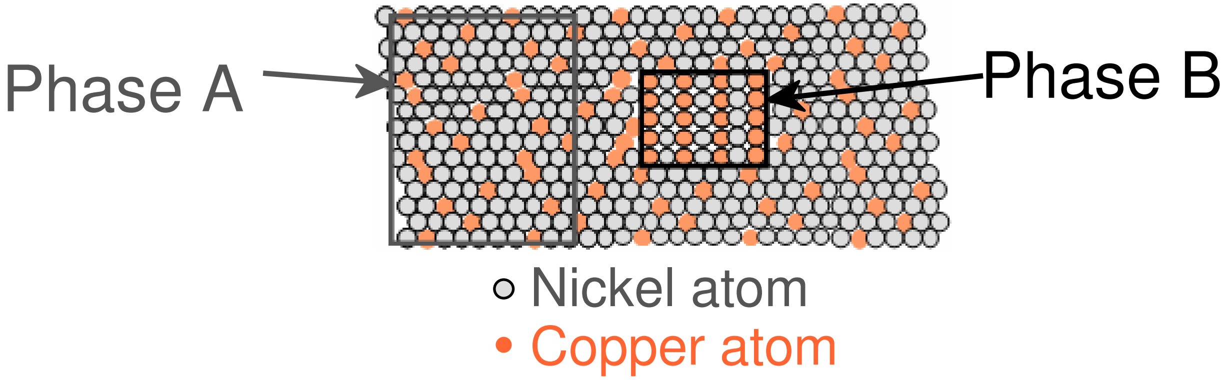
Chapter 9: Phase Diagrams

ISSUES TO ADDRESS...

- When we combine two elements...
  what equilibrium state do we get?
- In particular, if we specify...
  --a composition (e.g., wt% Cu - wt% Ni), and
  --a temperature (*T*)
  then...
  How many phases do we get?
  What is the composition of each phase?
  How much of each phase do we get?



Phase Equilibria: Solubility Limit

Introduction

- Solutions – solid solutions, single phase
- Mixtures – more than one phase

Adapted from Fig. 9.1, *Callister 7e.*

- Solubility Limit:
  Max concentration for which only a single phase solution occurs.

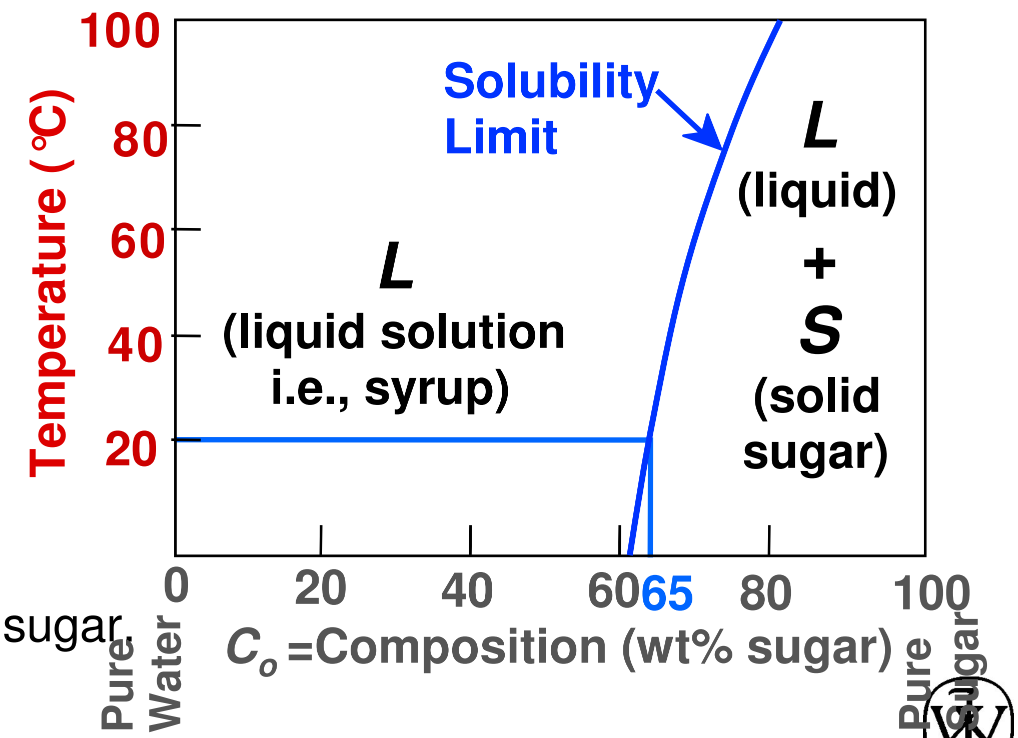
Question: What is the solubility limit at 20°C?

Answer: 65 wt% sugar.

If C_o < 65 wt% sugar: syrup

If C_o > 65 wt% sugar: syrup + sugar.

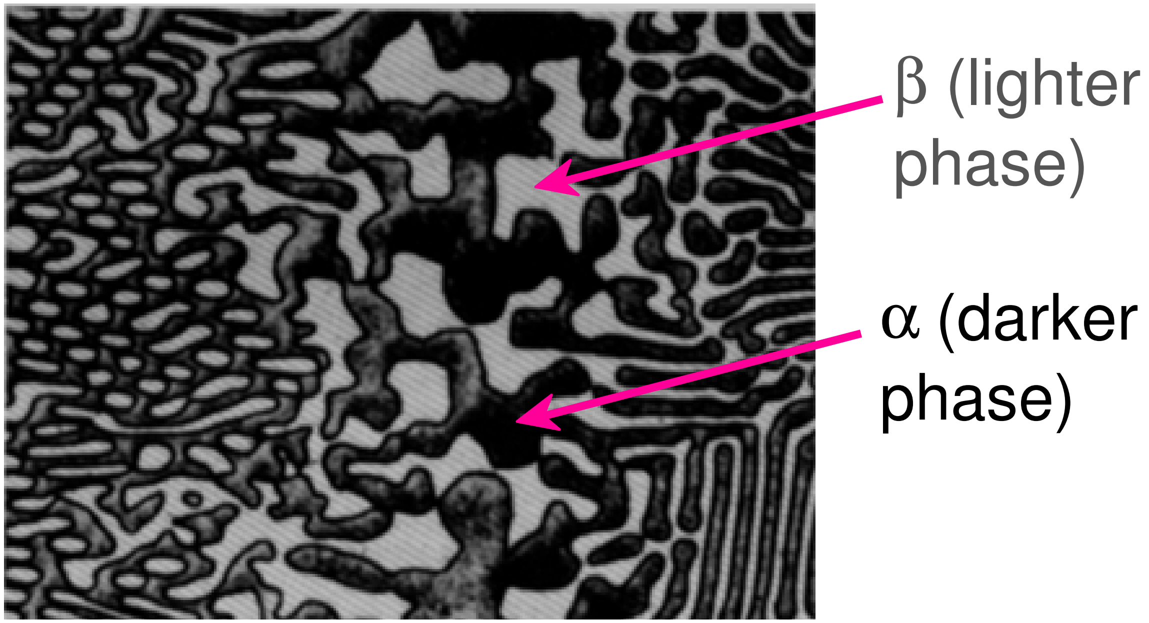
Sucrose/Water Phase Diagram



Components and Phases

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

Aluminum-Copper Alloy



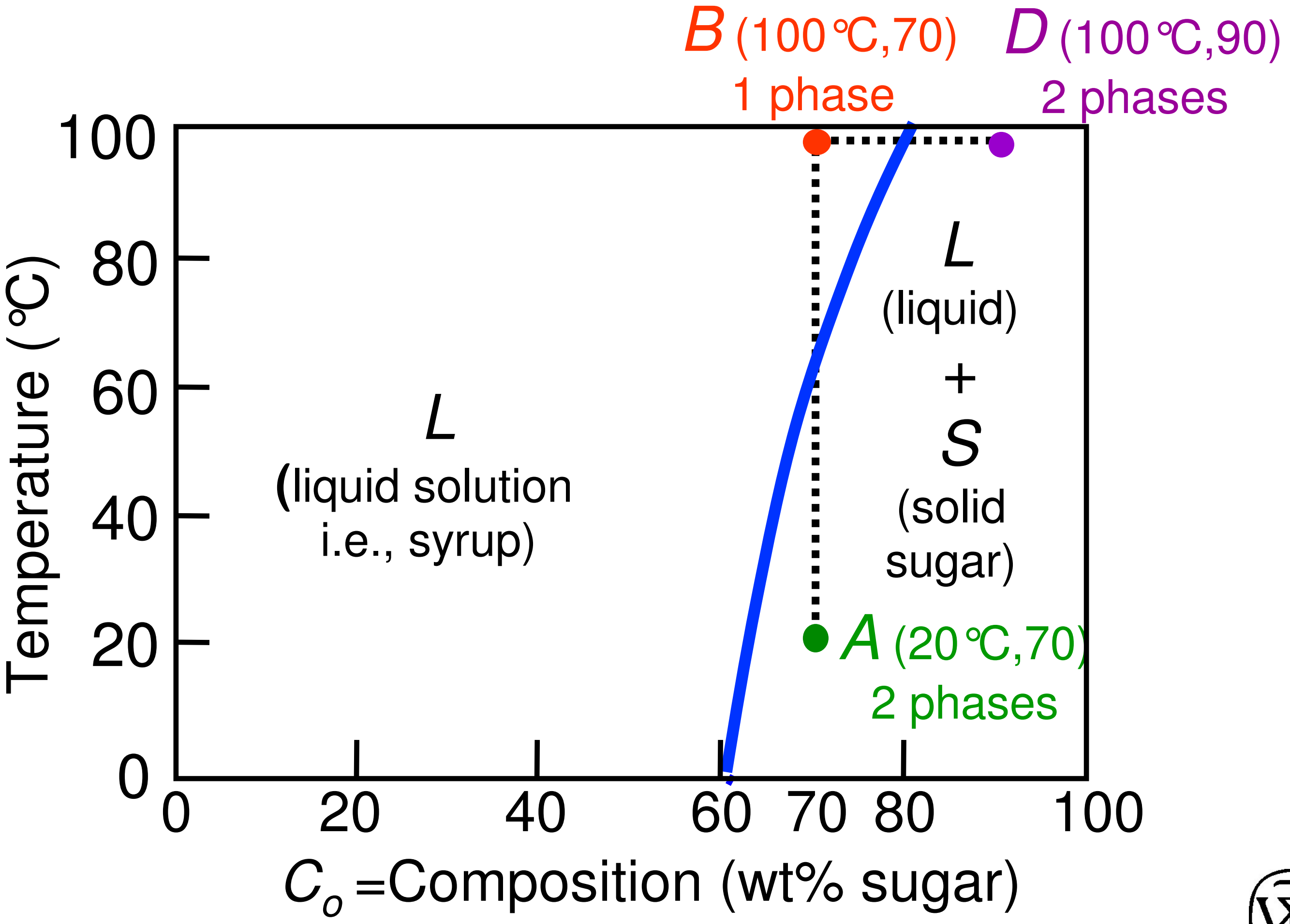
Adapted from chapter-opening photograph, Chapter 9, *Callister 3e.*

A phase maybe defined as a homogeneous portion of a system that has uniform physical and chemical characteristics.

Effect of *T* & Composition (C_o)

- Changing *T* can change # of phases: path *A* to *B*.
- Changing C_o can change # of phases: path *B* to *D*.

water-
sugar
system



Adapted from
Fig. 9.1,
Callister 7e.

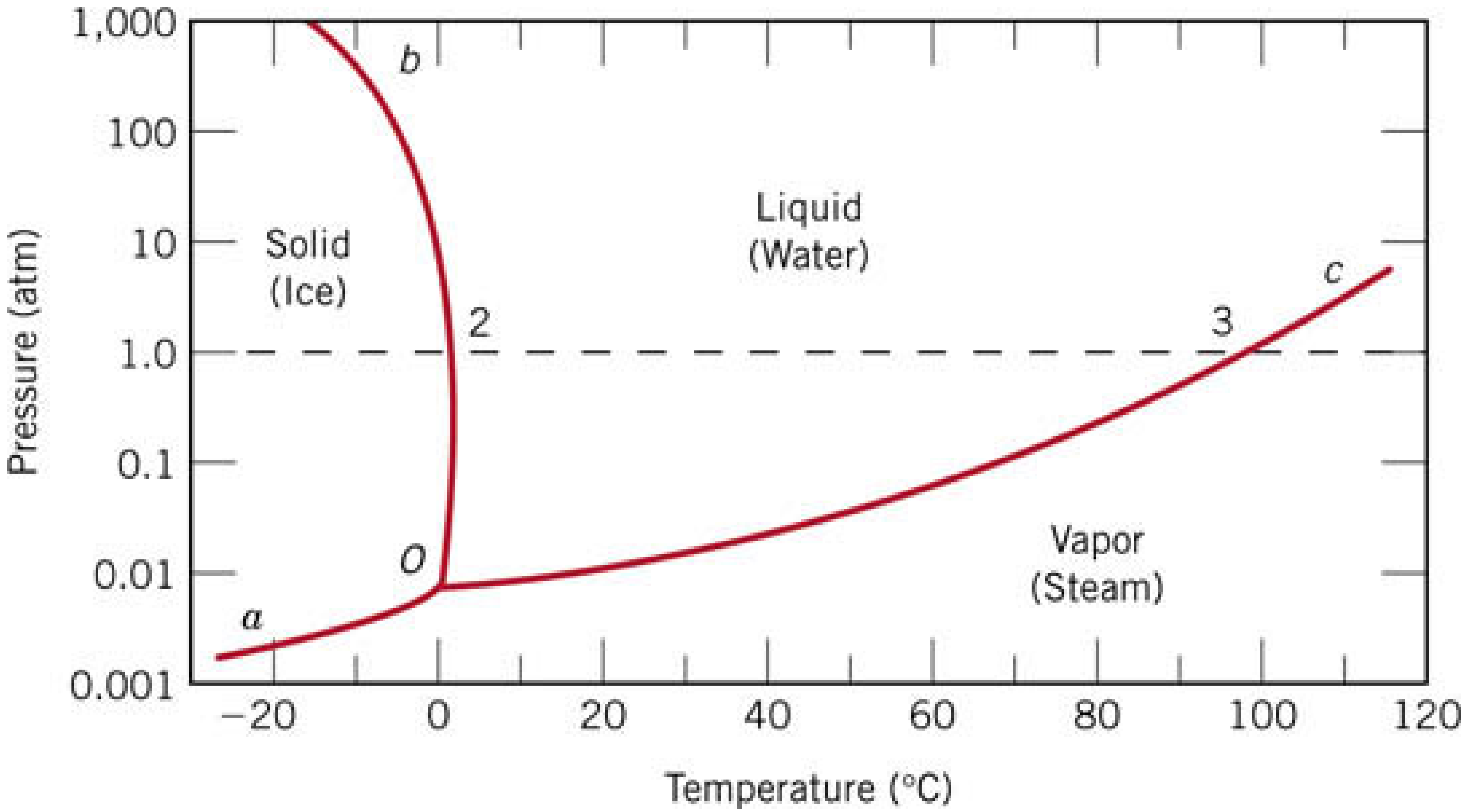
Phase Equilibrium

Equilibrium: minimum energy state for a given T, P, and composition (i.e. equilibrium state will persist indefinitely for a fixed T, P and composition).

Phase Equilibrium: If there is more than 1 phase present, phase characteristics will stay constant over time.

Phase diagrams tell us about equilibrium phases as a function of T, P and composition (here, we'll always keep P constant for simplicity).

Unary Systems



Triple point

Phase Equilibria

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

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

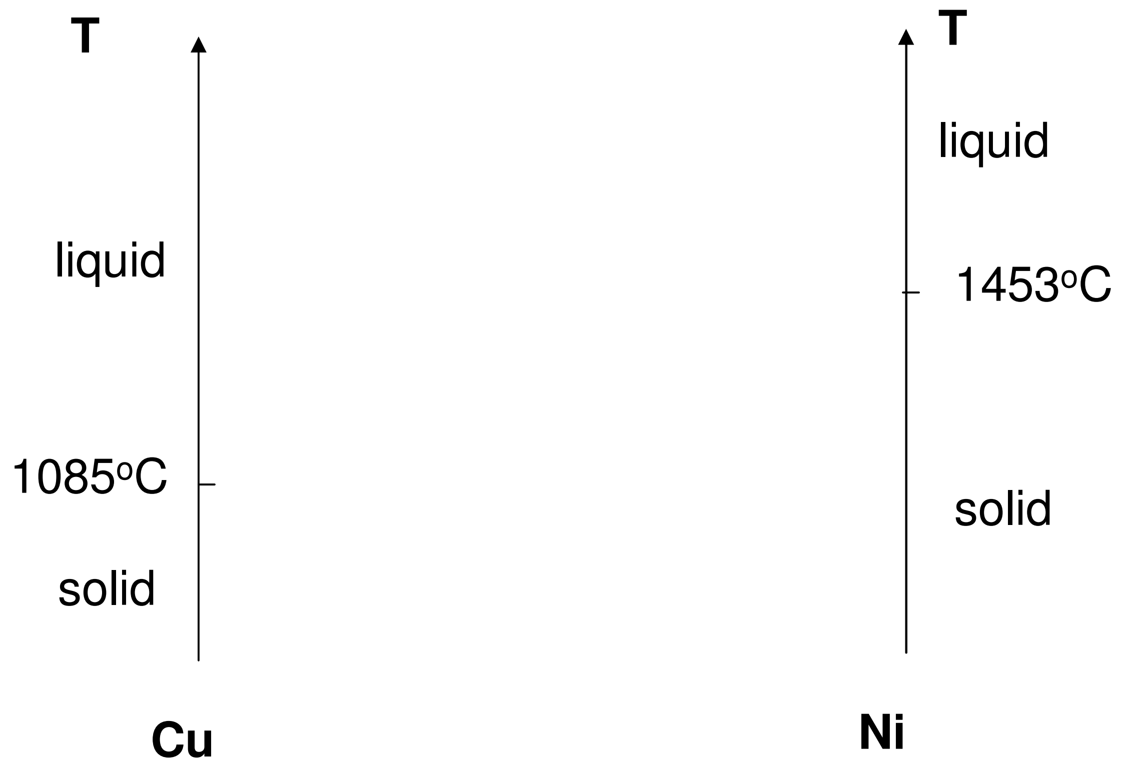
- Both have the same crystal structure (FCC) and have similar electronegativities and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.
- Ni and Cu are totally miscible in all proportions.

Unary Systems

Single component system

Consider 2 metals:

Cu has melting T = 1085°C
Ni has melting T = 1453°C (at standard P = 1 atm)



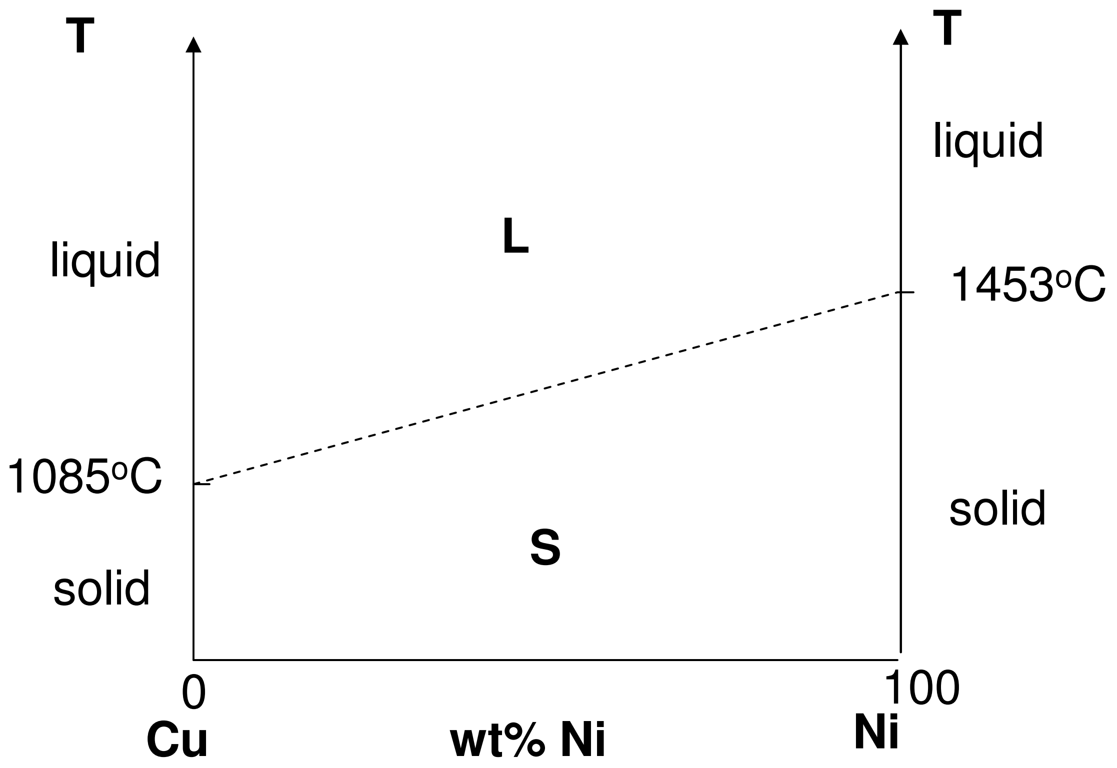
What happens when Cu and Ni are mixed?

