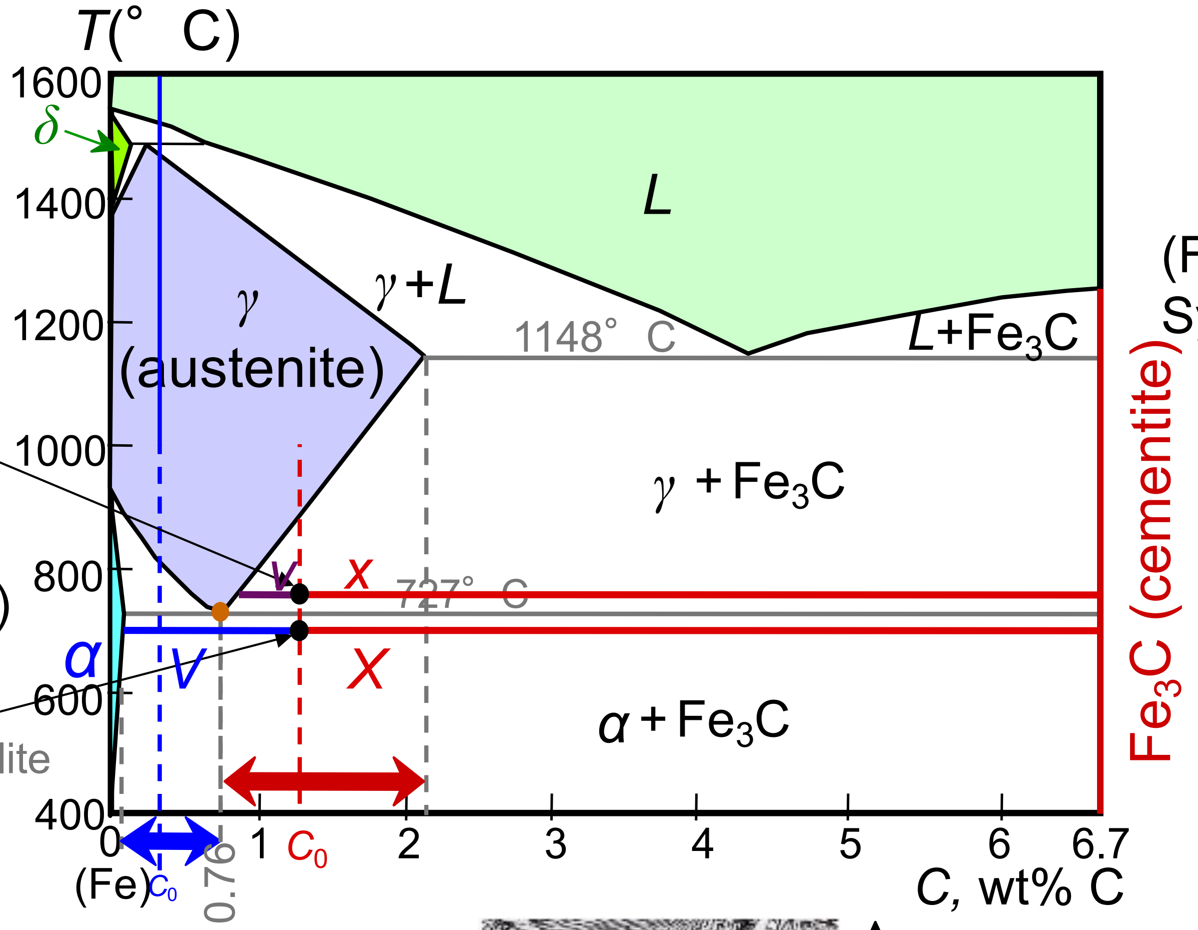
Adapted from Figs. 9.24 and 9.32, *Callister & Rethwisch 10e.*
[Figure 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

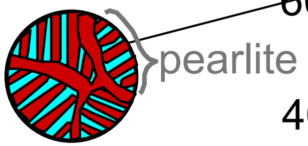


Adapted from Fig. 9.33, *Callister & Rethwisch 10e.*
(Copyright 1971 by United States Steel Corporation.)

