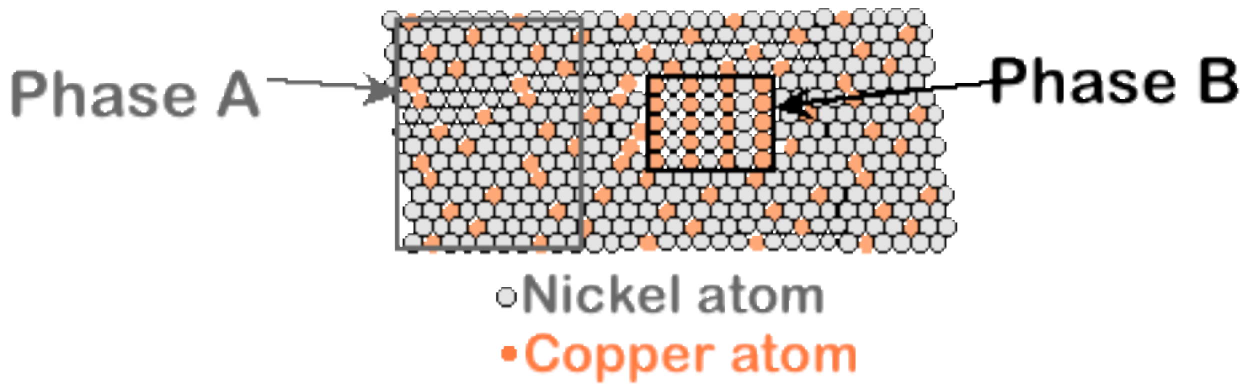
CHAPTER 9: PHASE DIAGRAMS

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?

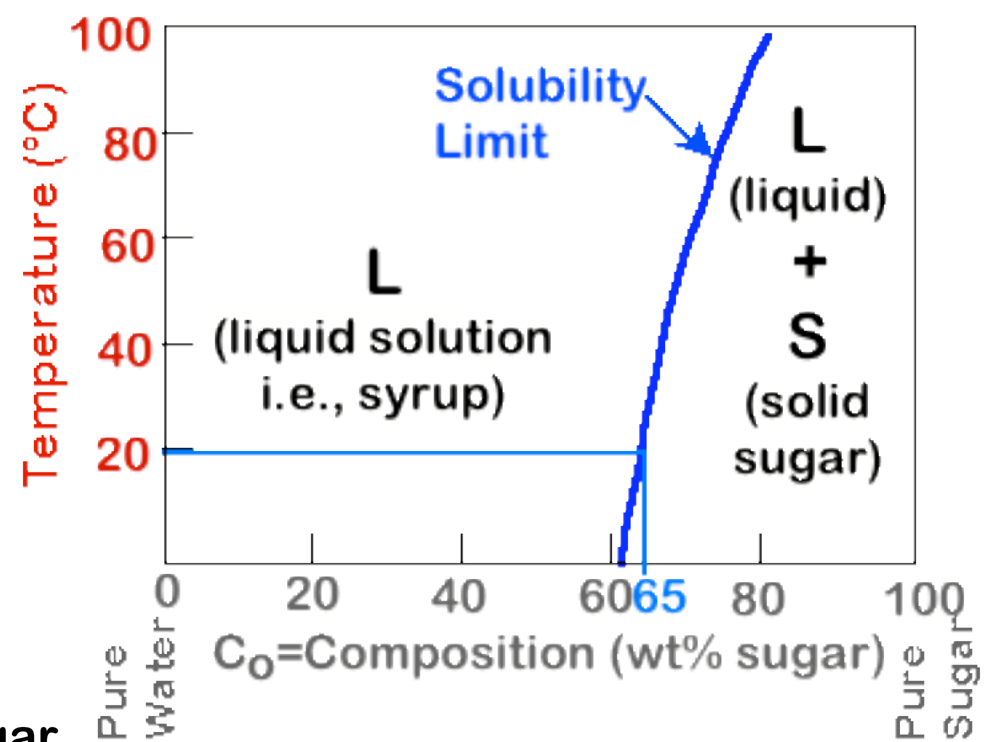


THE SOLUBILITY LIMIT

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

- **Ex: Phase Diagram: Water-Sugar System**

  Question: What is the solubility limit at 20C?
  Answer: 65wt% sugar.
  If C_o < 65wt% sugar: sugar
  If C_o > 65wt% sugar: syrup + sugar.



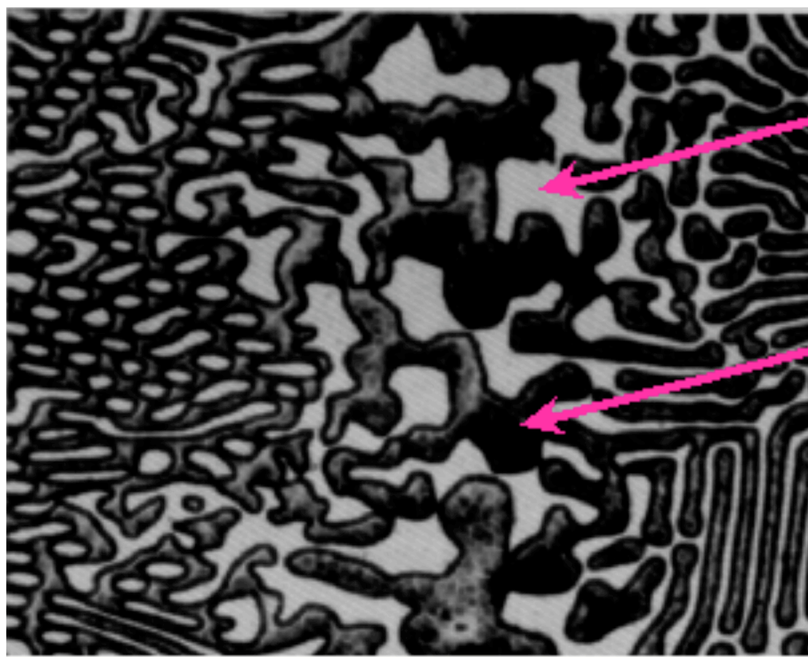
Adapted from Fig. 9.1, *Callister 6e.*

- **Solubility limit increases with T:**
  e.g., if T = 100C, solubility limit = 80wt% sugar.