Binary Isomorphous Systems

2 components

Complete liquid and solid solubility

Expect T_m of solution to lie in between T_m of two pure components



For a pure component, complete melting occurs before T increases (sharp phase transition). But for multicomponent systems, there is usually a coexistence of L and S.

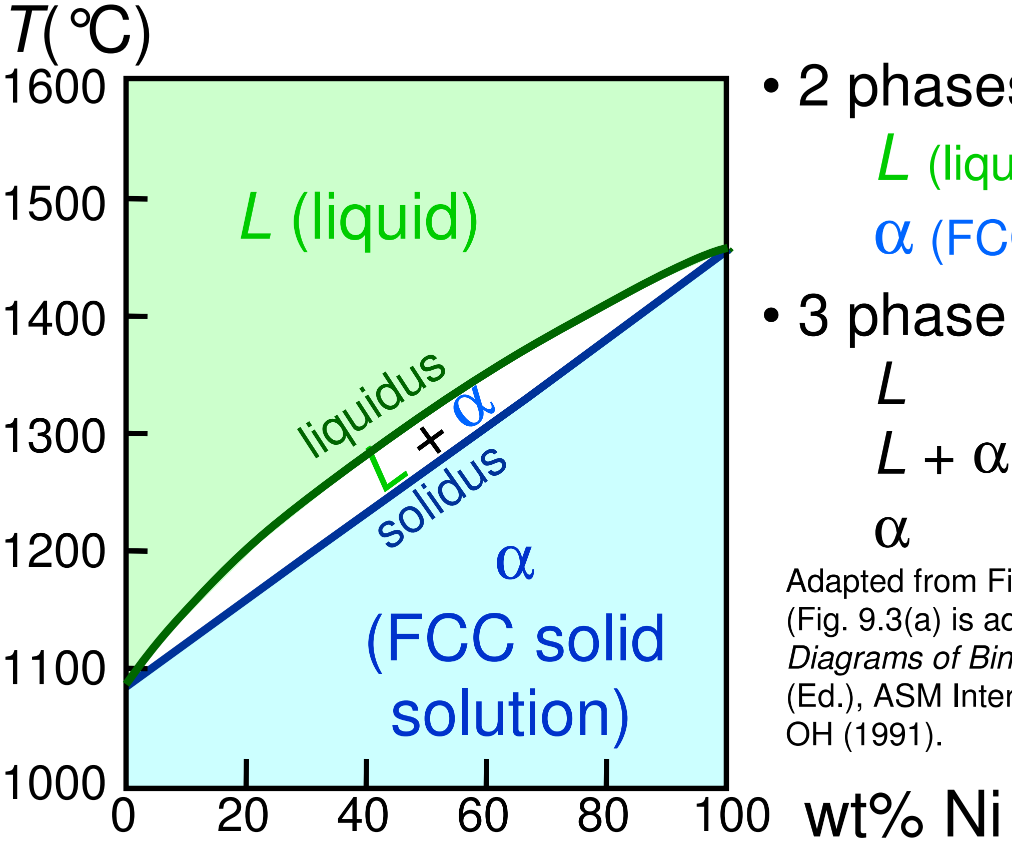
Phase Diagrams

- Indicate phases as function of T, C_o, and P.
- For this course:

  -binary systems: just 2 components.

  -independent variables: T and C_o (P = 1 atm is almost always used).

- Phase Diagram for Cu-Ni system



- 2 phases:
  - L (liquid)
  - α (FCC solid solution)
- 3 phase fields:
  - L
  - $L + \alpha$
  - α

Adapted from Fig. 9.3(a), *Callister 7e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

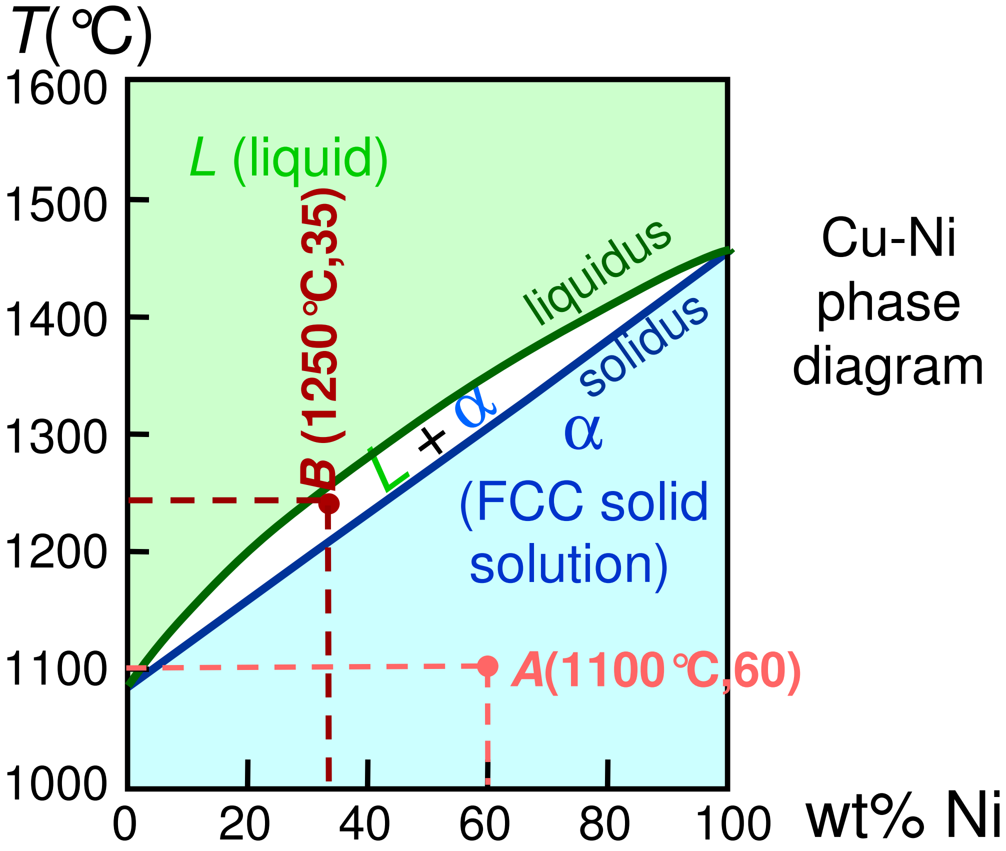
Phase Diagrams:
and types of phases

- Rule 1: If we know *T* and C_o, then we know:
  --the # and types of phases present.

- Examples:

  A(1100°C, 60):
  1 phase: α

  B(1250°C, 35):
  2 phases: *L* + α



Cu-Ni phase diagram

Adapted from Fig. 9.3(a), *Callister 7e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH, 1991).

Phase Diagrams:
composition of phases

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

- Examples:

  C_o = 35 wt% Ni

  At T_A = 1320°C:

  Only Liquid (L)

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

  At T_D = 1190°C:

  Only Solid (α)

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

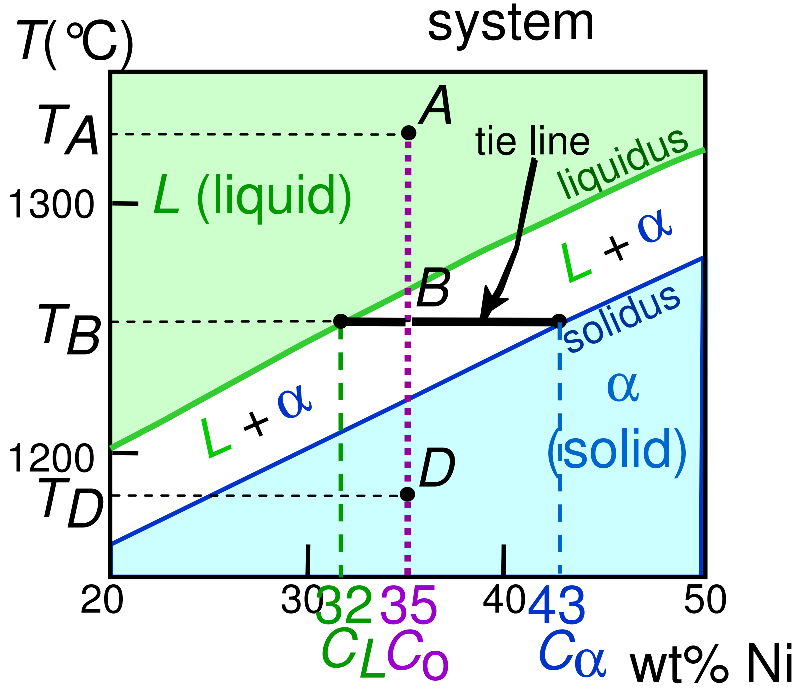
  At T_B = 1250°C:

  Both α and L

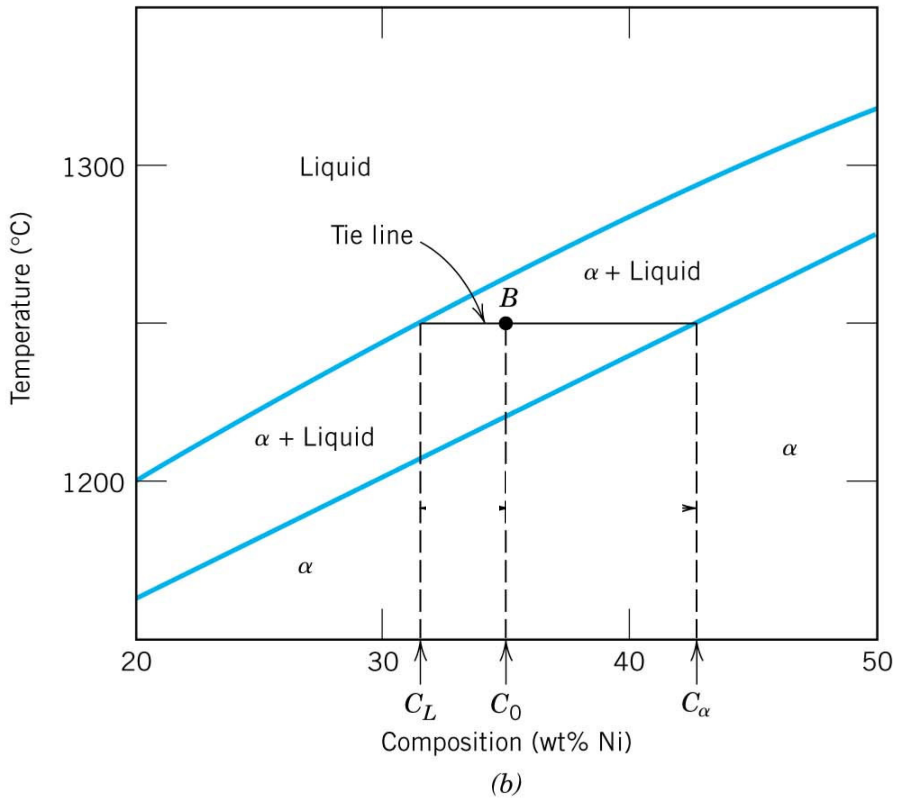
  $C_L = C_{\text{liquidus}}$ (= 32 wt% Ni here)

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

Cu-Ni system



Adapted from Fig. 9.3(b), *Callister 7e.* (Fig. 9.3(b) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH, 1991.)



Determining phase composition in 2-phase region:

1. Draw the tie line.
2. Note where the tie line intersects the liquidus and solidus lines (i.e. where the tie line crosses the phase boundaries).
3. Read off the composition at the boundaries:
    - **Liquid** is composed of $\mathbf{C_L}$ amount of Ni (31.5 wt% Ni).
    - **Solid** is composed of $\mathbf{C_\alpha}$ amount of Ni (42.5 wt% Ni).

Phase Diagrams:

weight fractions of phases

- Rule 3: If we know T and C_o, then we know:
  --the amount of each phase (given in wt%).
- Examples:

C_o = 35 wt% Ni

At T_A: Only Liquid (L)

W_L = 100 wt%, $W_\alpha = 0$

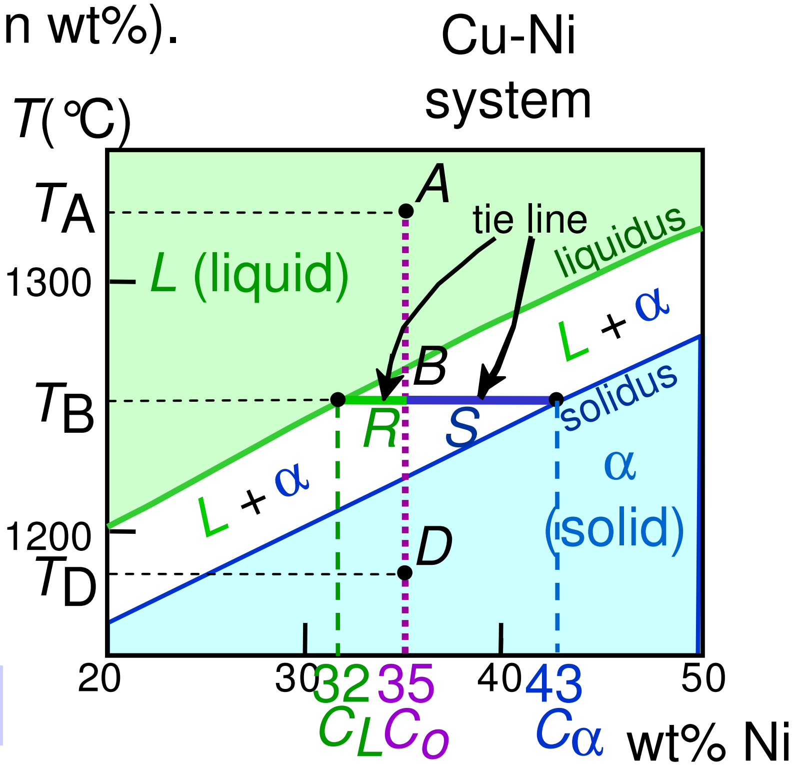
At T_D: Only Solid (α)

$W_L = 0$, W_α = 100 wt%

At T_B: Both α and L

$$\boxed{W_L = \frac{S}{R+S}} = \frac{43-35}{43-32} = 73\ wt\%$$

$$\boxed{W_\alpha = \frac{R}{R+S}} = 27\text{ wt\%}$$



Adapted from Fig. 9.3(b), *Callister 7e.*
(Fig. 9.3(b) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH, 1991.)

Lever Rule: Derivation

Since we have only 2 phases:

$$W_L + W_\alpha = 1 \qquad (1)$$

Conservation of mass requires that:

Amount of Ni in α-phase + amount of Ni in liquid phase = total amount of Ni

or

$$W_\alpha C_\alpha + W_L C_L = C_o \qquad (2)$$

From 1st condition, we have: $W_\alpha = 1 - W_L$

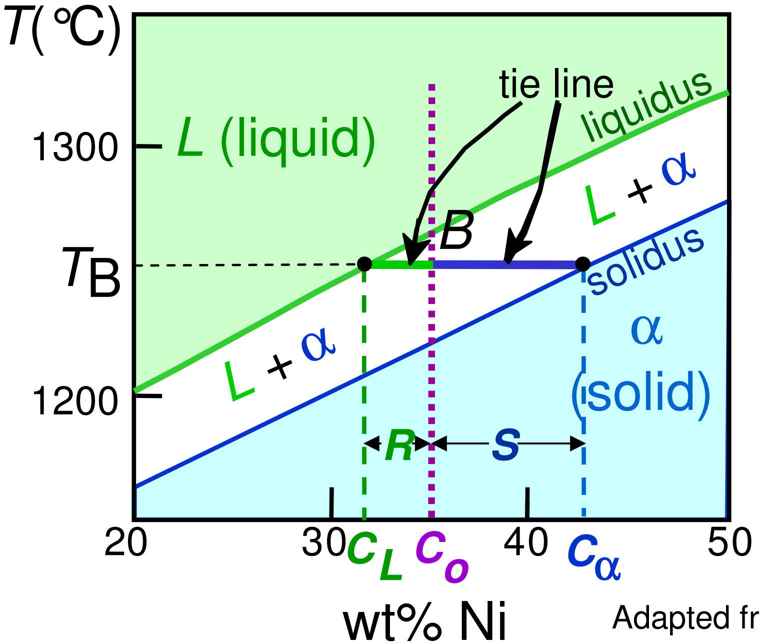
Sub-in to (2): $(1 - W_L)C_\alpha + W_L C_L = C_o$

Solving for W_L and W_α gives :

$$\boxed{W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L}} \qquad \boxed{W_\alpha = \frac{C_o - C_L}{C_\alpha - C_L}}$$

The Lever Rule

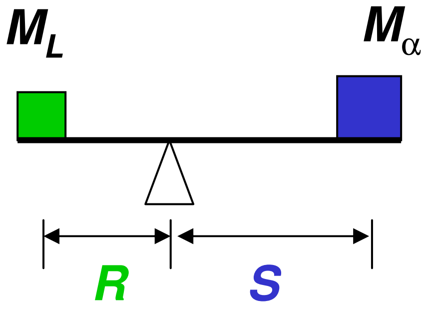
- Tie line – connects the phases in equilibrium with each other - essentially an isotherm



Adapted from Fig. 9.3(b), *Callister 7e.*

How much of each phase?

Think of it as a lever (teeter-totter)



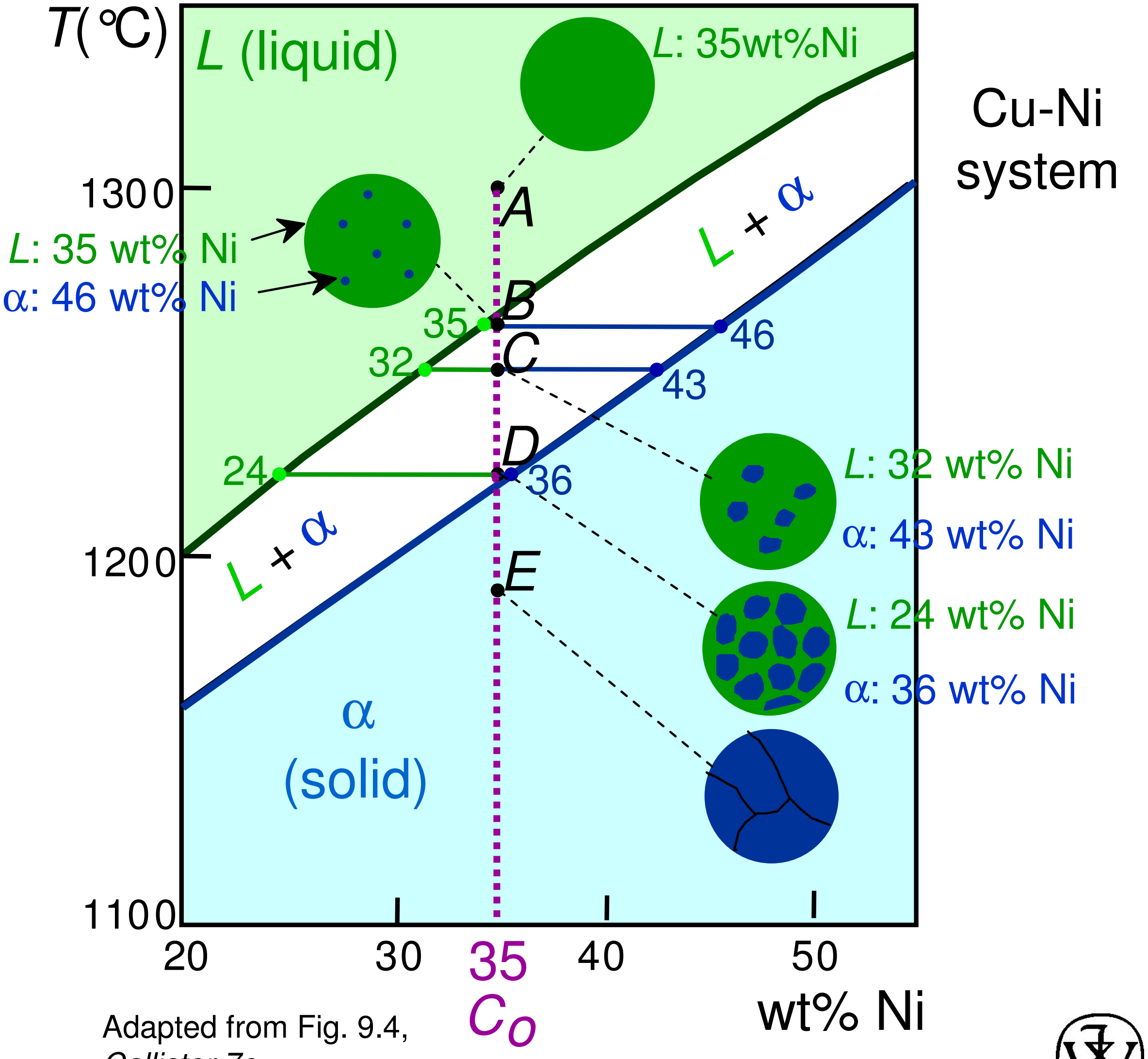
$$M_\alpha \cdot S = M_L \cdot R$$

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

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

Ex: Cooling in a Cu-Ni Binary

- 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.
- Consider
  C_o = 35 wt%Ni.