Hypereutectoid Steel







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

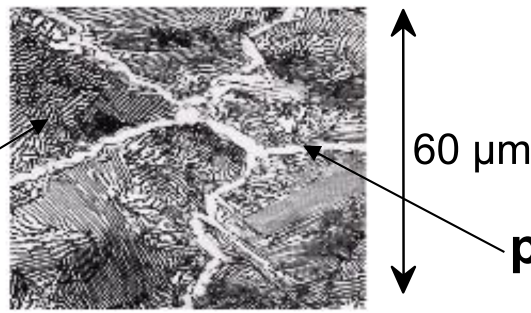
$W_{Fe_3C} = (1 - W_{\gamma})$

$W_{pearlite} = W_{\gamma}$

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

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

Adapted from Figs. 9.24 and 9.32, *Callister & Rethwisch 10e.* [Figure 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



Hypereutectoid steel

pearlite

proeutectoid Fe_3C

Adapted from Fig. 9.33, *Callister & Rethwisch 10e.* (Copyright 1971 by United States Steel Corporation.)

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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

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

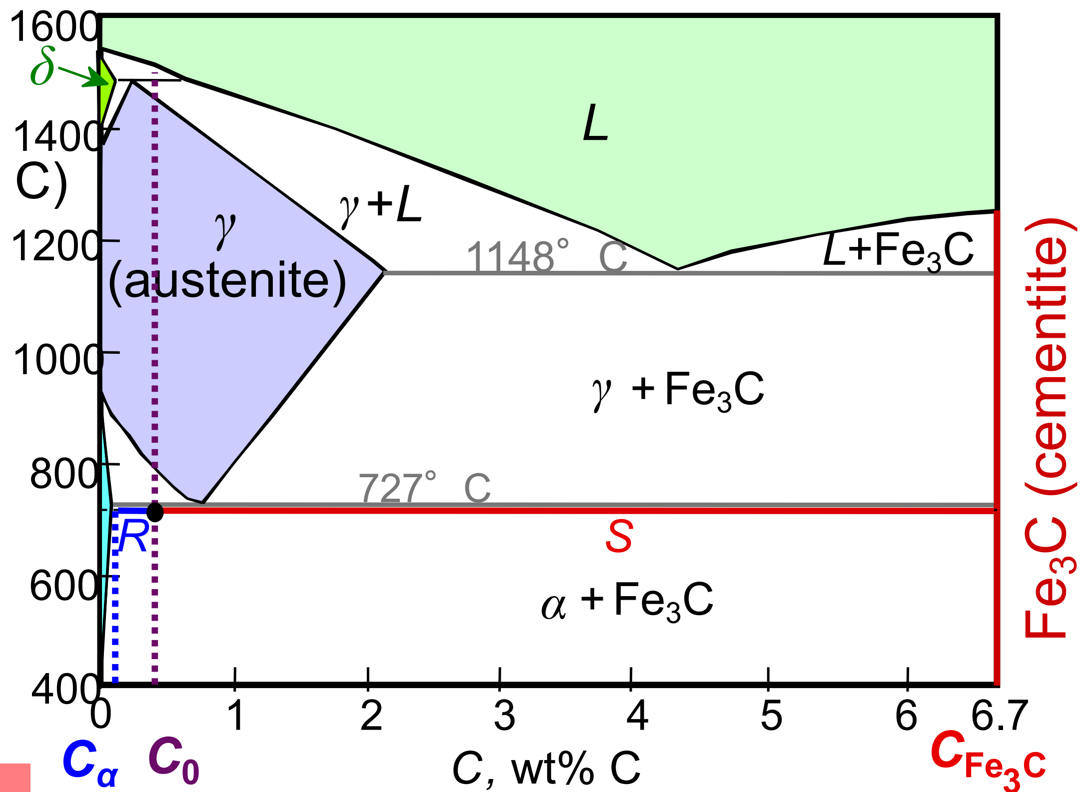
$$= \frac{0.40 - 0.022}{6.70 - 0.022} = 0.057$$