COMPONENTS AND PHASES

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

Aluminum-
Copper
Alloy



β (lighter
phase)

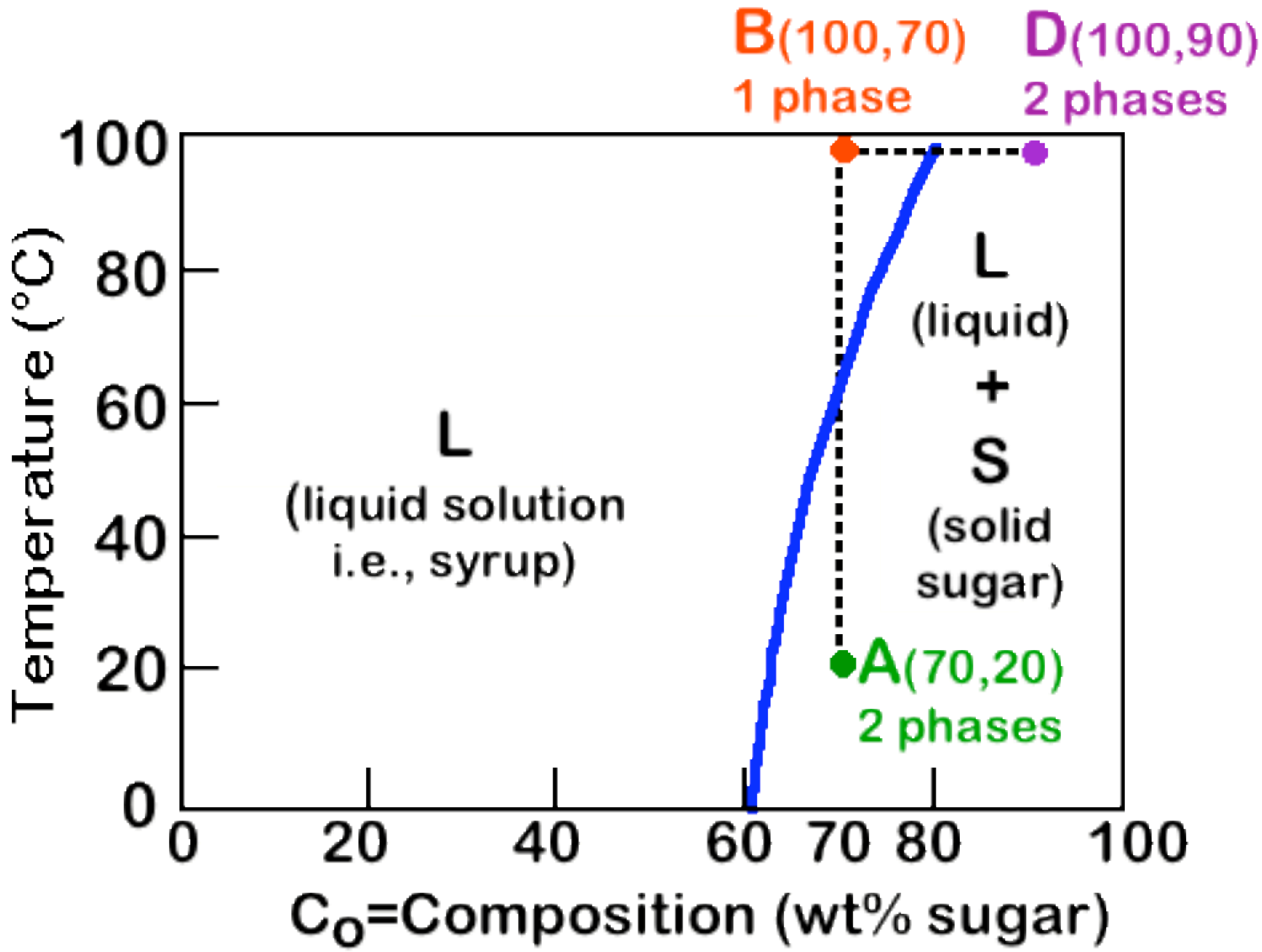
α (darker
phase)

Adapted from
Fig. 9.0,
Callister 3e.