Adapted from Fig. 9.4, *Callister 7e.*

Microstructures in Isomorphous Alloys

Microstructures will vary on the cooling rate (i.e. processing conditions)

1. Equilibrium Cooling: Very slow cooling to allow phase equilibrium to be maintained during the cooling process.

a (T>1260^{o}C): start as homogeneous liquid solution.

b (T ~ 1260^{o}C): liquidus line reached. α phase begins to nucleate. C_α = 46 wt% Ni; C_L = 35 wt% Ni

c (T= 1250^{o}C): calculate composition and mass fraction of each phase.

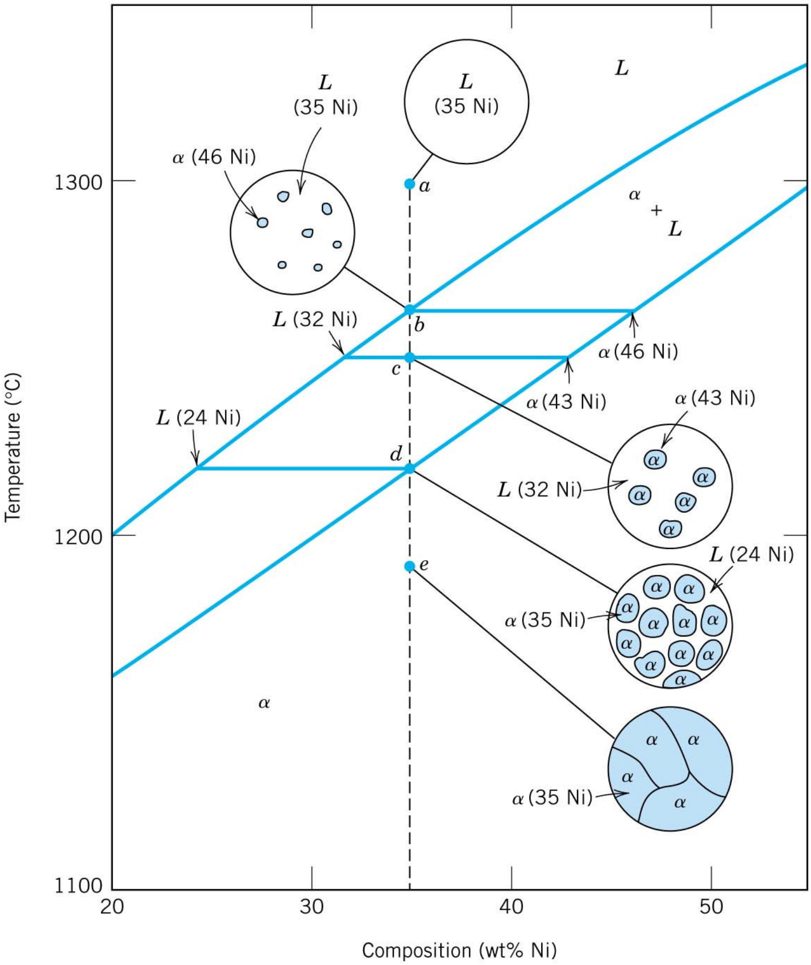
C_α = 43 wt% Ni; C_L = 32 wt% Ni

d (T~ 1220^{o}C): solidus line reached. Nearly complete solidification.

C_α = 35 wt% Ni; C_L = 24 wt% Ni

e (T<1220^{o}C): homogeneous solid solution with 35 wt% Ni.

FIGURE 9.3 Schematic representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.



Non-equilibrium cooling

Since diffusion rate is especially low in solids, consider case where:

Cooling rate >> diffusion rate in solid
Cooling rate << diffusion rate in liquid
(equilibrium maintained in liquids phase)

Non-equilibrium cooling

a’ (T>1260^{o}C): start as homogeneous liquid solution.

b’ (T ~ 1260^{o}C): liquidus line reached. α phase begins to nucleate.
C_{α} = 46 wt% Ni; C_{L} = 35 wt% Ni

c’ (T= 1250^{o}C): solids that formed at pt **b’** remain with same composition (46wt%) and new solids with 42 wt% Ni form around the existing solids (Why around them?).

d’ (T~ 1220^{o}C): solidus line reached. Nearly complete solidification.

•Previously solidified regions maintain original composition and further solidification occurs at 35 wt% Ni.

e (T<1220^{o}C): Non-equilibrium solidification complete (with phase segregation).

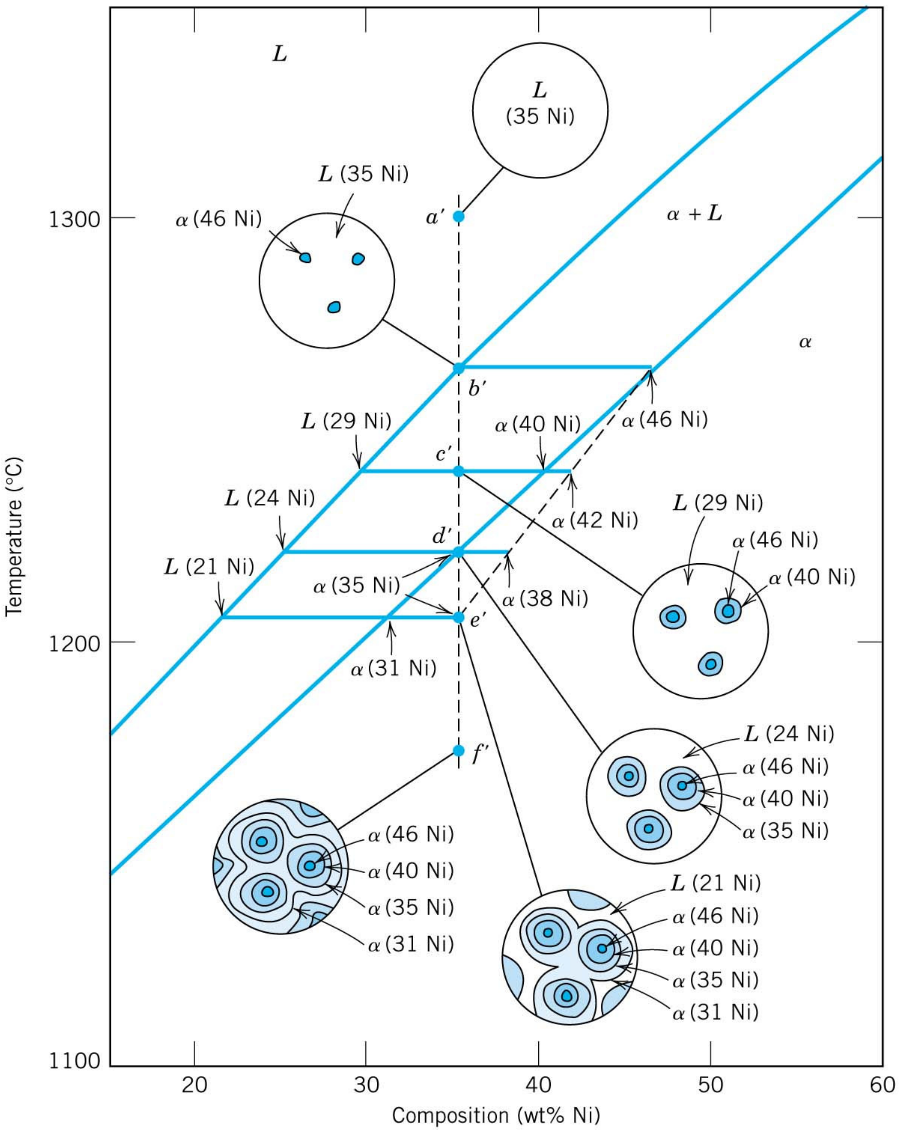
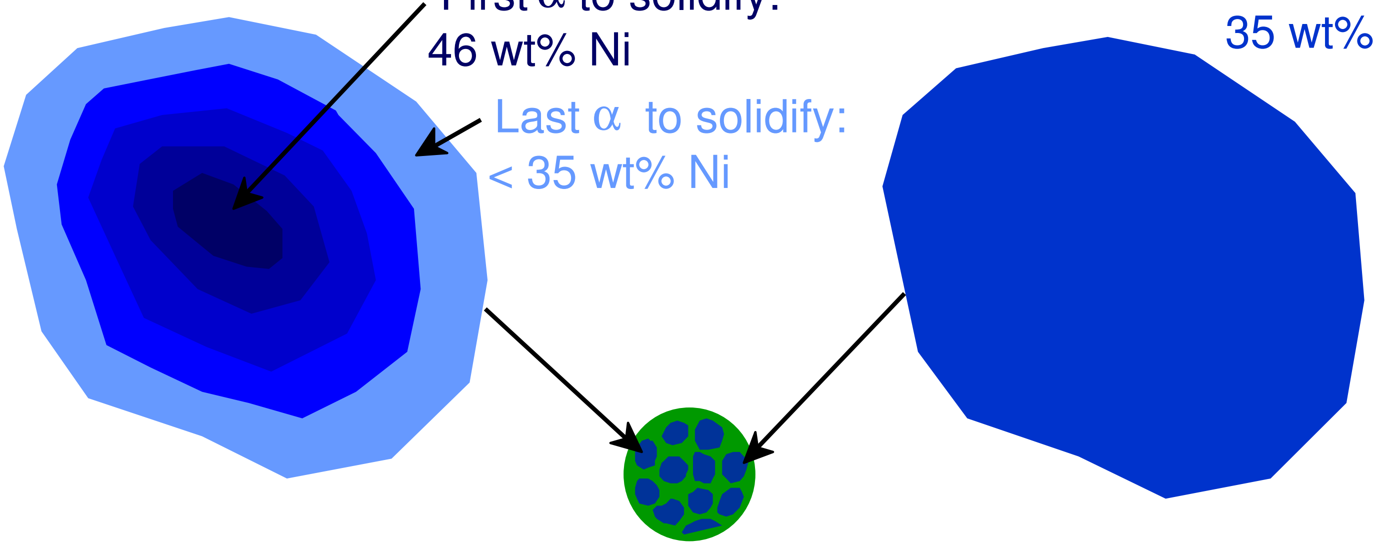


FIGURE 9.4 Schematic representation of the development of microstructure during the nonequilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.

Cored vs Equilibrium Phases

- 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.

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



First α to solidify:
46 wt% Ni

Last α to solidify:
< 35 wt% Ni

Uniform C_α:
35 wt% Ni

Cored structure can be eliminated by a homogenization heat treatment at a temperature below the solidus point for the particular alloy composition.

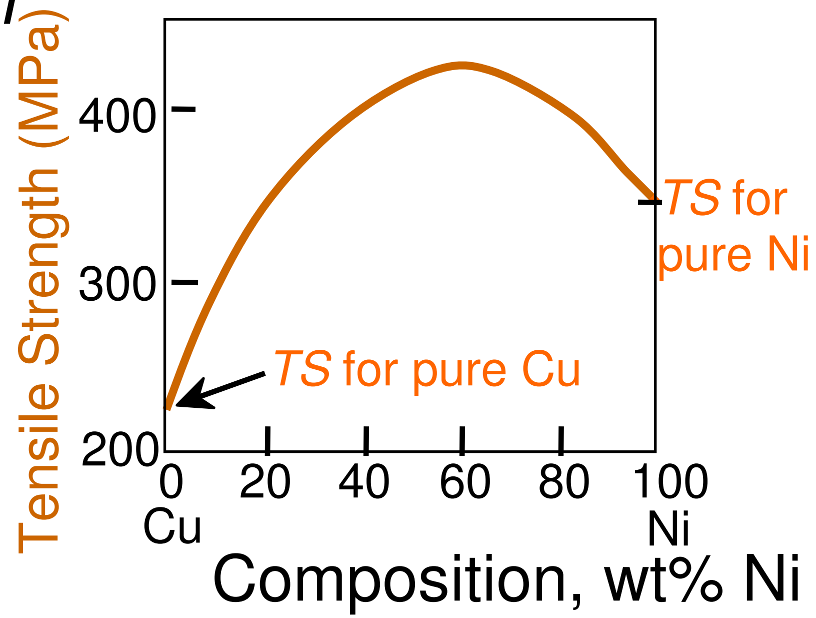
Mechanical Properties: Cu-Ni System

- Effect of solid solution strengthening on:

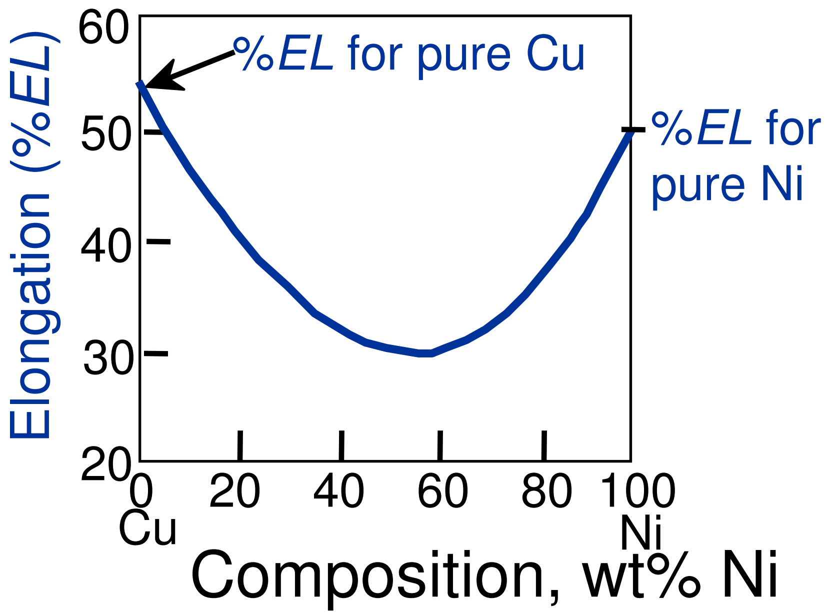
--Tensile strength (*TS*)

--Ductility (%*EL*,%*AR*)

At RT



Adapted from Fig. 9.6(a), *Callister 7e.*



Adapted from Fig. 9.6(b), *Callister 7e.*

--Peak as a function of C_o

--Min. as a function of C_o

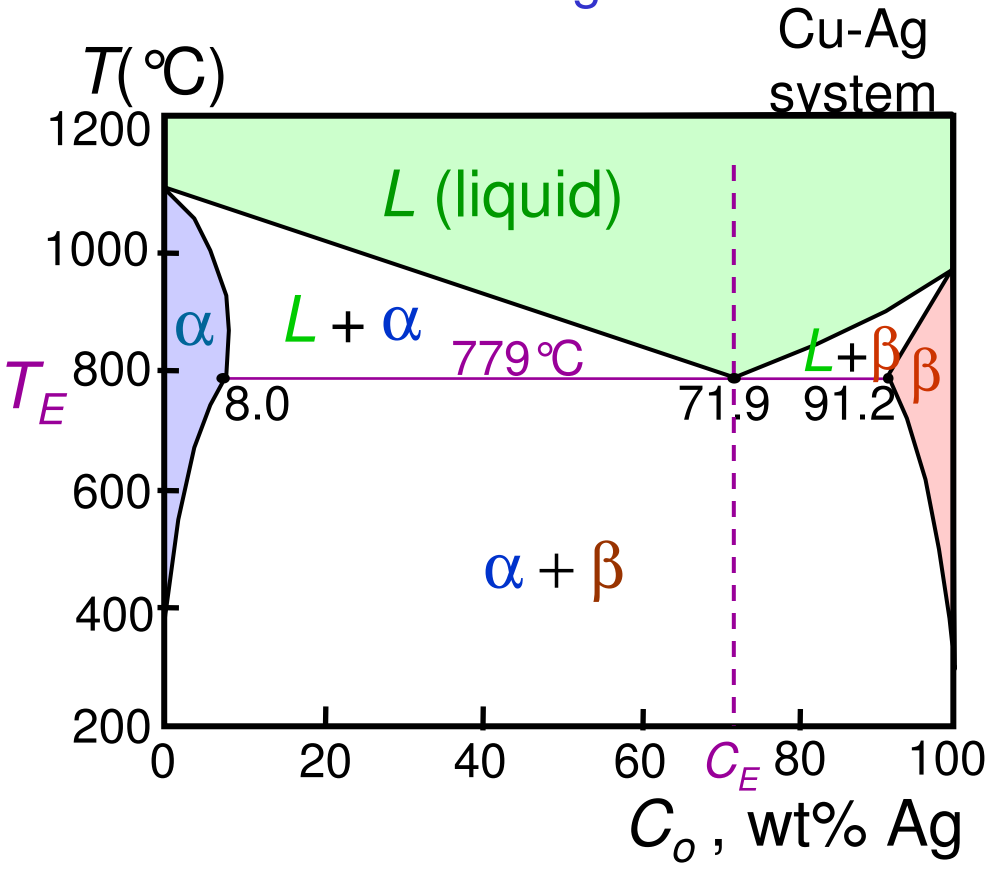
Binary-Eutectic Systems

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: Min. melting T_E composition



- **Eutectic transition**

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

Adapted from Fig. 9.7, *Callister 7e.*

Eutectic Point

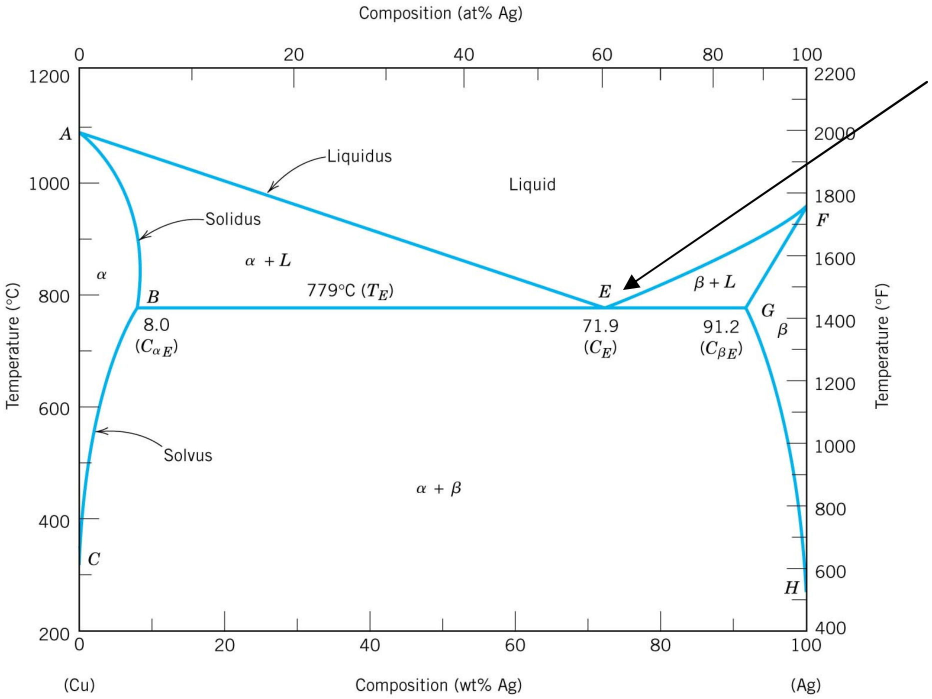


FIGURE 9.6 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Cu-Ag phase diagram

Eutectic point: Where 2 liquidus lines meet (pt. E).
Sometimes also referred to as invariant point.

Eutectic Reaction:

$$L(C_E) \underset{\text{heat}}{\overset{\text{cool}}{\rightleftarrows}} \alpha(C_{\alpha E}) + \beta(C_{\beta E})$$

similar to one component (pure) system except 2 solid phases.

Eutectic Isotherm: Horizontal solidus line at $T = T_E$.

Single phase regions: α, β, L-phase
2-Phase coexistence regions: α+β, α+L and β+L

EX: Pb-Sn Eutectic System (1)

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, find...