Amount of Fe_3C in 100 g

= (100 g)W_{Fe_3C}

= (100 g)(0.057) = 5.7 g

Fig. 9.24, *Callister & Rethwisch 10e.* [From *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

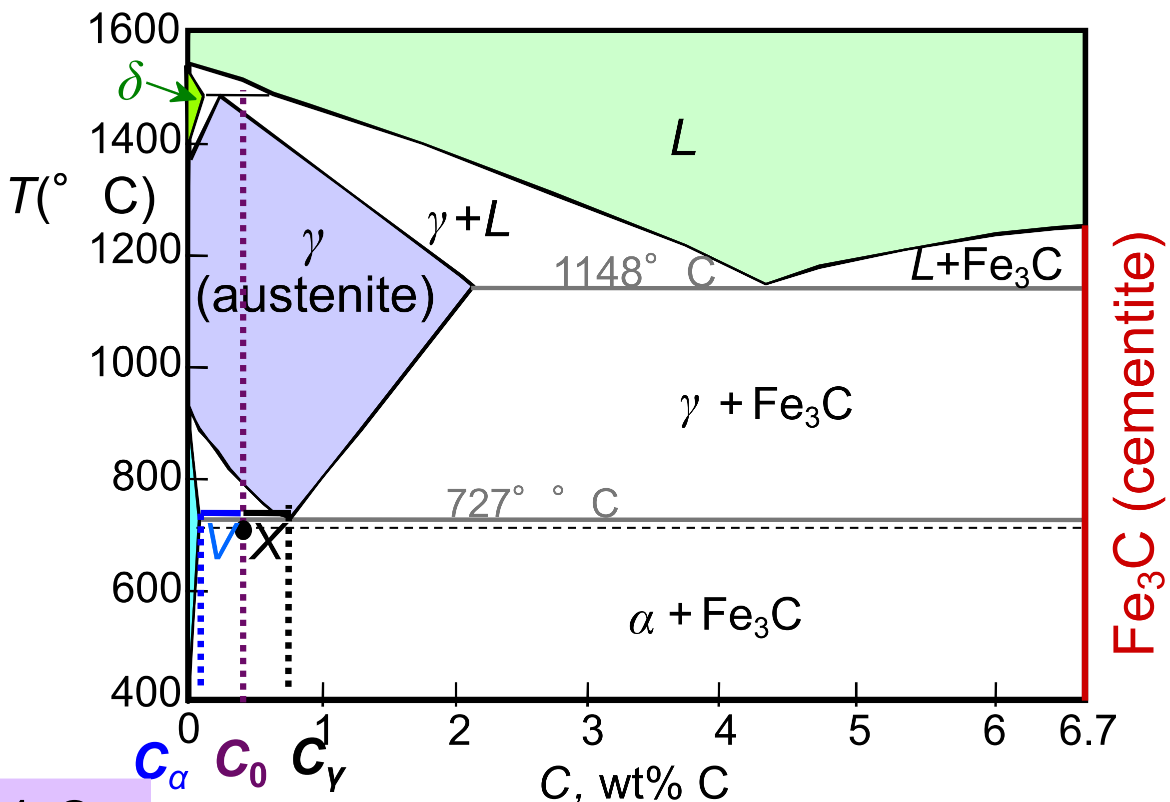


Solution to Example Problem (cont.)