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

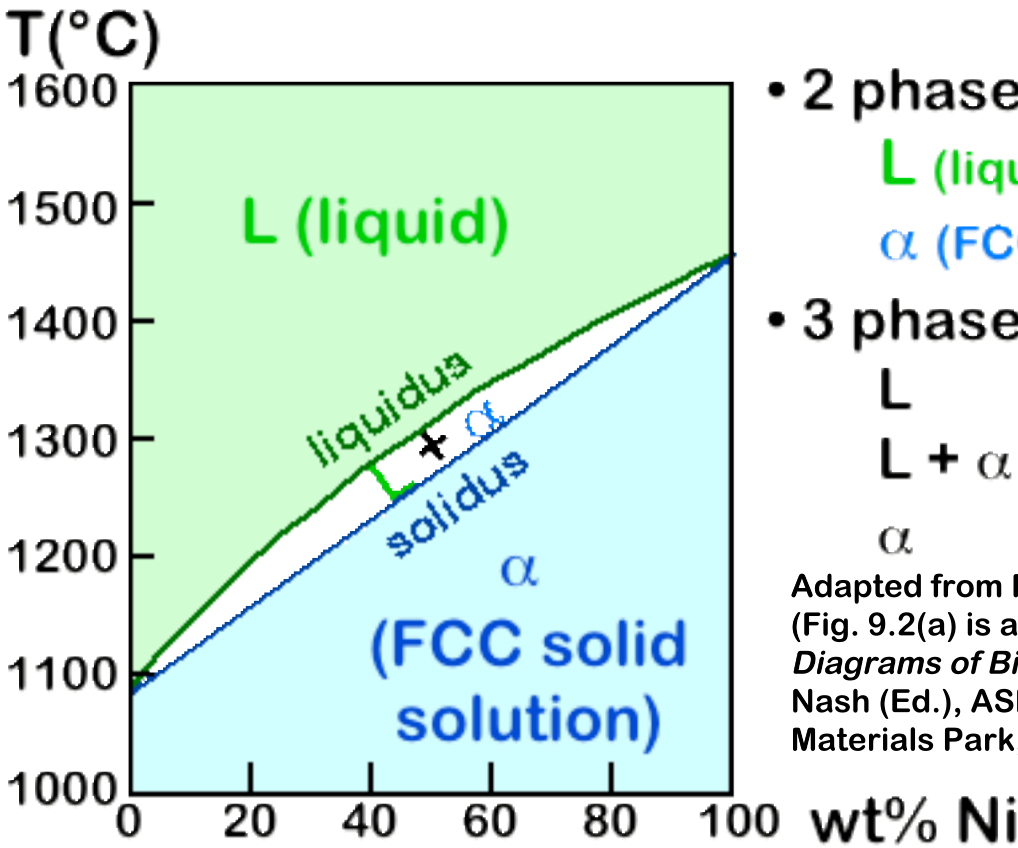


Adapted from
Fig. 9.1,
Callister 6e.

PHASE DIAGRAMS

- Tell us about phases as function of T, C_o, P.
- For this course:
  --binary systems: just 2 components.
  --independent variables: T and C_o (P = 1atm is always used).

- **Phase Diagram** for Cu-Ni system



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

Adapted from Fig. 9.2(a), *Callister 6e.* (Fig. 9.2(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

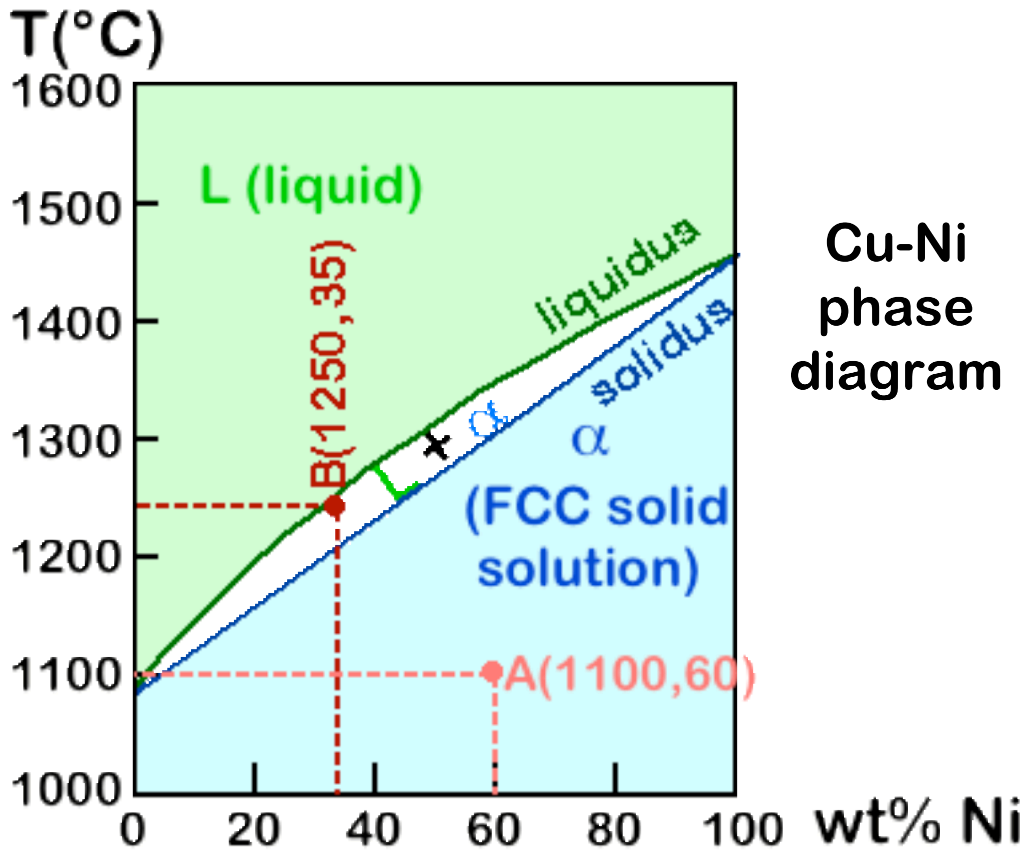
PHASE DIAGRAMS: # and types of phases

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

- **Examples:**

  A(1100, 60):
  1 phase: α

  B(1250, 35):
  2 phases: L + α



Cu-Ni phase diagram

Adapted from Fig. 9.2(a), *Callister 6e.* (Fig. 9.2(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 = 35wt%Ni

  At T_A:

  Only Liquid (L)

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

  At T_D:

  Only Solid (α)

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

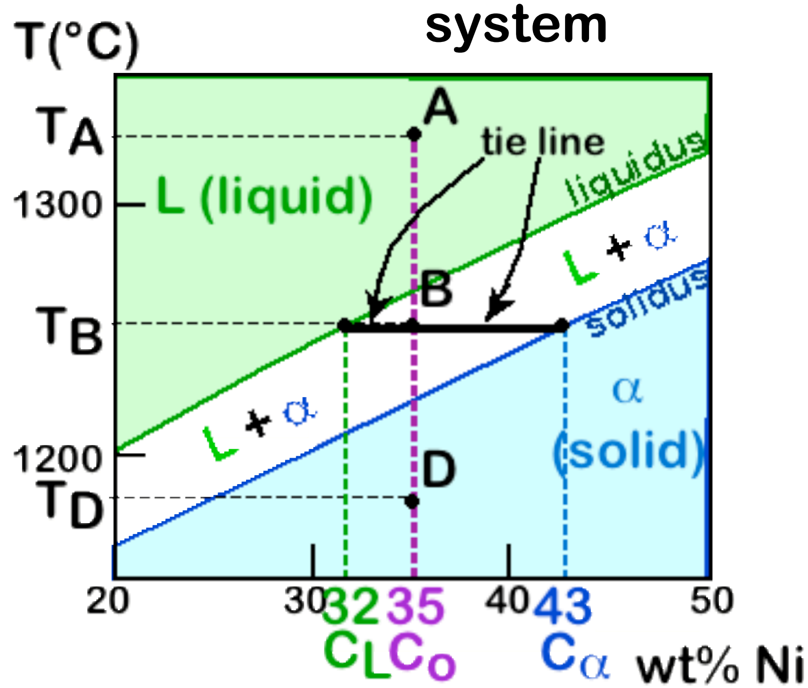
  At T_B:

  Both α and L

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

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

Cu-Ni system



Adapted from Fig. 9.2(b), *Callister 6e.* (Fig. 9.2(b) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH, 1991.)