  --the phases present: $\alpha + \beta$

  --compositions of phases:

  C_O = 40 wt% Sn

  C_α = 11 wt% Sn

  C_β = 99 wt% Sn

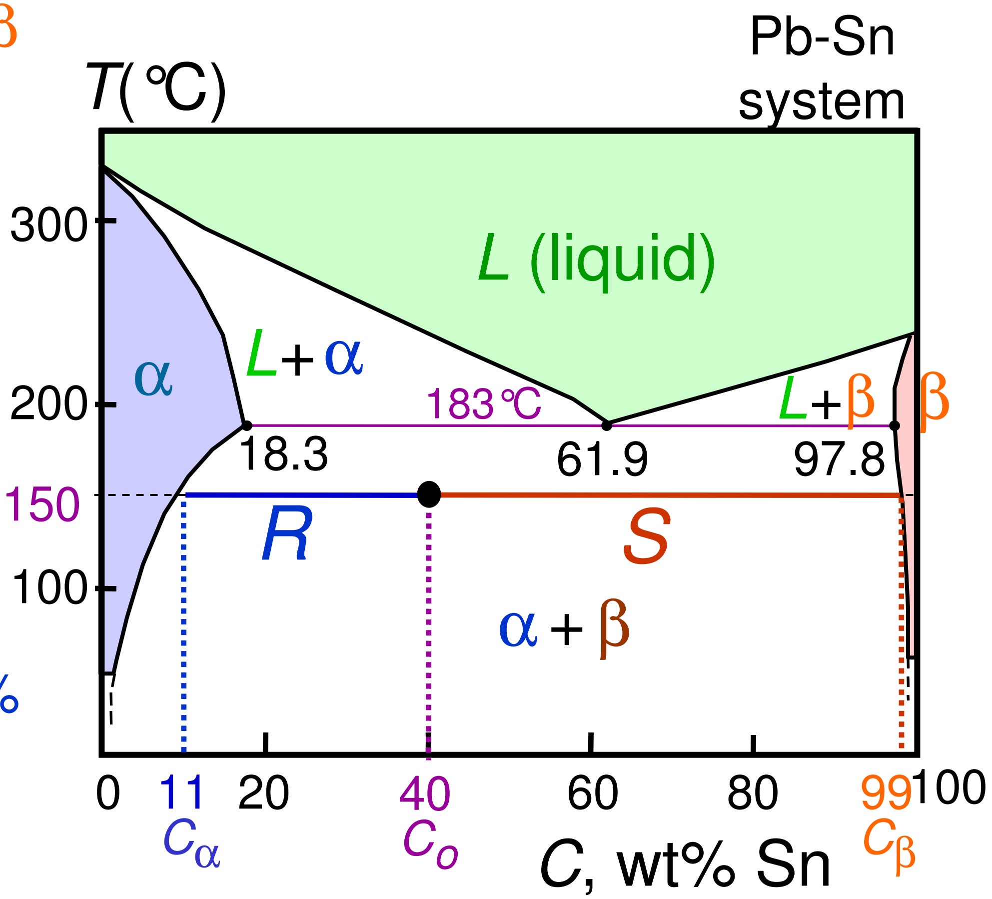
  --the relative amount of each phase:

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

$$= \frac{99 - 40}{99 - 11} = \frac{59}{88} = 67 \text{ wt\%}$$

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

$$= \frac{40 - 11}{99 - 11} = \frac{29}{88} = 33 \text{ wt\%}$$



Adapted from Fig. 9.8, *Callister 7e.*

EX: Pb-Sn Eutectic System (2)

- For a 40 wt% Sn-60 wt% Pb alloy at 200°C, find...

--the phases present: $\alpha + L$

--compositions of phases:

C_O = 40 wt% Sn

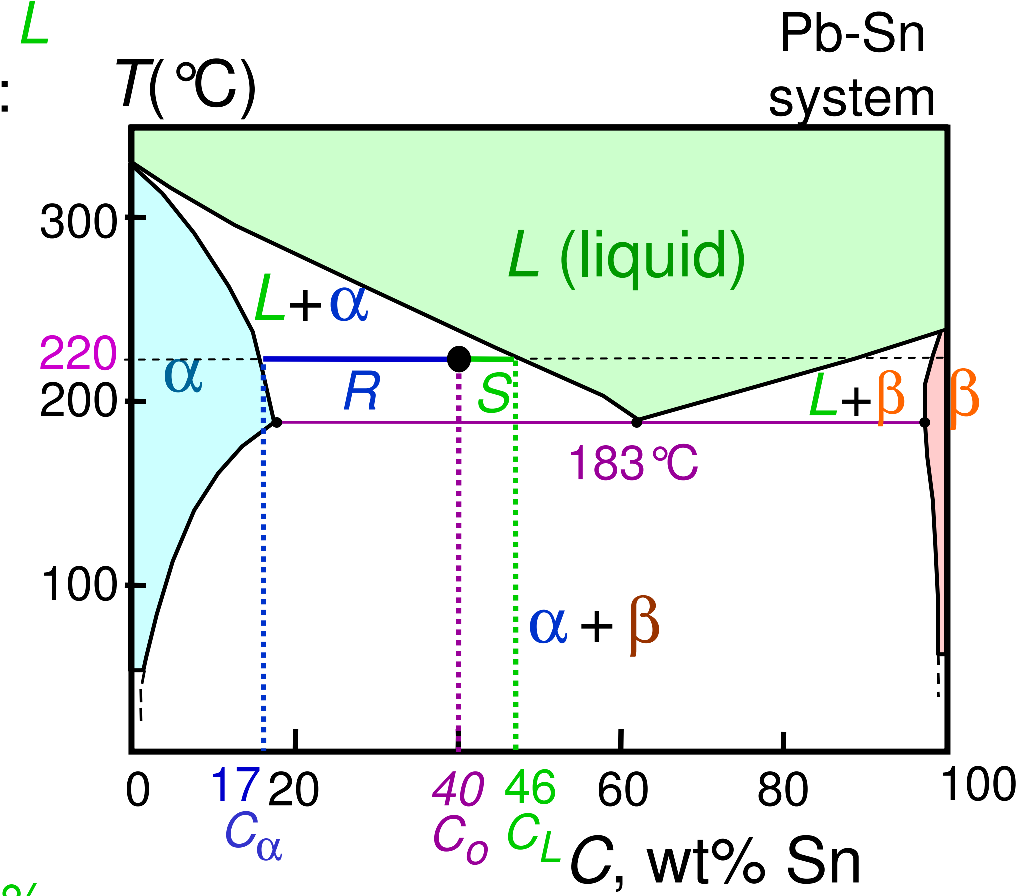
C_α = 17 wt% Sn

C_L = 46 wt% Sn

--the relative amount of each phase:

$$W_\alpha = \frac{C_L - C_O}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 21 \text{ wt\%}$$

$$W_L = \frac{C_O - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 79 \text{ wt\%}$$



Adapted from Fig. 9.8, *Callister 7e.*

Microstructures in Eutectic Systems: I

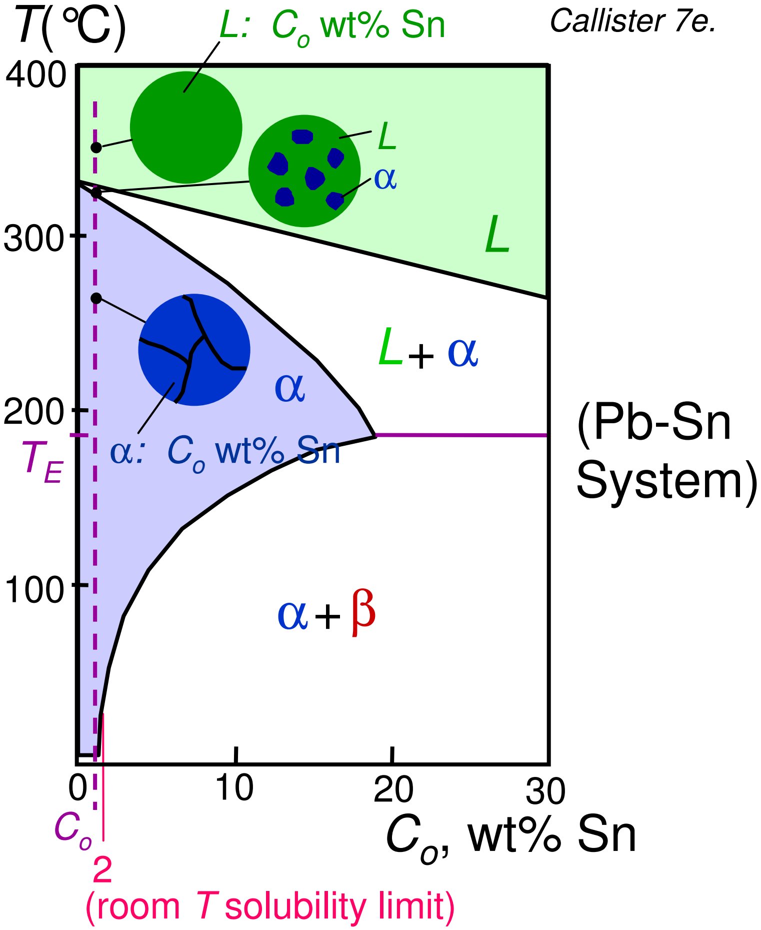
- $C_o < 2$ wt% Sn

1. One component rich composition.
a: start with homogeneous liquid.
b: α-phase solids with liquid.
Compositions and mass fractions can be found via tie lines and lever rule.
c: α-phase solid solution only.

Net result: polycrystalline α solid.

Cooling at this composition is similar to binary isomorphous systems.

Adapted from Fig. 9.11, *Callister 7e.*

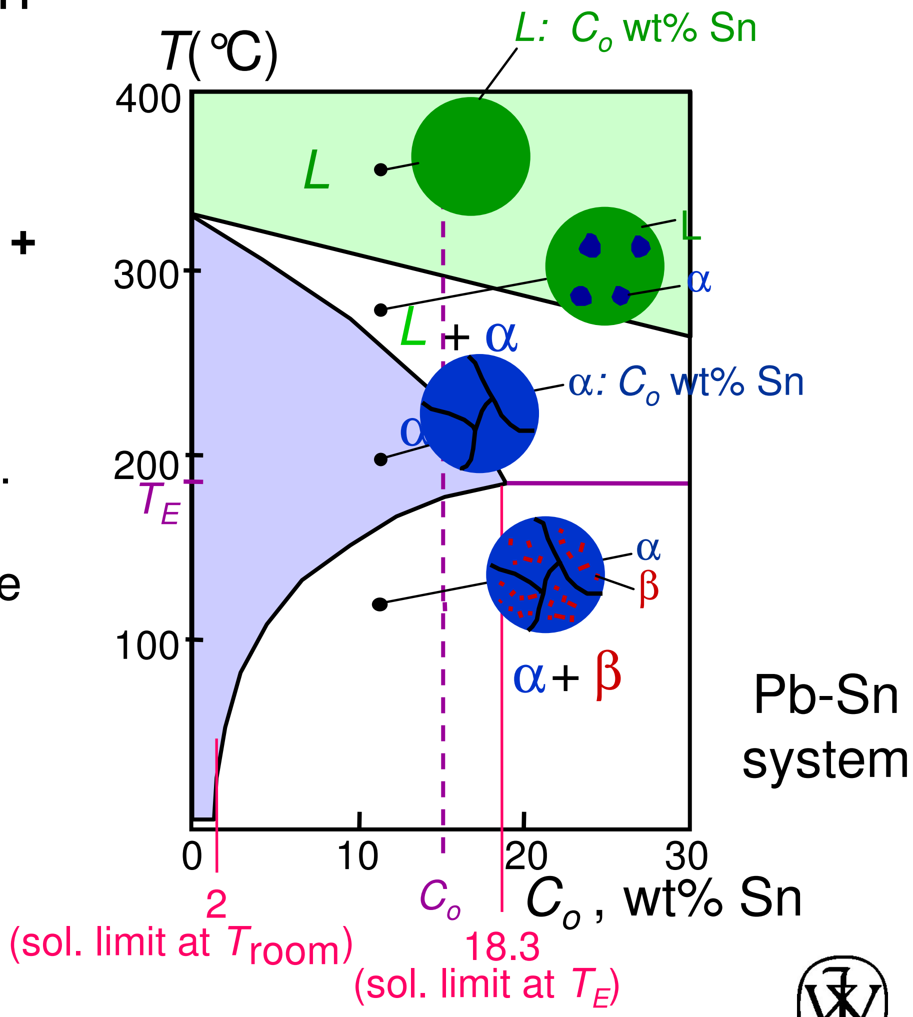


Microstructures in Eutectic Systems: II

Adapted from Fig. 9.12, *Callister 7e.*

- 2 wt% Sn < C_o < 18.3 wt% Sn

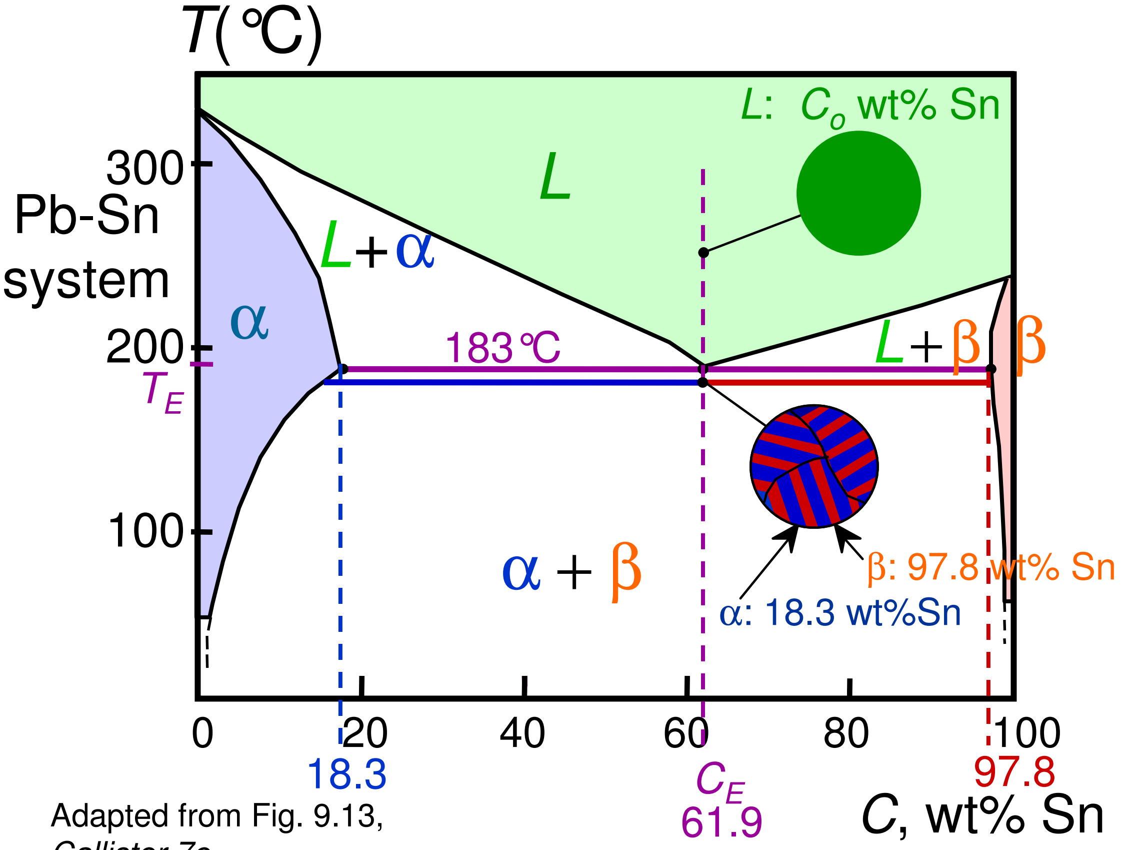
2. One-component rich but cooling to α + β coexistence.
d: homogeneous liquid.
e: α + L phase (same as previous but at different compositions and mass fractions).
f: all α-phase solid solution.
g: α + β phase (passing through solvus line leads to exceeding solubility limit and β phase precipitates out).
Net result: polycrystalline α-solid with fine β crystals.



Pb-Sn system

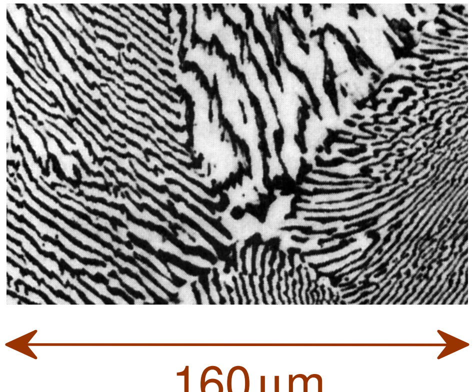
Microstructures in Eutectic Systems: III

- $C_o = C_E$
- Result: Eutectic microstructure (lamellar structure)
  --alternating layers (lamellae) of α and β crystals.



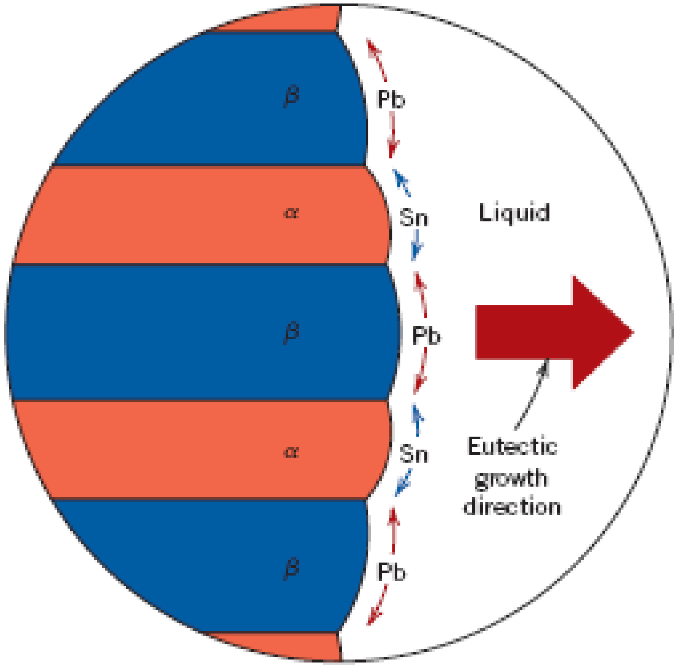
Adapted from Fig. 9.13, *Callister 7e.*

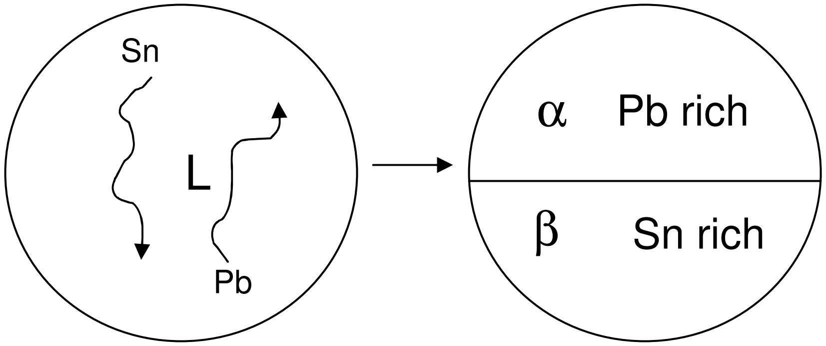
Micrograph of Pb-Sn eutectic microstructure