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

Fig. 9.24, *Callister & Rethwisch 10e.*
[From *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



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

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

Amount of pearlite in 100 g

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

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

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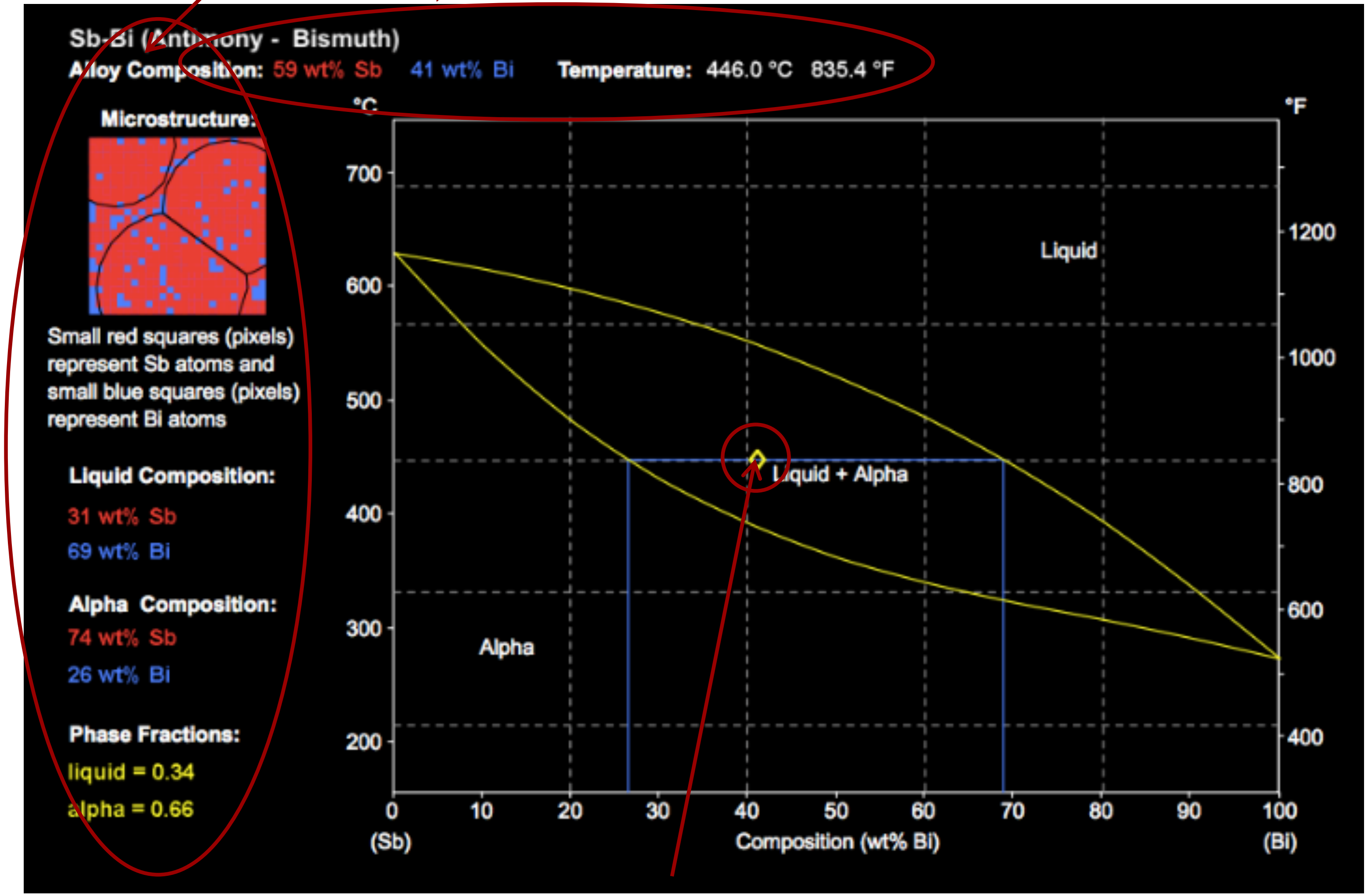
VMSE: Interactive Phase Diagrams

Microstructure, phase compositions, and phase fractions respond interactively



Change alloy composition

EXAMPLE PROBLEM 9.4

Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:

(a) The fractions of total ferrite and cementite phases

(b) The fractions of the proeutectoid ferrite and pearlite

(c) The fraction of eutectoid ferrite

Solution

Alloying with Other Elements

- $T_{eutectoid}$ changes:

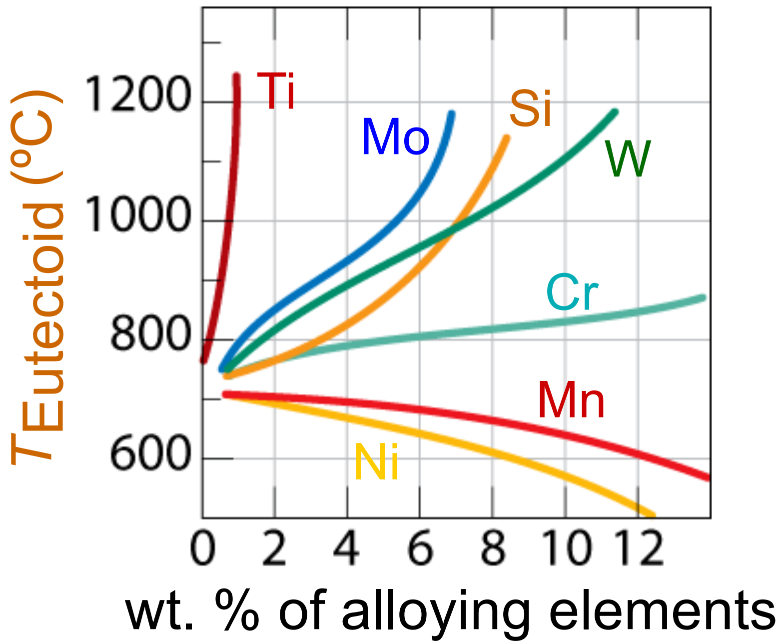


Fig. 9.34, *Callister & Rethwisch 10e*.
(From Edgar C. Bain, *Functions of the Alloying Elements in Steel,* 1939. Reproduced by permission of ASM International, Materials Park, OH.)

- $C_{eutectoid}$ changes:

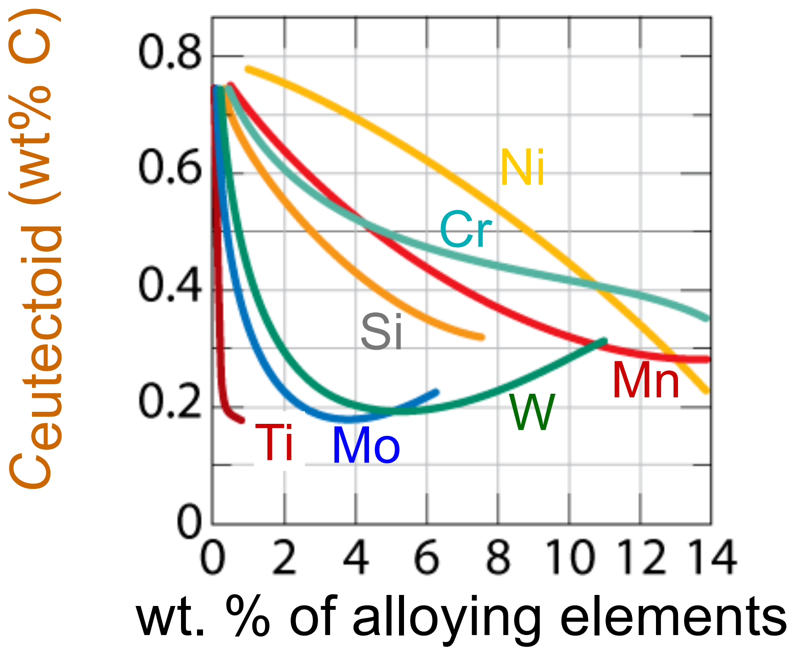


Fig. 9.35,*Callister & Rethwisch 10e*.
(From Edgar C. Bain, *Functions of the Alloying Elements in Steel,* 1939. Reproduced by permission of ASM International, Materials Park, OH.)

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.