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 = 35wt%Ni

At T_A: Only Liquid (L)

W_L = 100wt%, W_α = 0

At T_D: Only Solid (α)

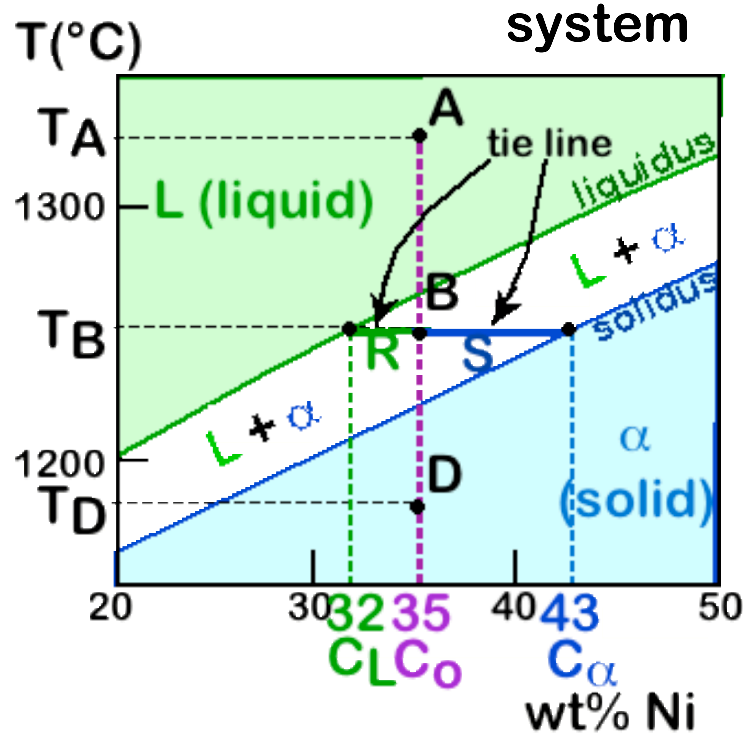
W_L = 0, W_α = 100wt%

At T_B: Both α and L

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

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

Cu-Ni system



Adapted from Fig. 9.2(b), *Callister 6e.* (Fig. 9.2(b) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH, 1991.)

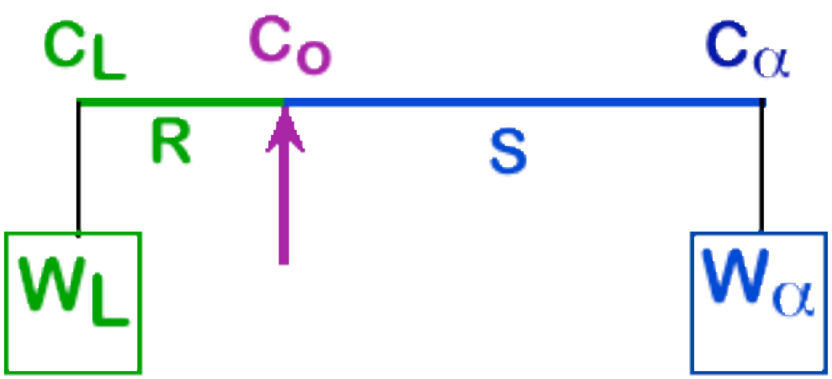
THE LEVER RULE: A PROOF

- Sum of weight fractions: $W_L + W_\alpha = 1$
- Conservation of mass (Ni): $C_o = W_L C_L + W_\alpha C_\alpha$
- Combine above equations:

$$W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L} = \frac{S}{R+S}$$

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

- A geometric interpretation:



moment equilibrium:

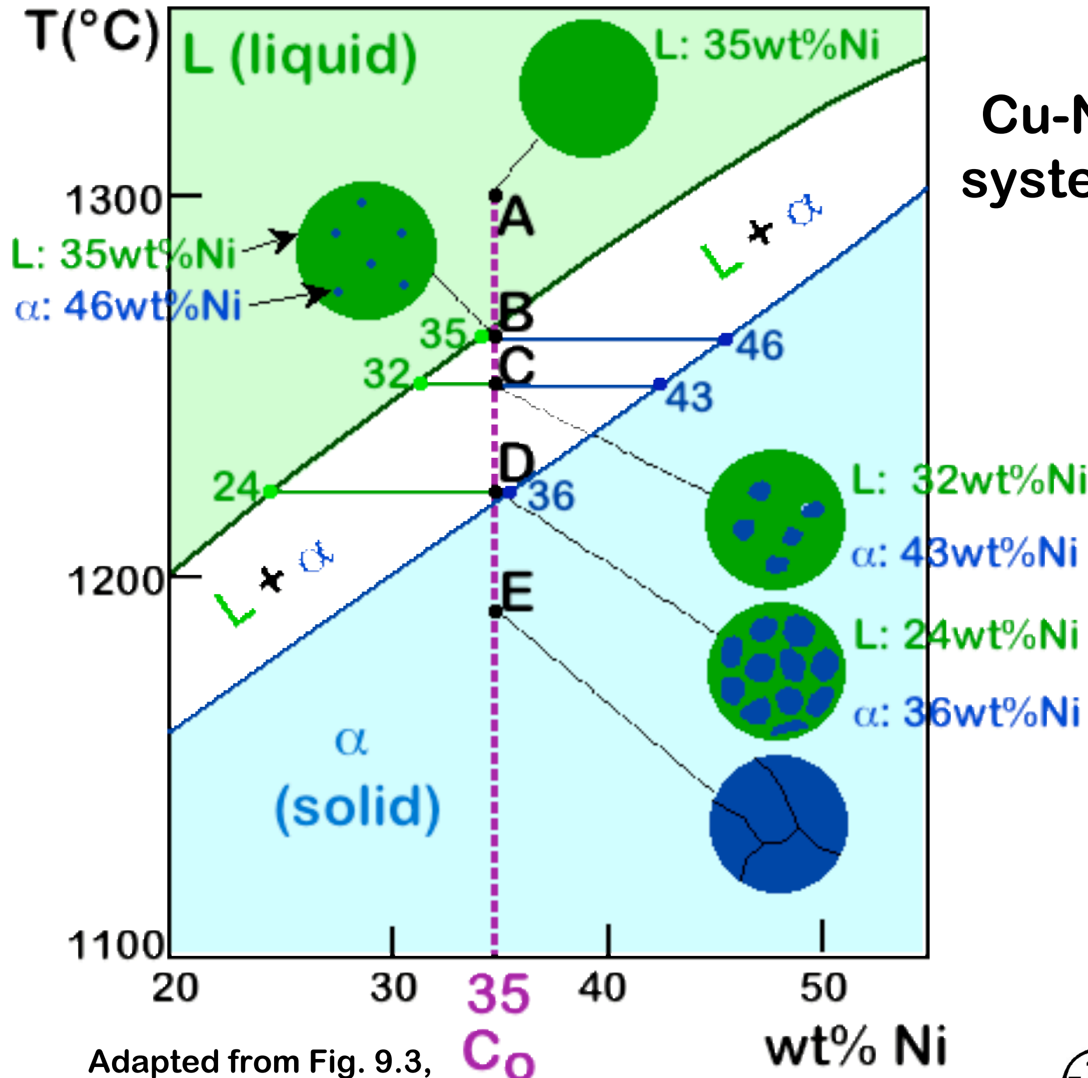
$$\boxed{W_L} R = W_\alpha S$$

$$\boxed{1 - W_\alpha}$$

solving gives Lever Rule

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; □ phase field extends from 0 to 100wt% Ni.
- **Consider** C_o = 35wt%Ni.