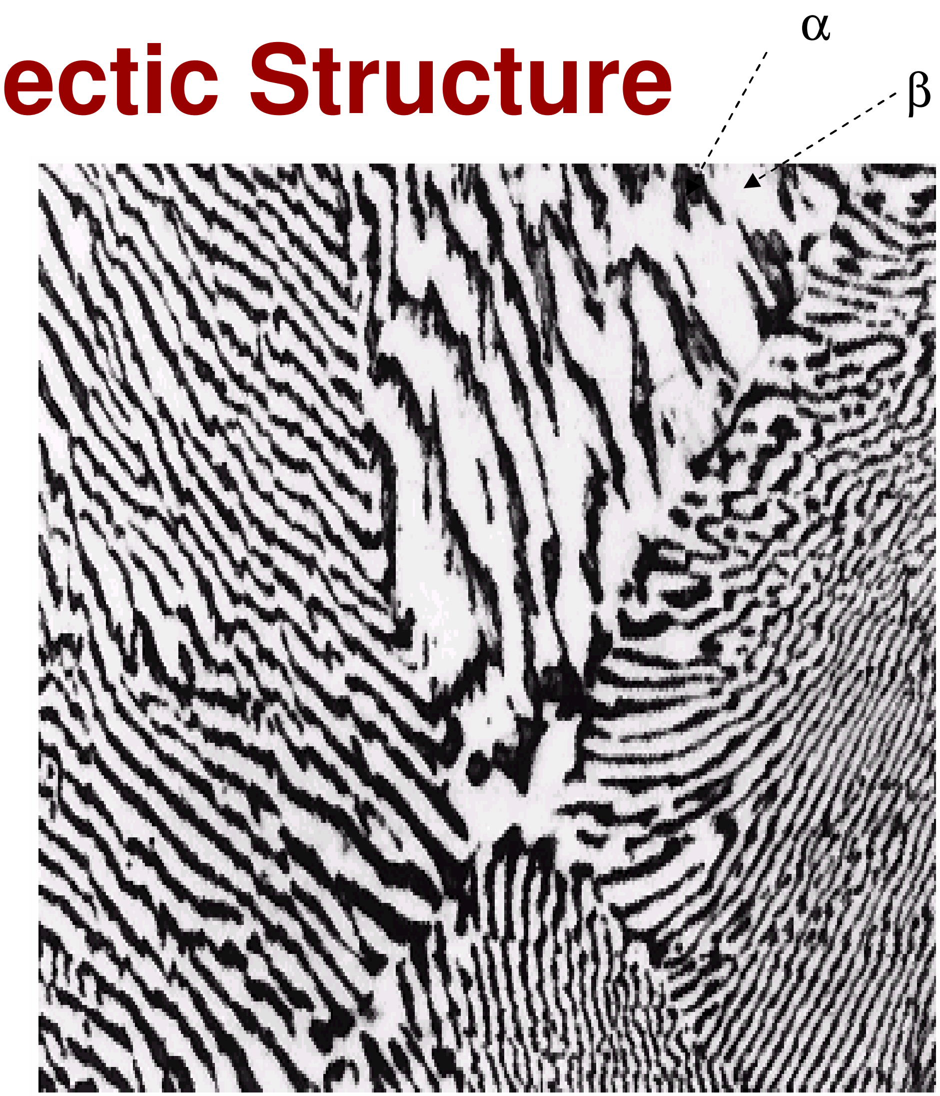


Adapted from Fig. 9.14, *Callister 7e.*

Lamellar Eutectic Structure







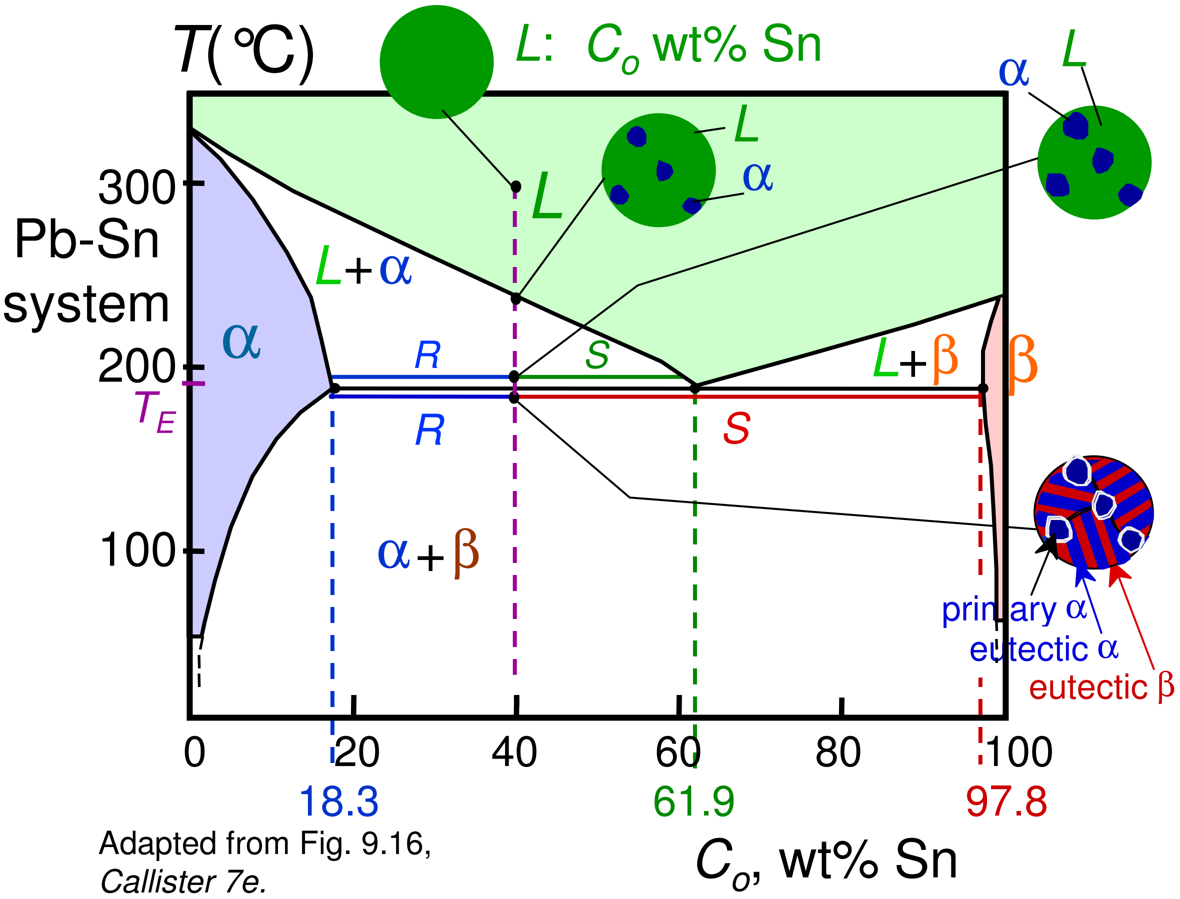
Adapted from Figs. 9.14 & 9.15, *Callister*

In order to achieve large homogeneous regions, **long diffusion lengths** are required.

Lamellar structure forms because relatively **short diffusion lengths** are required.

Microstructures in Eutectic Systems: IV

- 18.3 wt% Sn < C_o < 61.9 wt% Sn
- Result: α crystals and a eutectic microstructure



Adapted from Fig. 9.16, *Callister 7e.*

- Just above T_E:

C_α = 18.3 wt% Sn

C_L = 61.9 wt% Sn

$$W_\alpha = \frac{S}{R+S} = 50 \text{ wt\%}$$

$$W_L = (1 - W_\alpha) = 50 \text{ wt\%}$$

- Just below T_E:

C_α = 18.3 wt% Sn

C_β = 97.8 wt% Sn

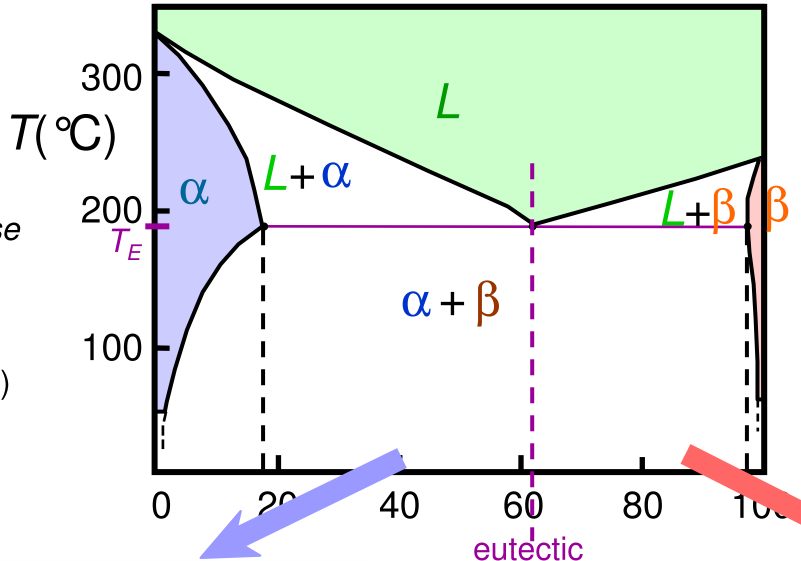
$$W_\alpha = \frac{S}{R+S} = 73 \text{ wt\%}$$

$$W_\beta = 27 \text{ wt\%}$$

Hypoeutectic & Hypereutectic

(Pb-Sn System)

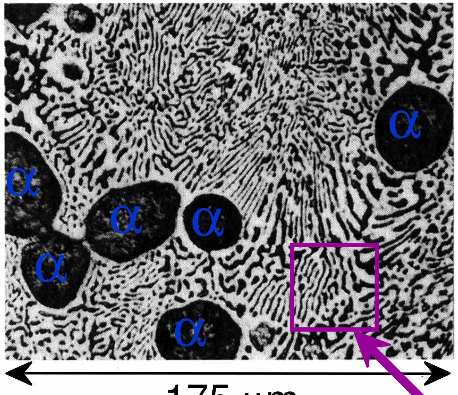
Adapted from Fig. 9.8, *Callister 7e.* (Fig. 9.8 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)



Microconstituent: an element of a microstructure with identifiable and characteristic structure (at pt. m there are 2 microconstituents: primary α and eutectic structures)

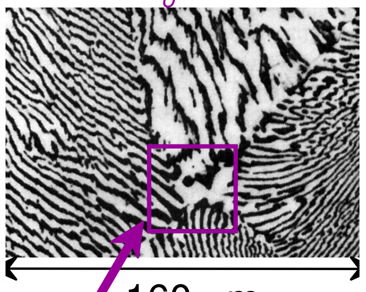
(Figs. 9.14 and 9.17 from *Metals Handbook*, 9th ed., Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)

hypoeutectic: C_o = 50 wt% Sn



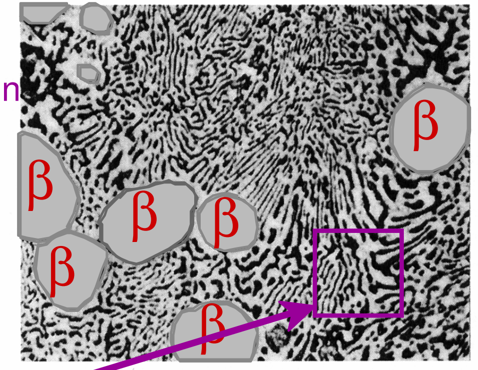
Adapted from Fig. 9.17, *Callister 7e.*

eutectic: C_o = 61.9 wt% Sn



Adapted from Fig. 9.14, *Callister 7e.*

hypereutectic: (illustration only)



Adapted from Fig. 9.17, *Callister 7e.* (Illustration only)

eutectic micro-constituent

Intermediate phases

Intermediate solid solutions (intermediate phases): Solid solutions that do not extend to pure components in the phase diagram.

Cu-Zn

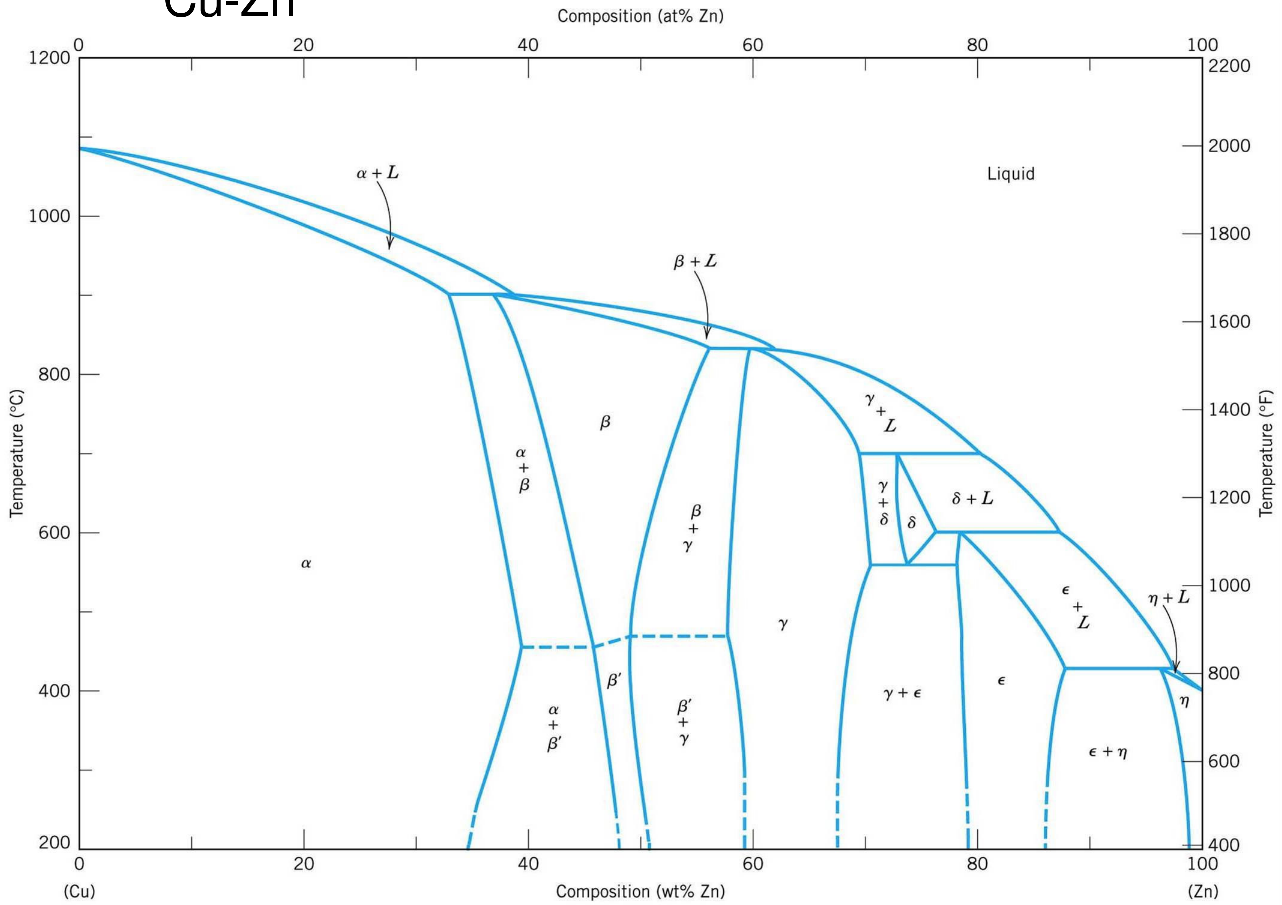


FIGURE 9.17 The copper–zinc phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Terminal solid solutions: α and η.

Intermediate solid solutions: β, γ, δ and ε.

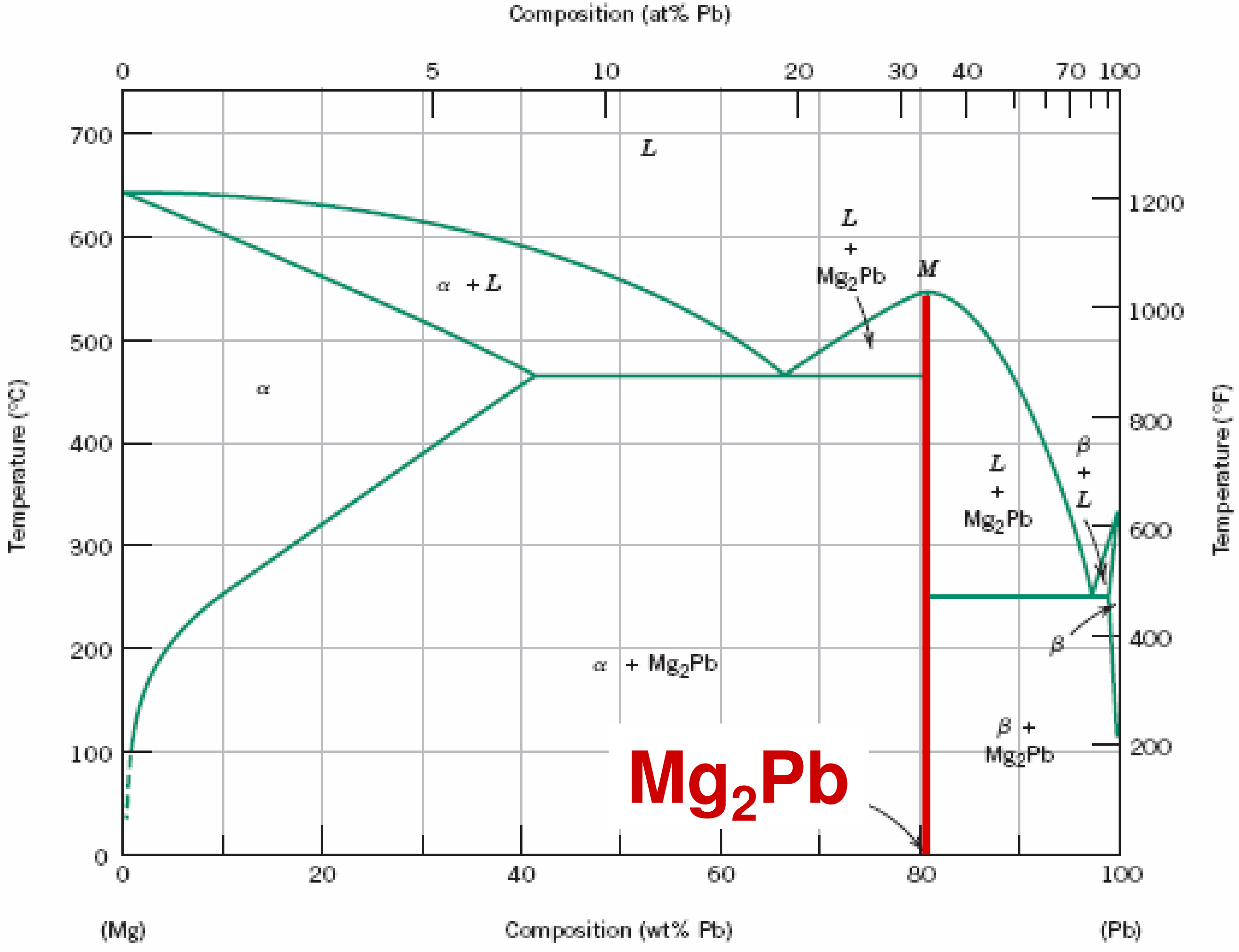
Tie lines and lever rule can be used to determine compositions and wt% of phases.

e.g. at 800°C with 70 wt% Zn

C_L = 78 wt% Zn

C_γ = 67 wt% Zn

Intermetallic Compounds



Adapted from Fig. 9.20, *Callister 7e.*

Note: intermetallic compound forms a discrete line - not an area - because stoichiometry (i.e. composition) is exact.