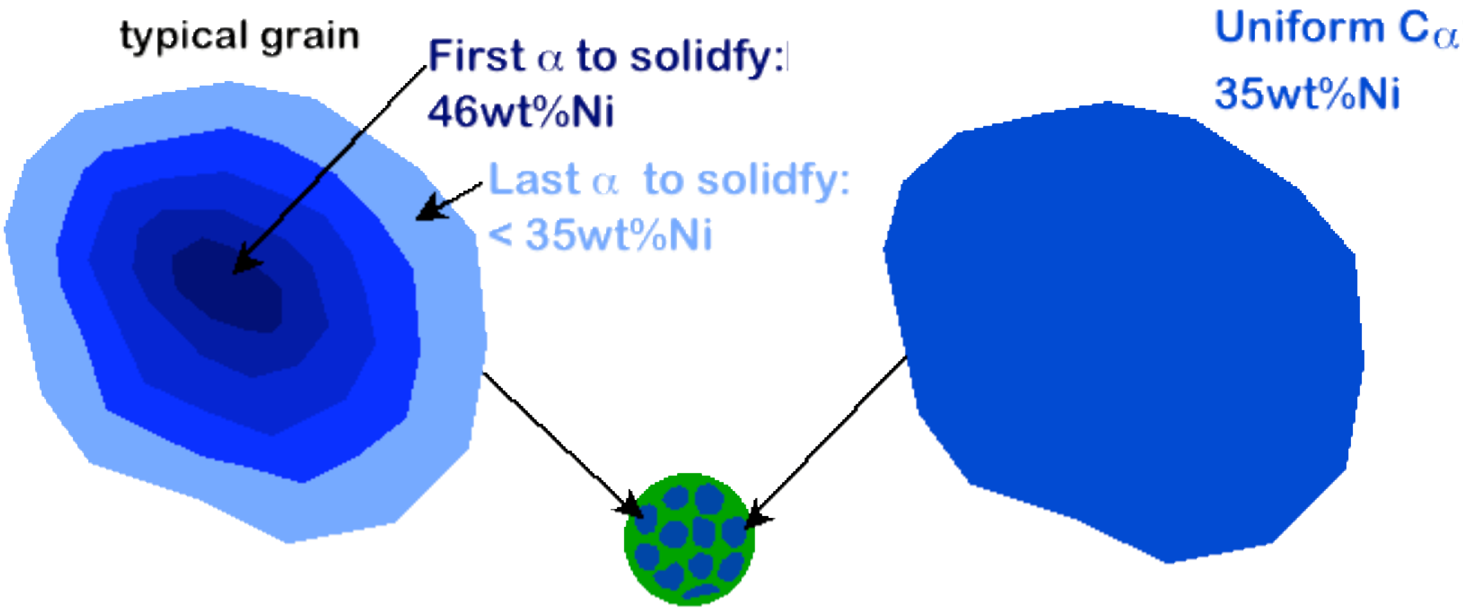
Cu-Ni system

Adapted from Fig. 9.3, *Callister 6e.*

CORED VS EQUILIBRIUM PHASES

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

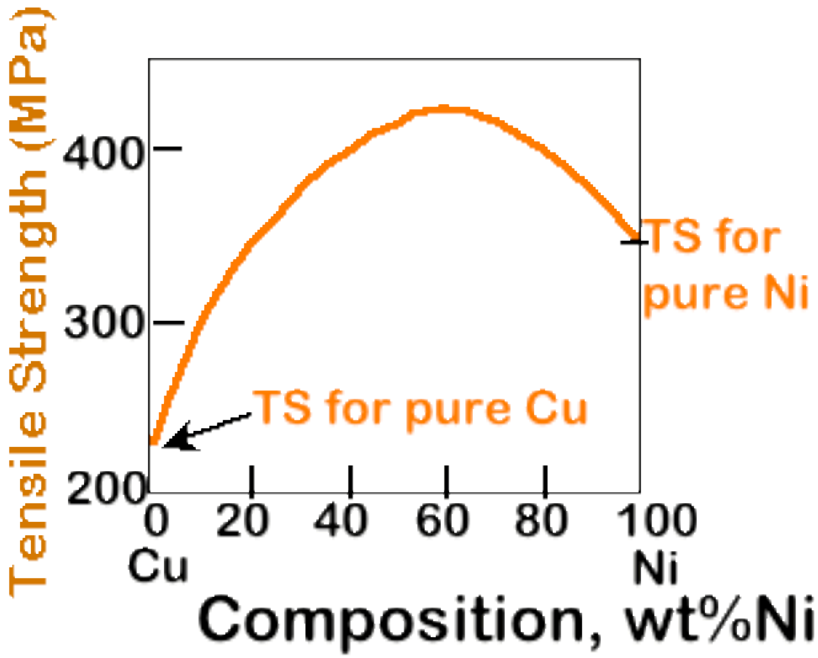
- Fast rate of cooling:
  Cored structure
- Slow rate of cooling:
  Equilibrium structure



MECHANICAL PROPERTIES: Cu-Ni System

- Effect of solid solution strengthening on:

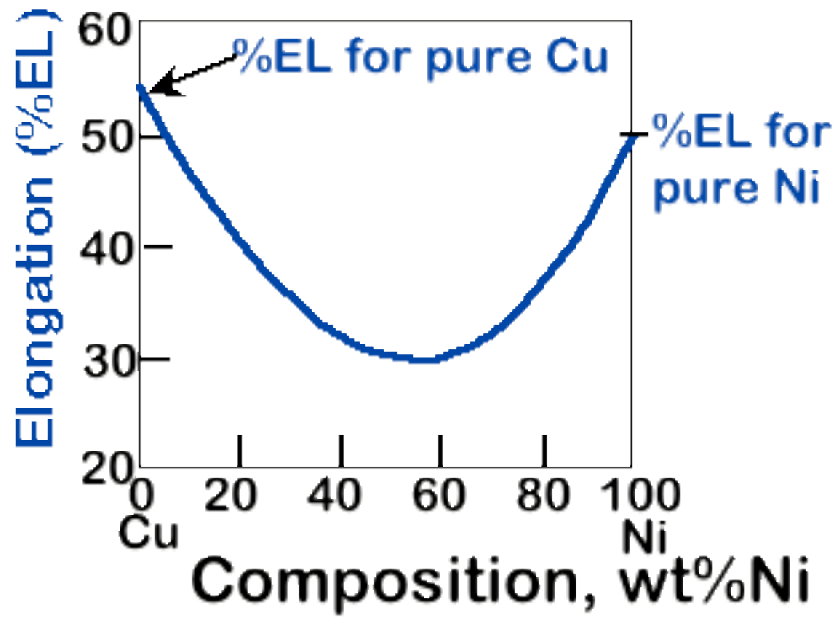
--Tensile strength (TS)



Adapted from Fig. 9.5(a), *Callister 6e.*

--Peak as a function of C_o

--Ductility (%EL,%AR)



Adapted from Fig. 9.5(b), *Callister 6e.*

--Min. as a function of C_o

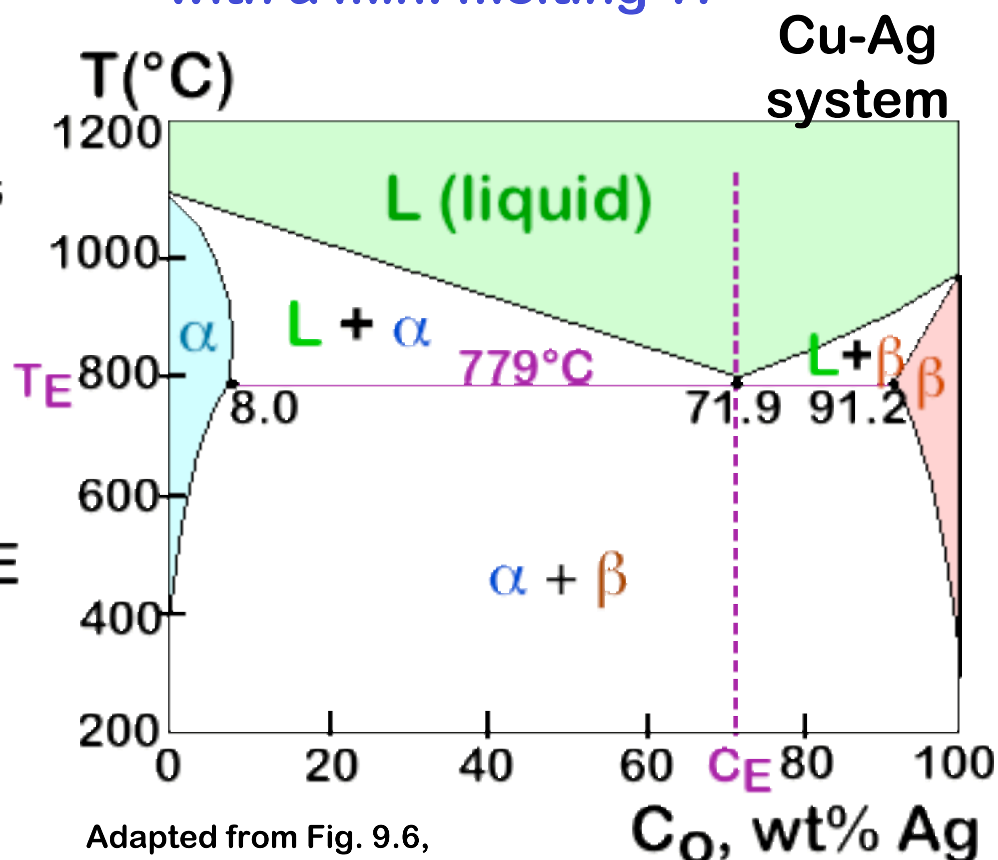
BINARY-EUTECTIC SYSTEMS

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 Ni
- T_E: No liquid below T_E
- C_E: Min. melting T composition

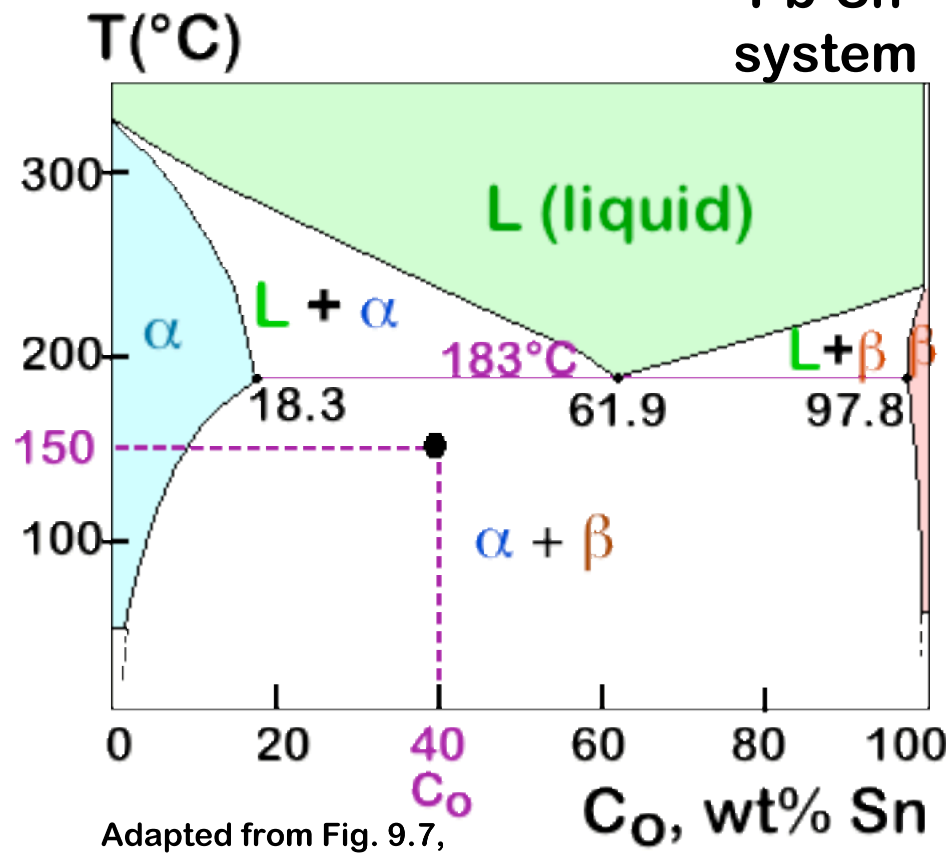


Adapted from Fig. 9.6, *Callister 6e.* (Fig. 9.6 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

EX: Pb-Sn EUTECTIC SYSTEM (1)

- For a 40wt%Sn-60wt%Pb alloy at 150C, find...
  - --the phases present: $\alpha + \beta$
  - --the compositions of the phases:

Pb-Sn system



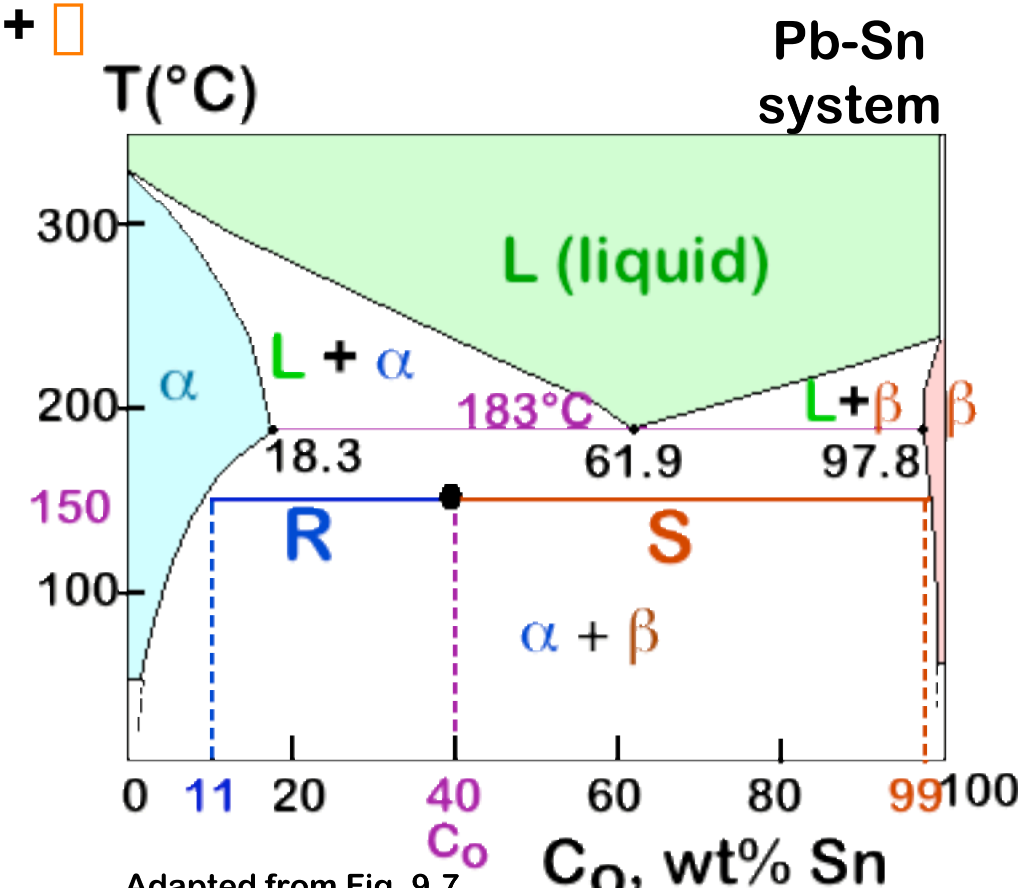
Adapted from Fig. 9.7, *Callister 6e.* (Fig. 9.7 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

EX: Pb-Sn EUTECTIC SYSTEM (2)