Eutectoid & Peritectic

- Eutectic - liquid in equilibrium with two solids

$$L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$$

- Eutectoid - solid phase in equation with two solid phases

$$S_2 \rightleftharpoons S_1 + S_3$$

intermetallic compound
- cementite

$$\gamma \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + Fe_3C \qquad (727^{\circ}C)$$

- Peritectic - liquid + solid 1 → solid 2 (Fig 9.21)

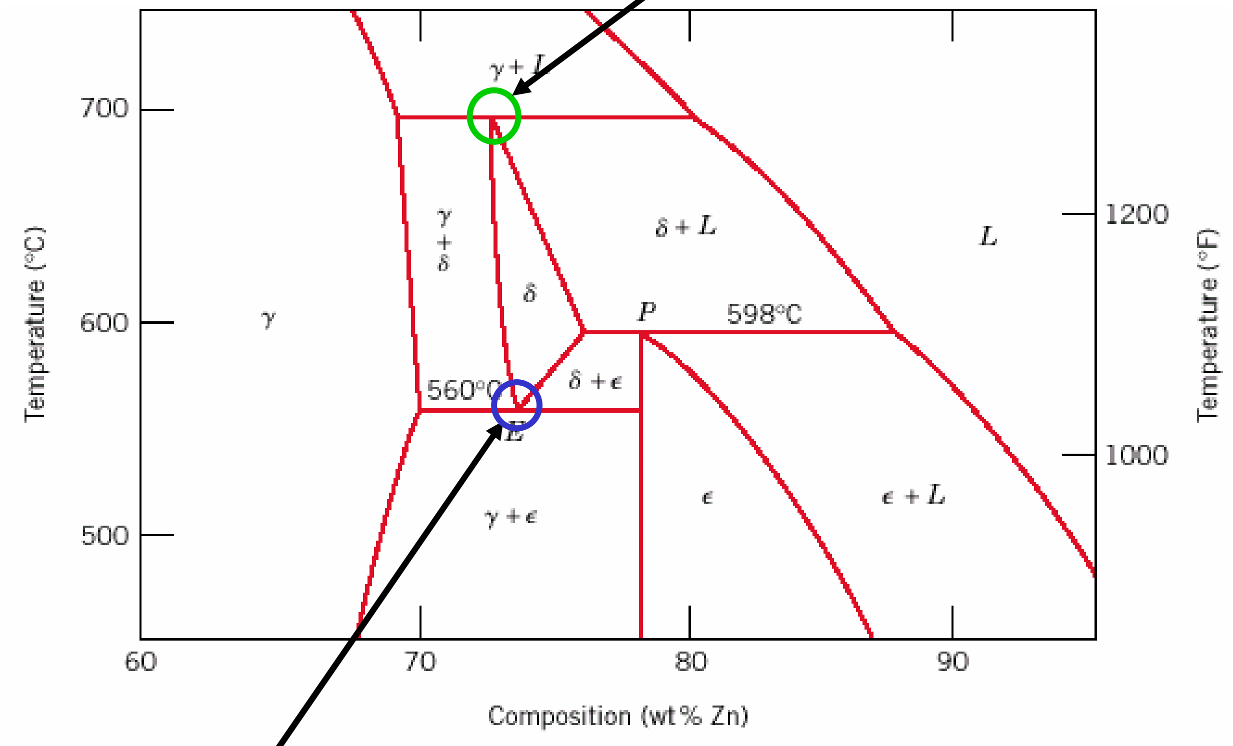
$$S_1 + L \rightleftharpoons S_2$$

$$\delta + L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \gamma \qquad (1493^{\circ}C)$$

Eutectoid & Peritectic

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

Cu-Zn Phase diagram



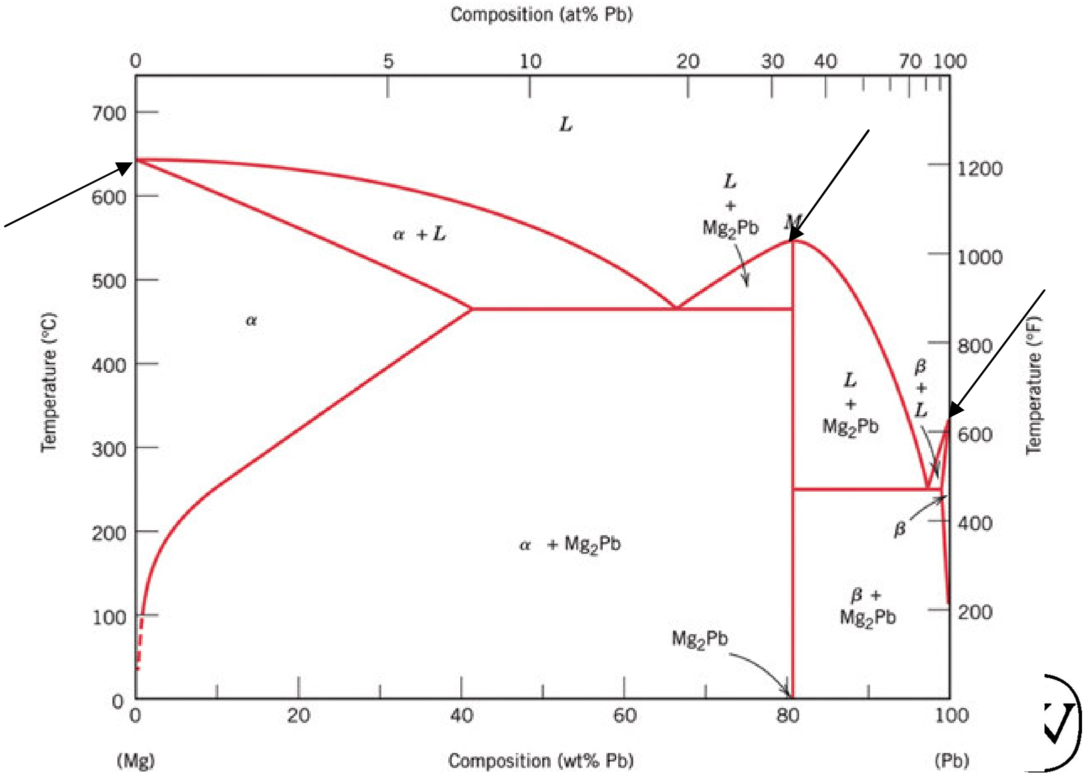
Adapted from
Fig. 9.21, *Callister 7e.*

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

Congruent phase transformation

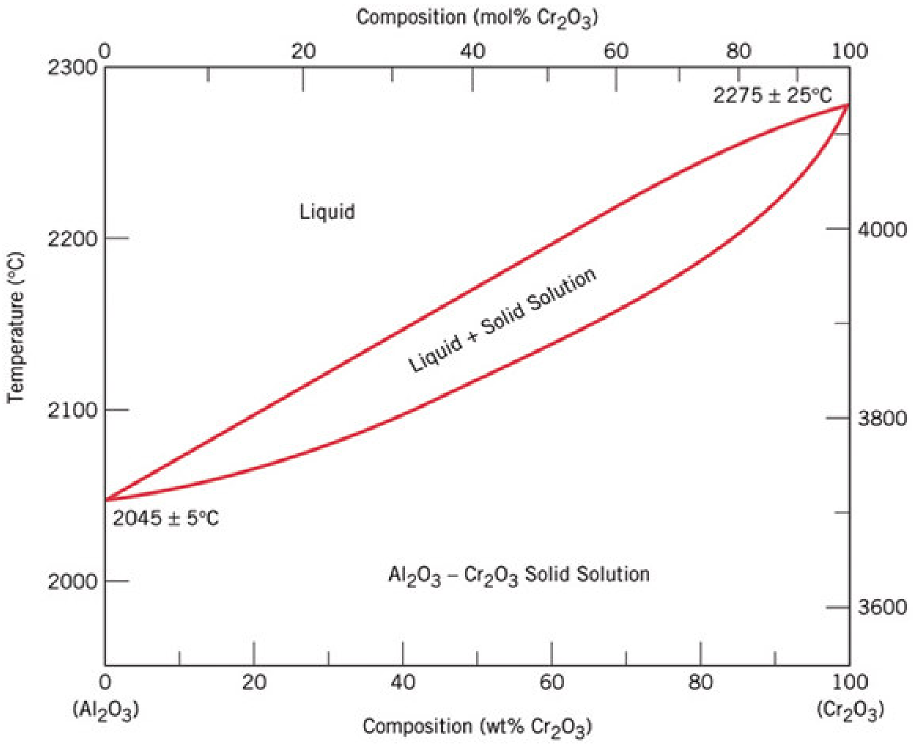
Congruent transformation: no change in composition upon phase transformation. (for example: allotropic transformation)

Incongruent transformation: phase transformation where at least one of the phases go through composition change. (for example: isomorphous, eutectic and eutectoid system)

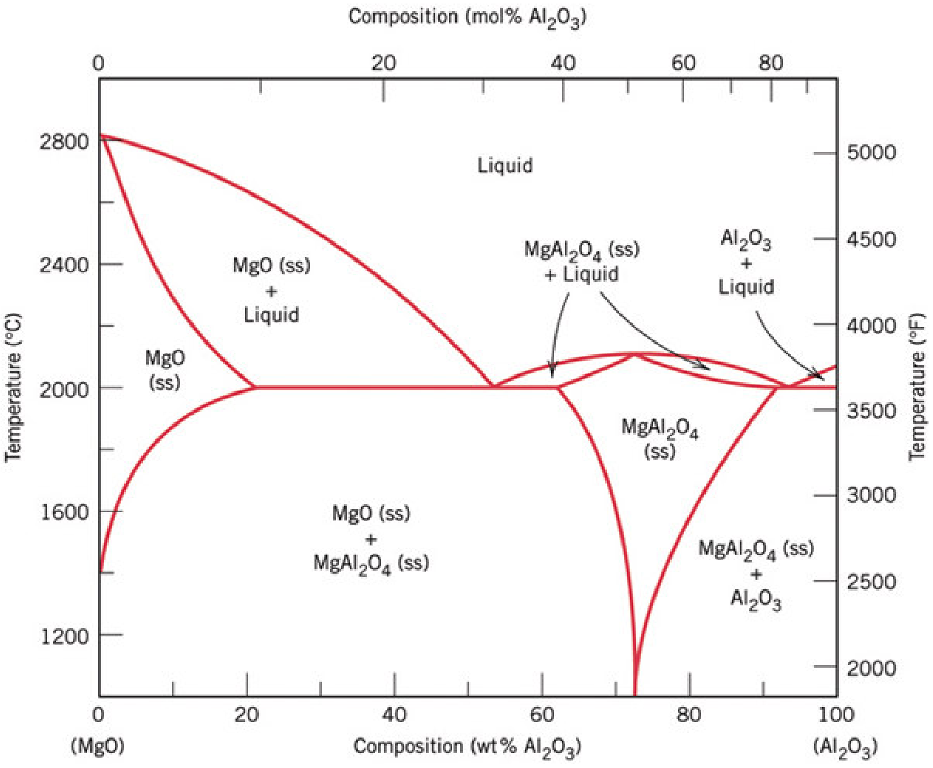


Ceramic phase diagrams

Al_2O_3-Cr_2O_3



MgO-Al_2O_3



Gibbs Phase Rule

A criterion for the number of phases that will coexist within a system at equilibrium

$$P + F = C + N$$

Number of phases present

Degree of freedom (externally controllable parameters: i.e. T, P, and C)

Number of components

Number of non-compositional variables (Temperature & Pressure)

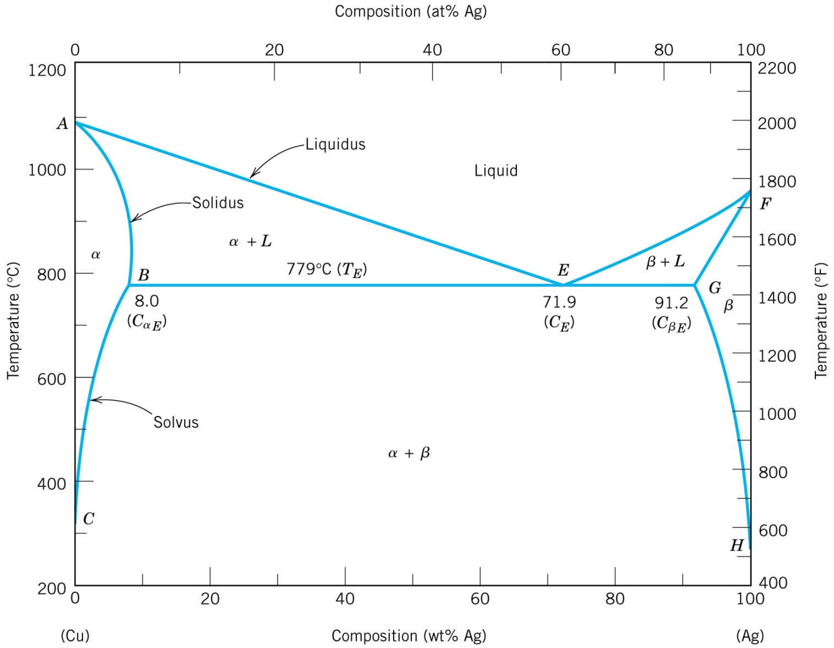


FIGURE 9.6 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

e.g. Cu-Ag phase diagram

Cu and Ag are the only components
-> $C = 2$

Temperature is the only non-compositional variable here (i.e. fixed pressure).
-> $N = 1$ (but in general $N = 2$)

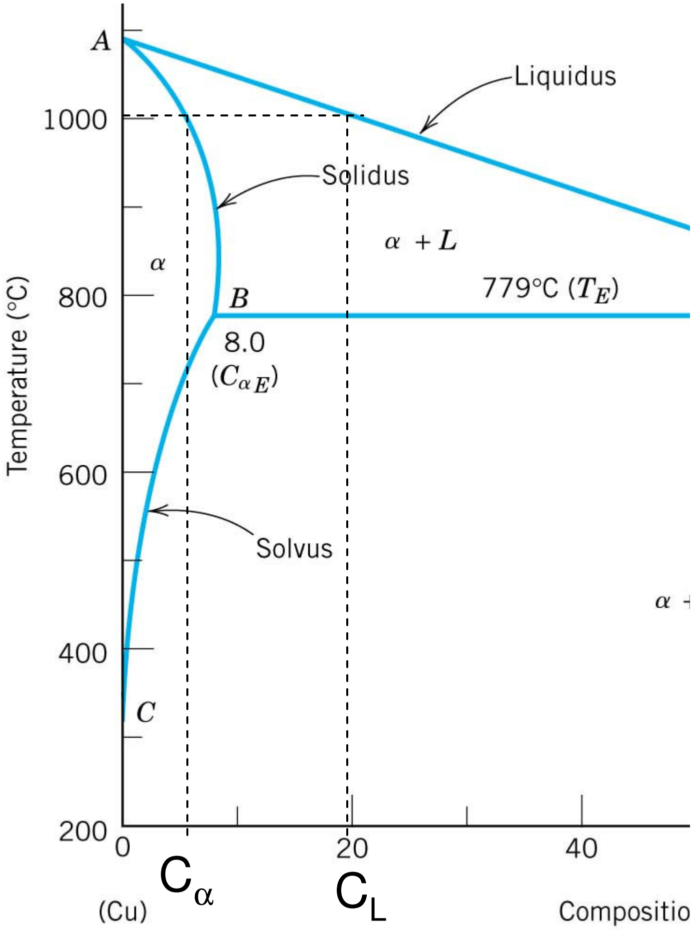
When 2 phases are present
-> $P = 2$ which leads to $\boldsymbol{F} = C+N-P = 2+1-2$ **= 1**

When only 1 phase is present.
-> $P = 1$ which leads to $\boldsymbol{F} = \mathbf{2}$

What does this mean? Why should you care?

Gibbs Phase Rule

In the previous example of Cu-Ag phase diagram, when $F = 1$, only one parameter (T or C) needs to be specified to completely define the system.



→ e.g. (for α+L region)

If T is specified to be 1000°C, compositions are already determined (C_α and C_L).

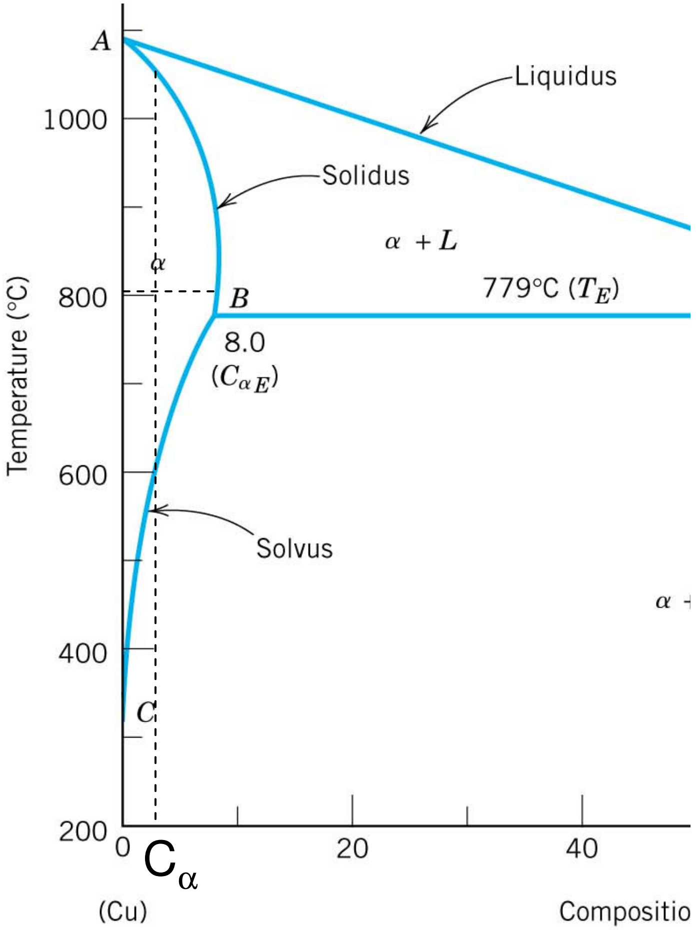
Or

If composition of the a phase is specified to be C_α then both T and C_L are already determined.

The nature of the phases is important, not the relative phase amounts.

Gibbs Phase Rule

When *F* = 2, both T and C have to be specified to completely define the state of the system.



→ e.g.(for α region)

If T is specified to be 800^{o}C, C_α can be any where between 0 to ~8 wt% Ag)

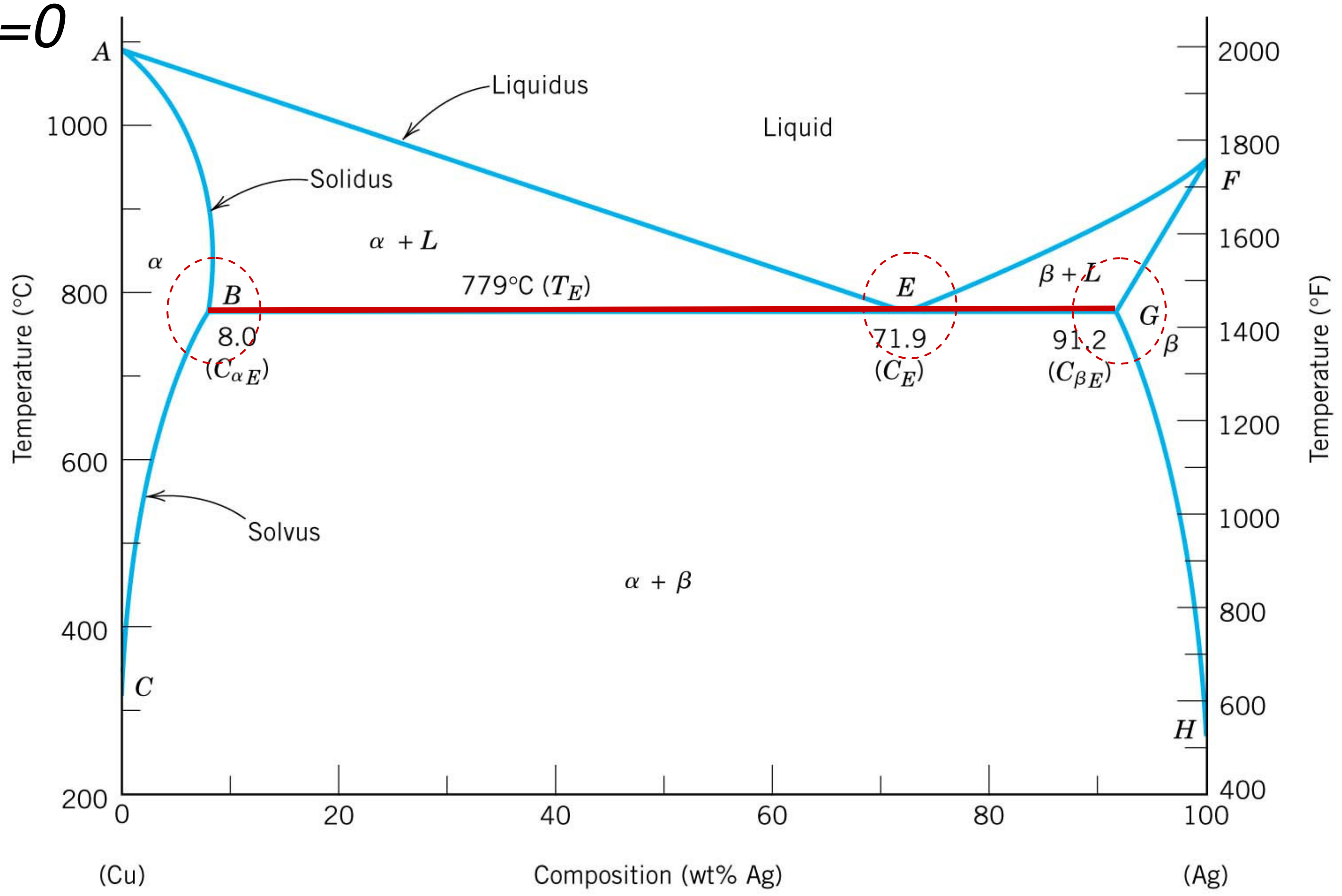
Or

If composition of the a phase is specified to be C_α = 3 wt%, then T and can be any where between ~600 to 1100^{o}C.

Gibbs Phase Rule

Where in the Cu—Ag diagram, is there a 0 degree of freedom?
(i.e. T, P, and C are all fixed)---eutectic isotherm

F=3-P=0



Concept Check

- Question: *For a ternary system, three components are present; temperature is also a variable. What is the maximum number of phases that may be present for a ternary system, assuming that pressure is held constant?*

Iron-Carbon System

structural material

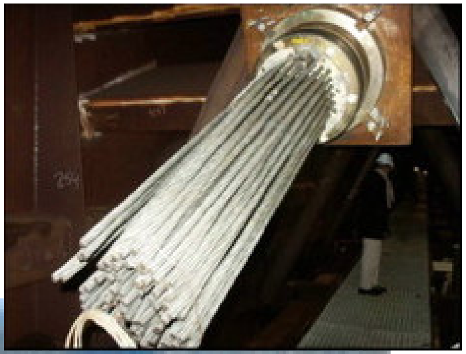
Ferrite Magnets

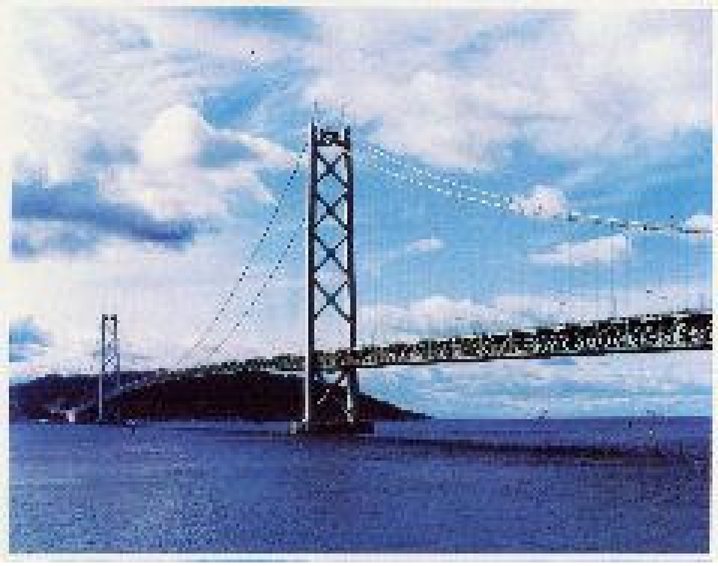
TVR Tuscan Speed 6, high-performance sports car with an austempered ductile iron crankshaft.

The world's first bridge made of iron in 1779. The entire structure is made of cast iron. (near Broseley, UK)

Iron-Carbon System

Steel bridges





The Akashi Kaikyo bridge, a 3-span 2-hinged truss-stiffened suspension bridge. completed in 1998. It connects Kobe with Awaji Island. It is the world's longest suspension bridge, with a span between the towers of 1.9 km.

Millau Viaduct in France, the highest bridge in the world.

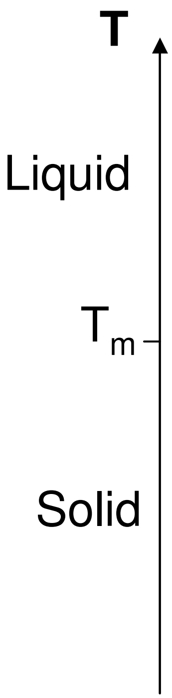
Golden Gate Bridge

Iron-Carbon System

- Iron-carbon (Fe-C) system is one of the most important binary systems due to the versatile uses of the iron-based structural alloys.
- This phase diagram is so important in understanding the equilibrium structure, and in the design of heat treatment process of iron alloys.
- The most important part of the phase diagram is the region below6.7 w% carbon. All practical iron-carbon alloys contain C below 6.7 w%. This part is of the phase diagram is thus the most analyzed part of the iron carbon phase diagram.

Iron-Carbon System

Typical metal (e.g. Cu)



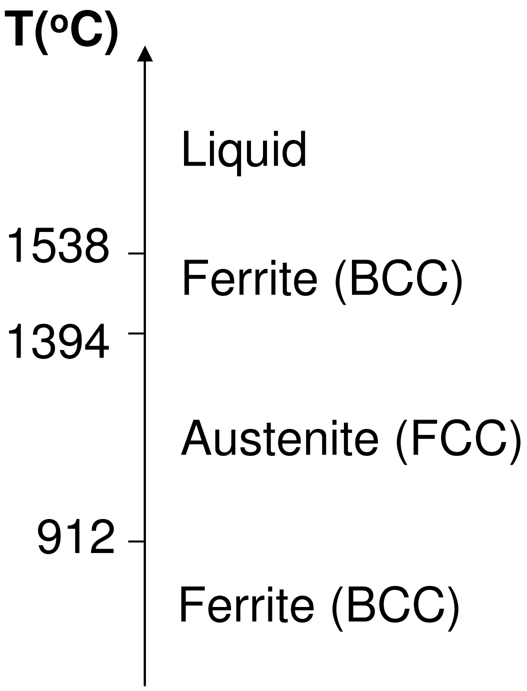
T

Liquid

T_m

Solid

Iron



T(°C)

Liquid

1538

Ferrite (BCC)

1394

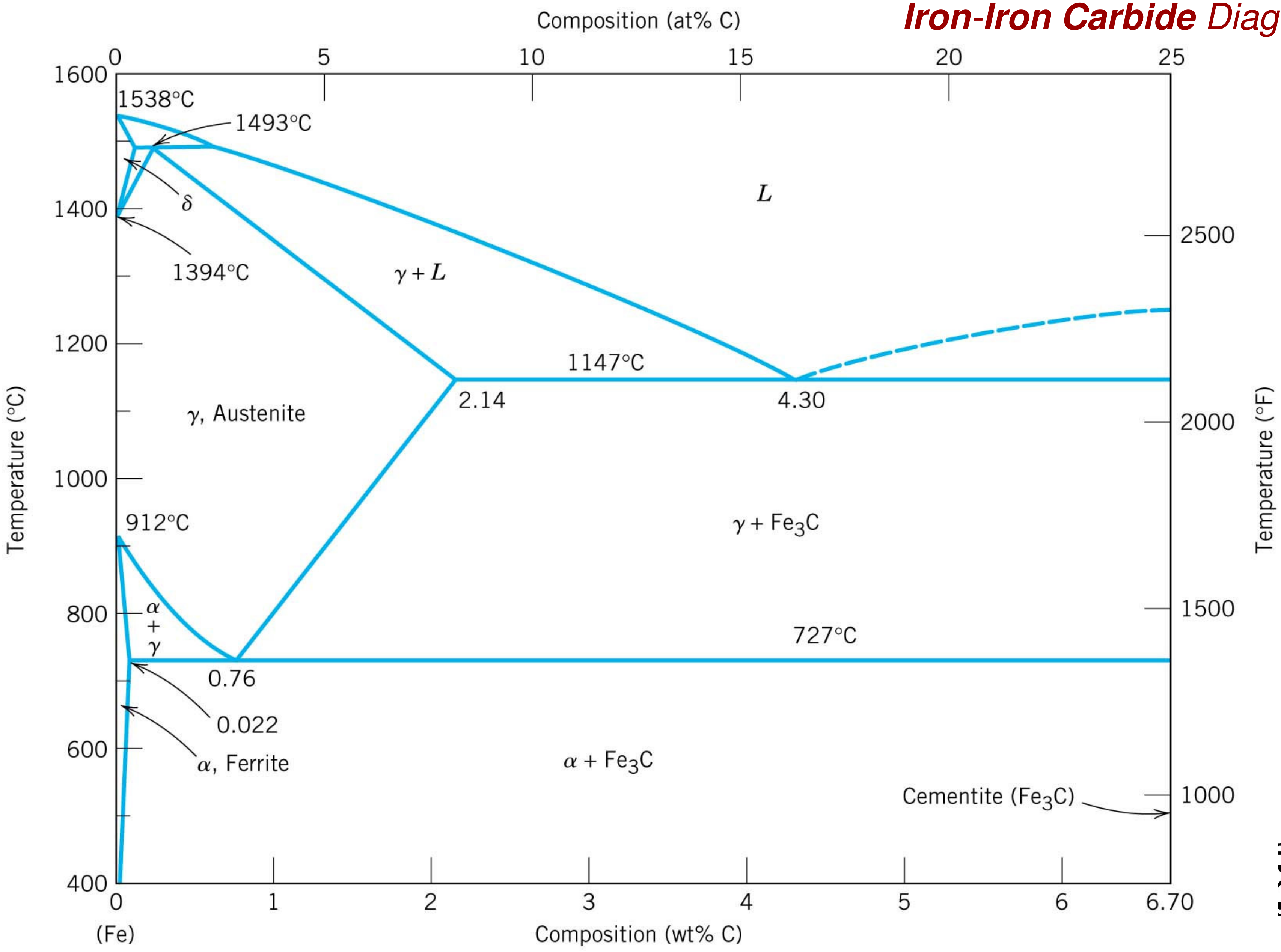
Austenite (FCC)

912

Ferrite (BCC)

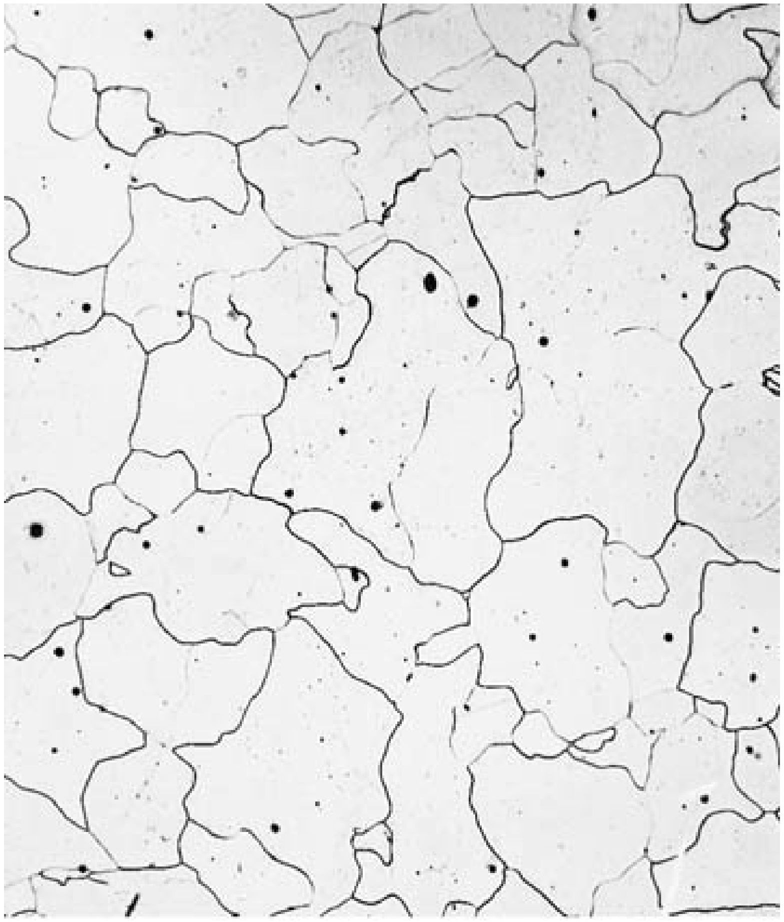
Iron-Carbon System

***Iron-Iron Carbide** Diagram*



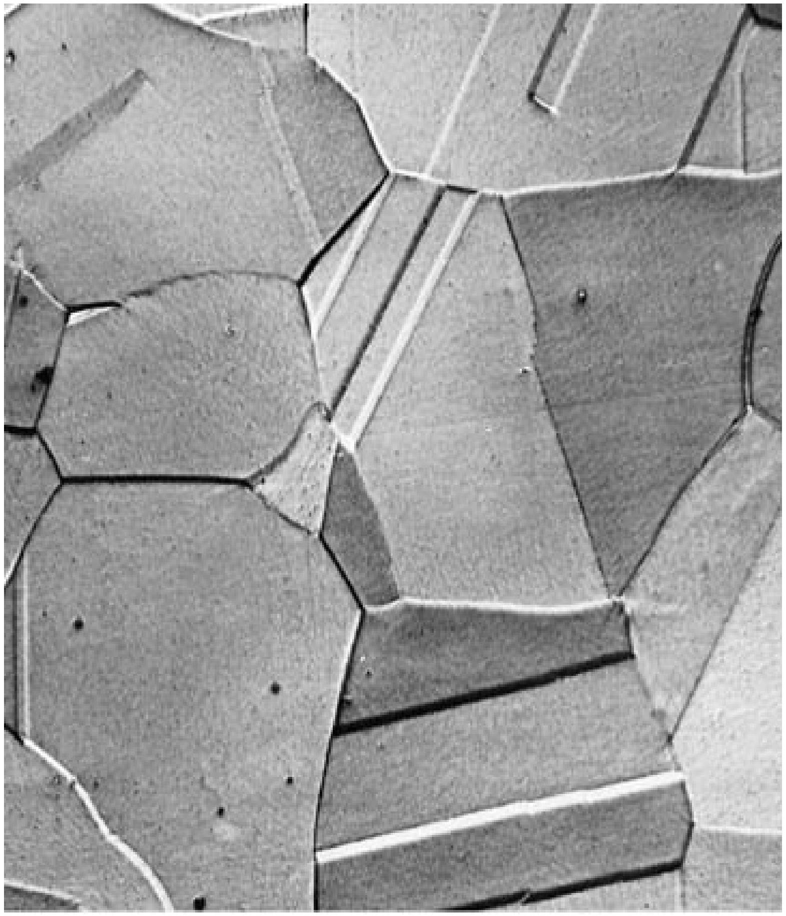
Remarks on Fe-C system

- C is an interstitial element in Fe matrix.
- C has limited solid solubility in the alpha BCC phase (narrow region close to pure iron). Max solid solubility of C in alpha iron is 0.022 w% at 727 °C.
- Alpha iron an be made magnetic below 768°C.
- Austenite phase is not stable below at 727 °C. Max solid solubility of C into austenite is 2.14 w% at 1147°C, much larger that that in alpha phase.
- Austenite is a non-magnetic phase, and heat treatment of Fe-C alloys involving austenite is so important.
- Cementite phase (intermetallic, Fe_3C) forms over a large region of the Fe-C phase diagram, but it is a metastable phase (heating above 650 °C for years decomposes this phase into alpha iron and graphite). Cementite is very hard and brittle.
- δ ferrite is stable only at relatively high T, it is of no technological importance and is not discussed further.


(a)

Ferrite (90x)

Relatively soft
Density: 7.88g/cm^3


(b)

Austenite (x325)

Classification Scheme of Ferrous Alloys

- **Iron**

  Pure ion contains less than 0.008wt% C

- **Steel**

  0.008-2.14 wt% C, in practice,<1.0 wt% C

- **Cast Iron**

  2.14-6.70 wt% C, in practice, <4.5 wt% C

Iron-Carbon (Fe-C) Phase Diagram

Eutectoid cooling:

$$\gamma\ (0.76\ \text{wt\% C}) \underset{\text{heat}}{\overset{\text{cool}}{\rightleftarrows}} \alpha\ (0.022\ \text{wt\% C}) + Fe_3C\ (6.7\ \text{wt\% C})$$

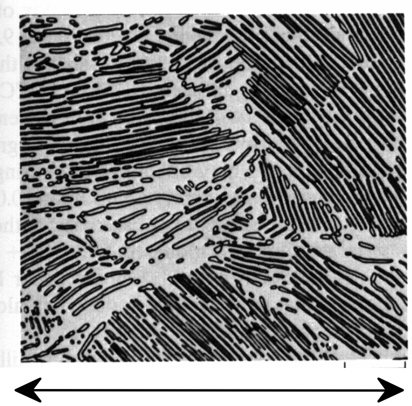
- 2 important points

-Eutectic (*A*):

$L \Rightarrow \gamma + Fe_3C$

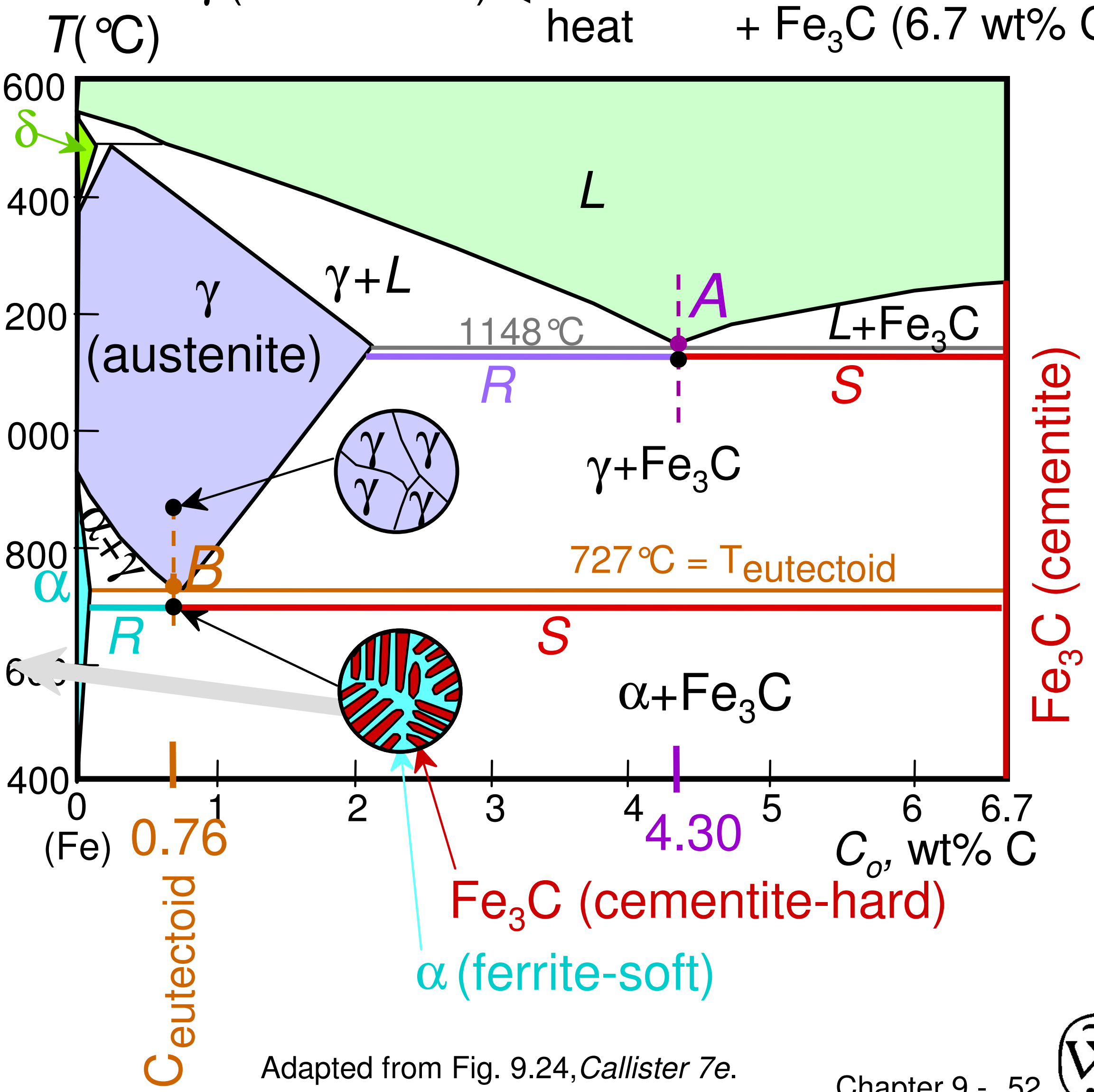
-Eutectoid (*B*):

$\gamma \Rightarrow \alpha + Fe_3C$



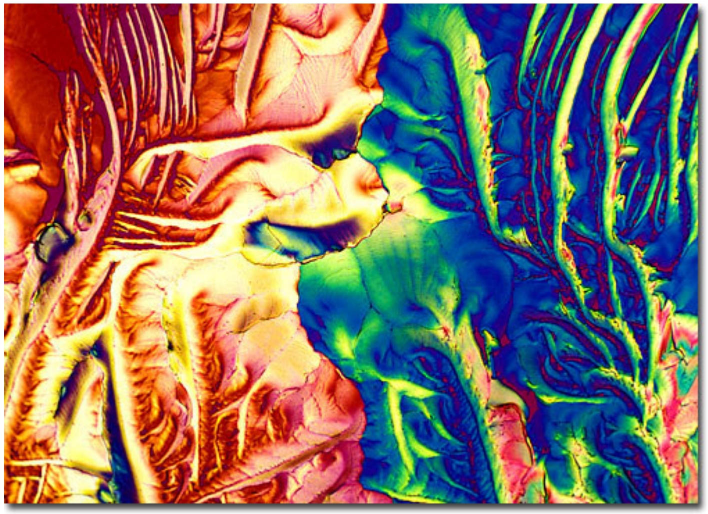
Result: Pearlite = alternating layers of α and Fe_3C phases

(Adapted from Fig. 9.27, *Callister 7e.*)

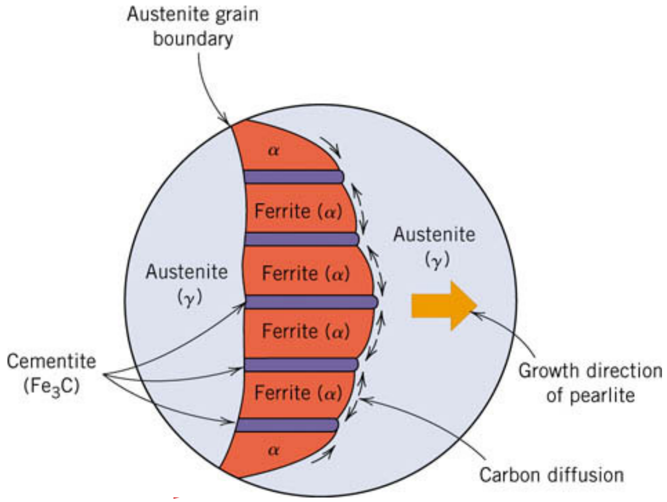


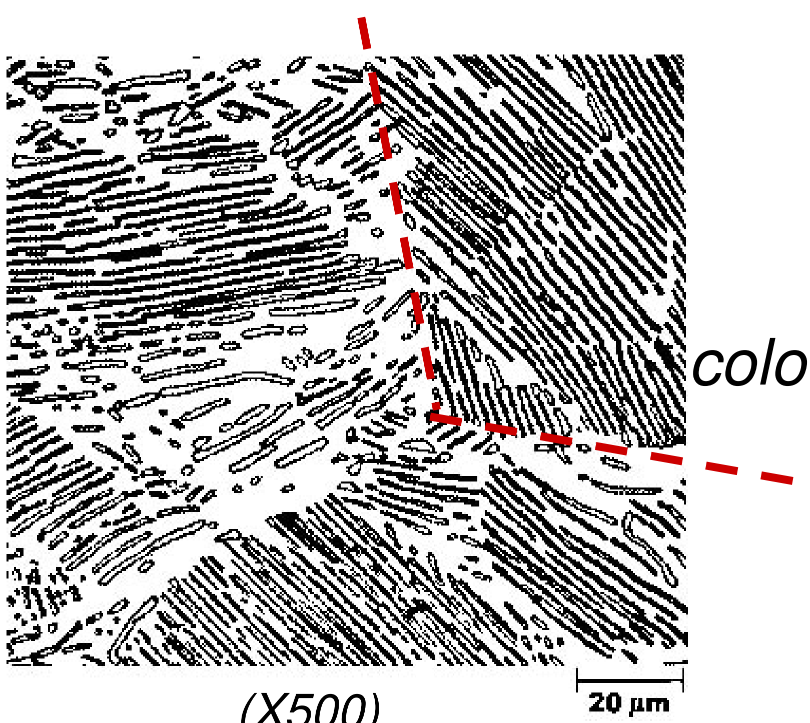
Adapted from Fig. 9.24, *Callister 7e.*

Pearlite



Pearl-microscope picture



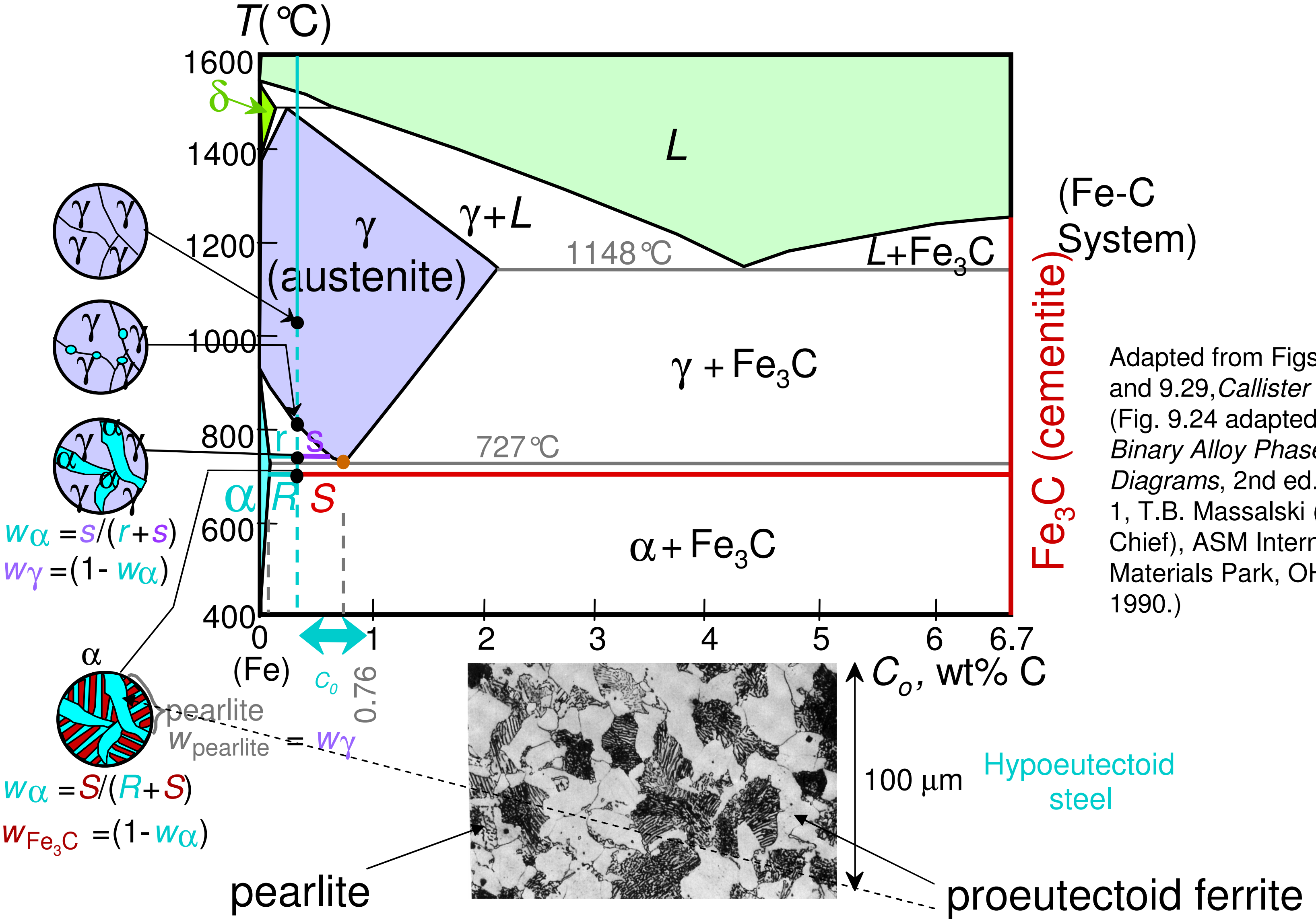


colonies

(X500)

Mechanically, pearlite has properties intermediate between the soft, ductile ferrite and the hard, brittle cementite.

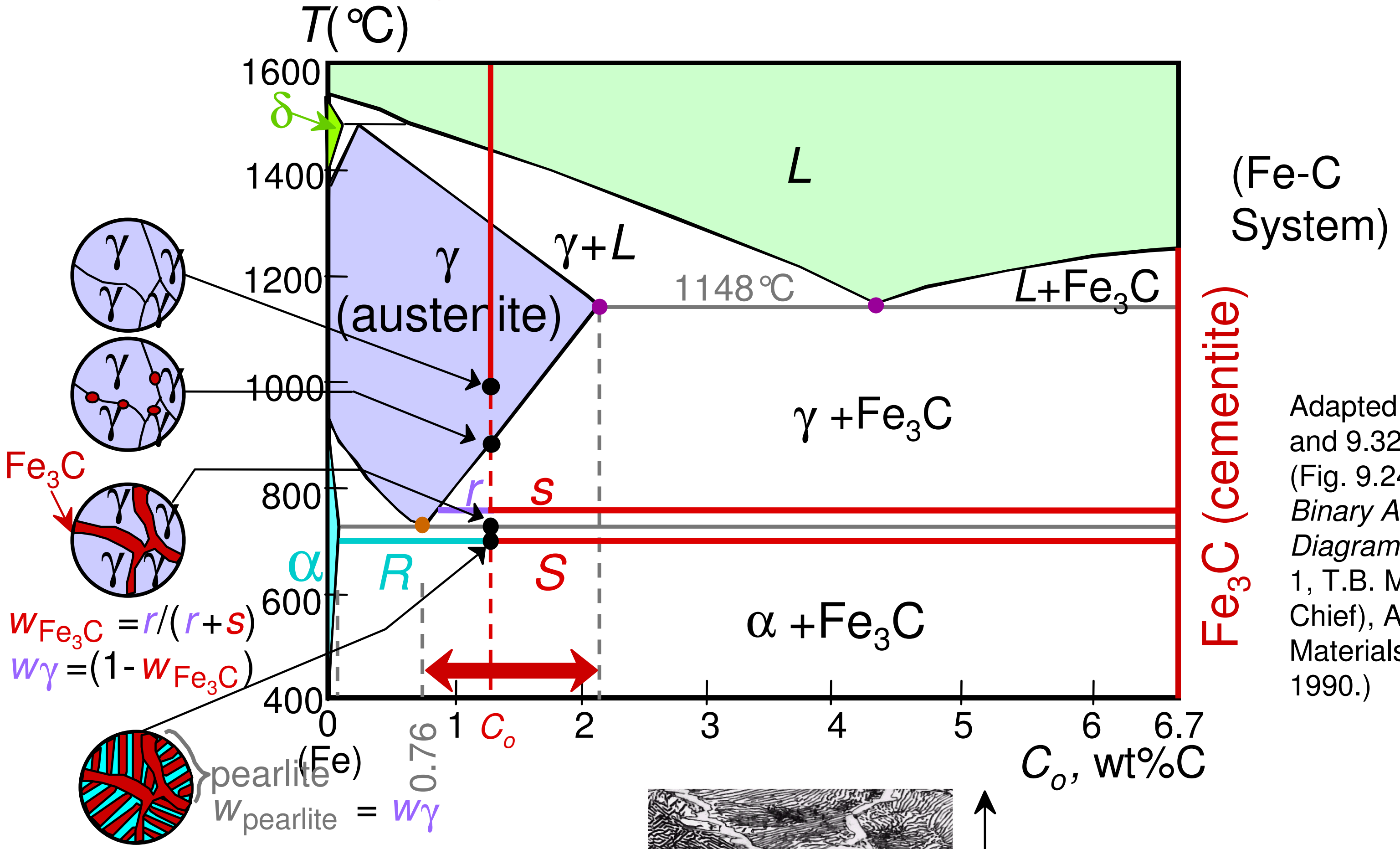
Hypoeutectoid Steel



Adapted from Figs. 9.24 and 9.29, *Callister 7e*. (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 7e*.

Hypereutectoid Steel



$w_{Fe_3C} = r/(r+s)$

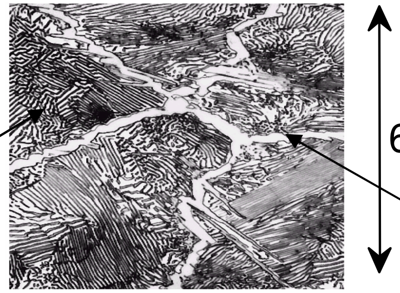
$w_\gamma = (1 - w_{Fe_3C})$

$w_{pearlite} = w_\gamma$

$w_\alpha = S/(R+S)$

$w_{Fe_3C} = (1 - w_\alpha)$

Adapted from Figs. 9.24 and 9.32, *Callister 7e*. (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.)



Hypereutectoid steel

Adapted from Fig. 9.33, *Callister 7e*.

Example: Phase Equilibria

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

a) composition of Fe_3C and ferrite (α)

b) the amount of carbide (cementite) in grams that forms per 100 g of steel

c) the amount of pearlite and proeutectoid ferrite (α)

Chapter 9 – Phase Equilibria

Solution: a) composition of Fe_3C and ferrite (α)

b) the amount of carbide (cementite) in grams that forms per 100 g of steel

$C_O = 0.40$ wt% C

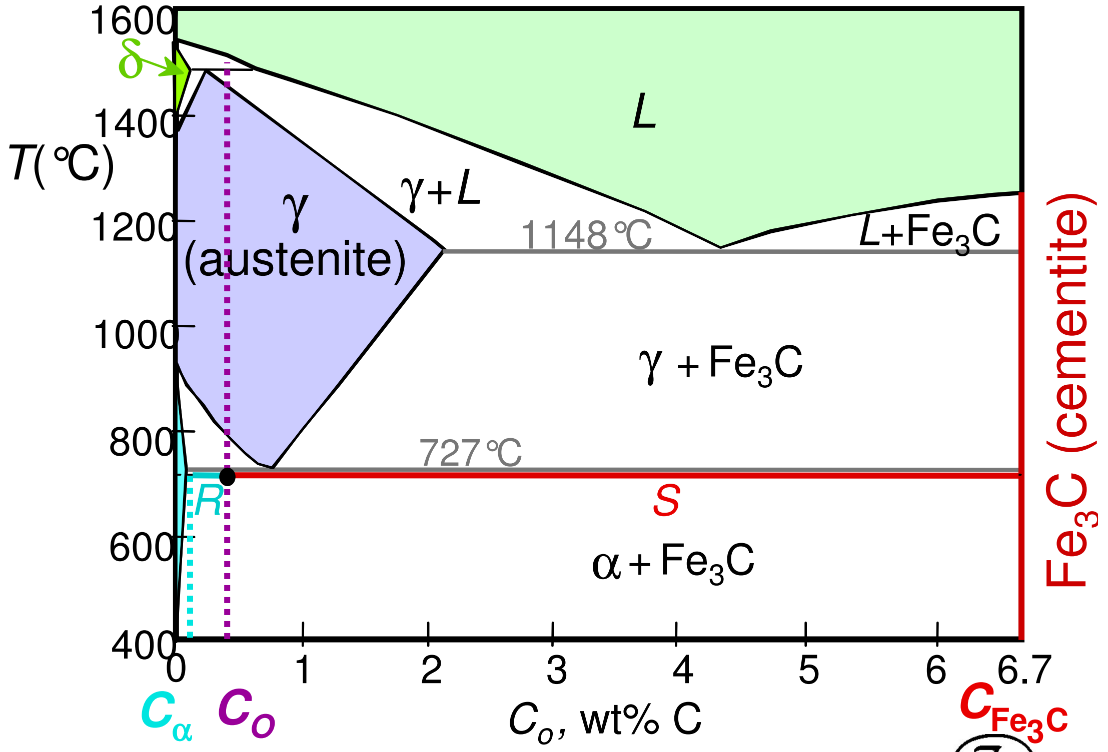
$C_\alpha = 0.022$ wt% C

$C_{Fe_3C} = 6.70$ wt% C

$$\frac{Fe_3C}{Fe_3C + \alpha} = \frac{C_o - C_\alpha}{C_{Fe_3C} - C_\alpha} \text{x} 100$$

$$= \frac{0.4 - 0.022}{6.7 - 0.022} x 100 = 5.7 \text{g}$$

$$\boxed{\begin{array}{l} Fe_3C = 5.7 \text{ g} \\ \alpha = 94.3 \text{ g} \end{array}}$$



Chapter 9 – Phase Equilibria

c. the amount of pearlite and proeutectoid ferrite (α)

note: amount of pearlite = amount of γ just above T_E

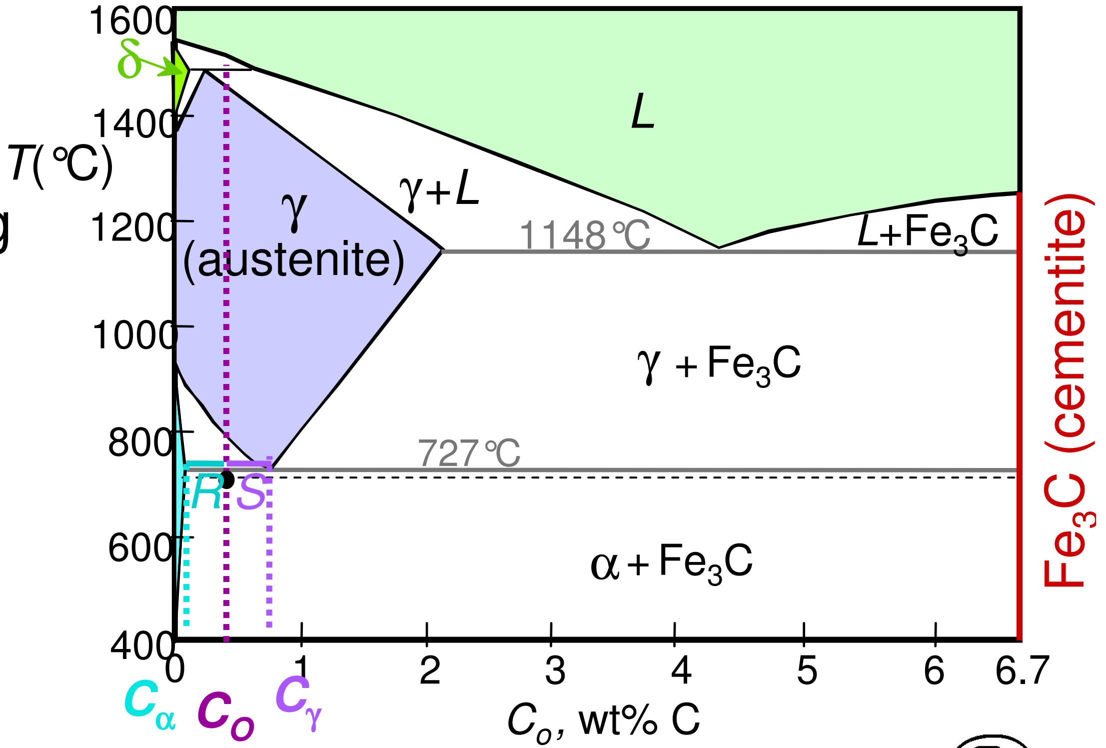
C_o = 0.40 wt% C

C_α = 0.022 wt% C

$C_{\text{pearlite}} = C_\gamma$ = 0.76 wt% C

$$\frac{\gamma}{\gamma+\alpha} = \frac{C_o - C_\alpha}{C_\gamma - C_\alpha} \text{ x } 100 = 51.2 \text{ g}$$

pearlite = 51.2 g
proeutectoid α = 48.8 g

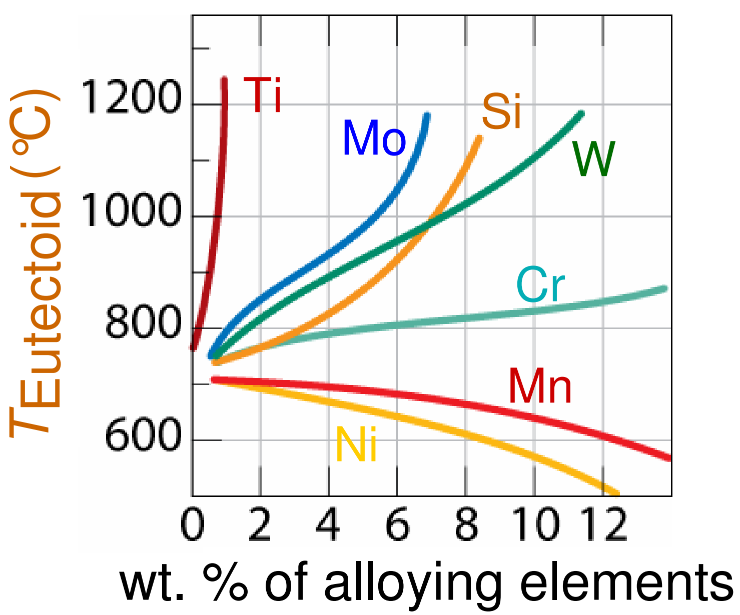


Effect of alloying elements on Fe-C phase diagram

- Most iron alloys such as austenitic and ferritic steels have many other alloying elements besides carbon.
- These alloying elements result in dramatic changes in the phase boundaries of the phase diagram.
- In particular, addition of other alloying elements result in significant shifts in the eutectoid temperature and concentration.
- This most important alloying aspect is the stabilization of FCC austenite phase all the way down to room temperature by adding Ni.
- Alloying elements are added to enhance various properties. But result in many other phases being deposited in the Fe-C base system.

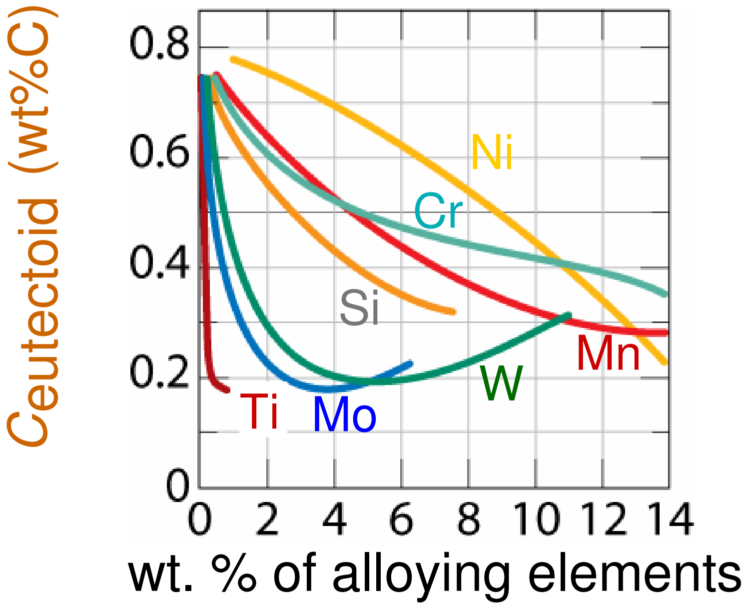
Alloying Steel with More Elements

- $T_{\text{eutectoid}}$ changes:



Adapted from Fig. 9.34,*Callister 7e*. (Fig. 9.34 from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 127.)

- $C_{\text{eutectoid}}$ changes:



Adapted from Fig. 9.35,*Callister 7e*. (Fig. 9.35 from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 127.)

Summary

- Phase diagrams are useful tools to determine:
  - --the number and types of phases,
  - --the wt% of each phase,
  - --and the composition of each phase

  for a given *T* and composition of the system.
- Alloying to produce a solid solution usually
  - --increases the tensile strength (*TS*)
  - --decreases the ductility.
- Binary eutectics and binary eutectoids allow for a range of microstructures.