- For a 40wt%Sn-60wt%Pb alloy at 150C, find...
  - --the phases present: □ + □
  - --the compositions of the phases:
    - C□ = 11wt%Sn
    - C□ = 99wt%Sn
  - --the relative amounts of each phase:

$$W_{\alpha} = \frac{59}{88} = 67\text{wt\%}$$

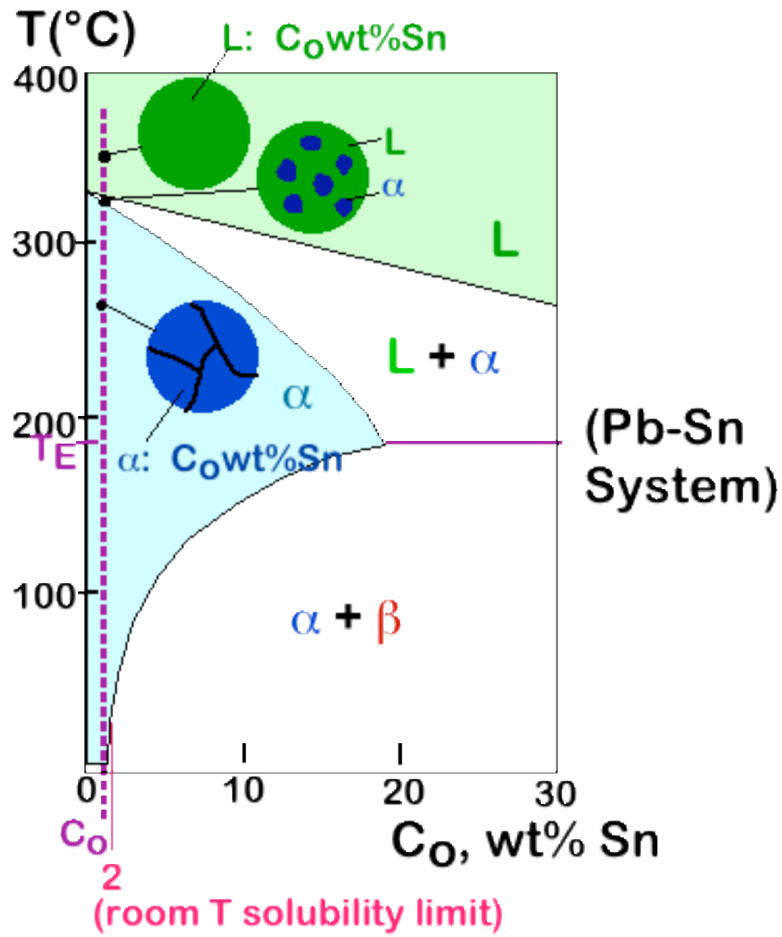
$$W_{\beta} = \frac{29}{88} = 33\text{wt\%}$$



Adapted from Fig. 9.7, *Callister 6e.* (Fig. 9.7 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

MICROSTRUCTURES IN EUTECTIC SYSTEMS-I

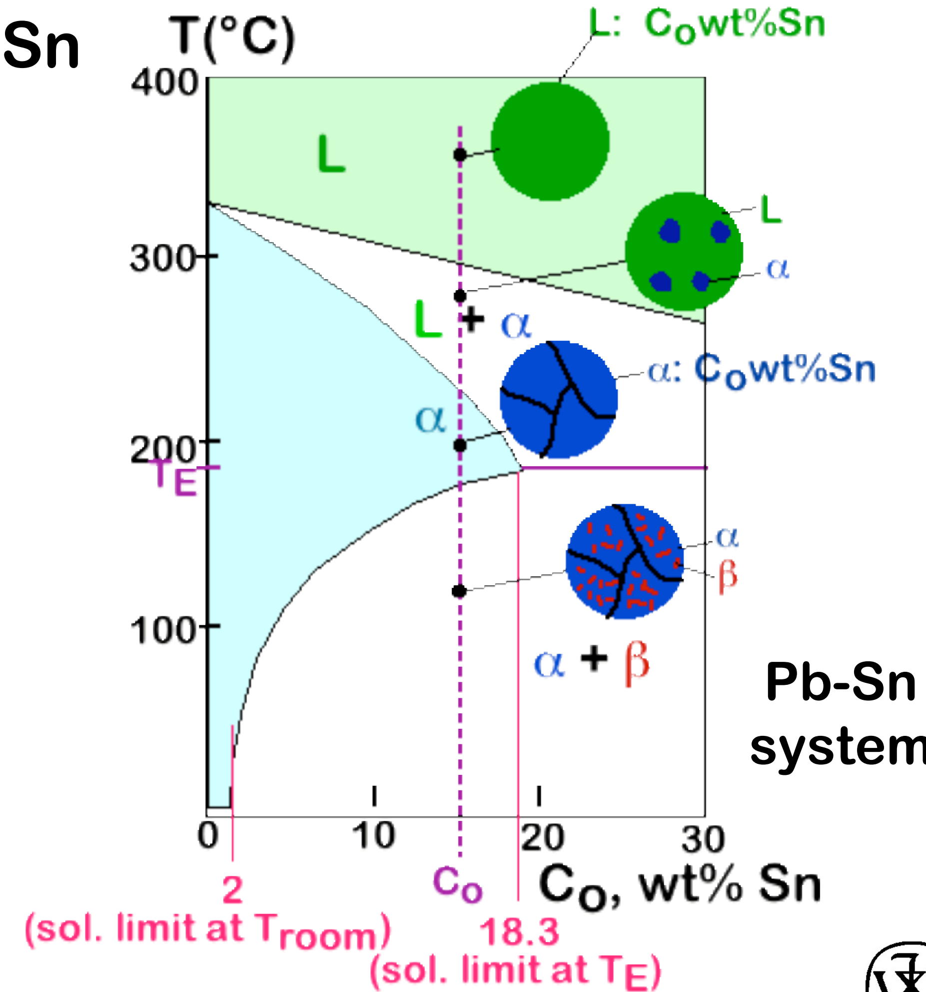
- C_o < 2wt%Sn
- Result:
  --polycrystal of grains.



Adapted from Fig. 9.9, *Callister 6e.*

MICROSTRUCTURES IN EUTECTIC SYSTEMS-II

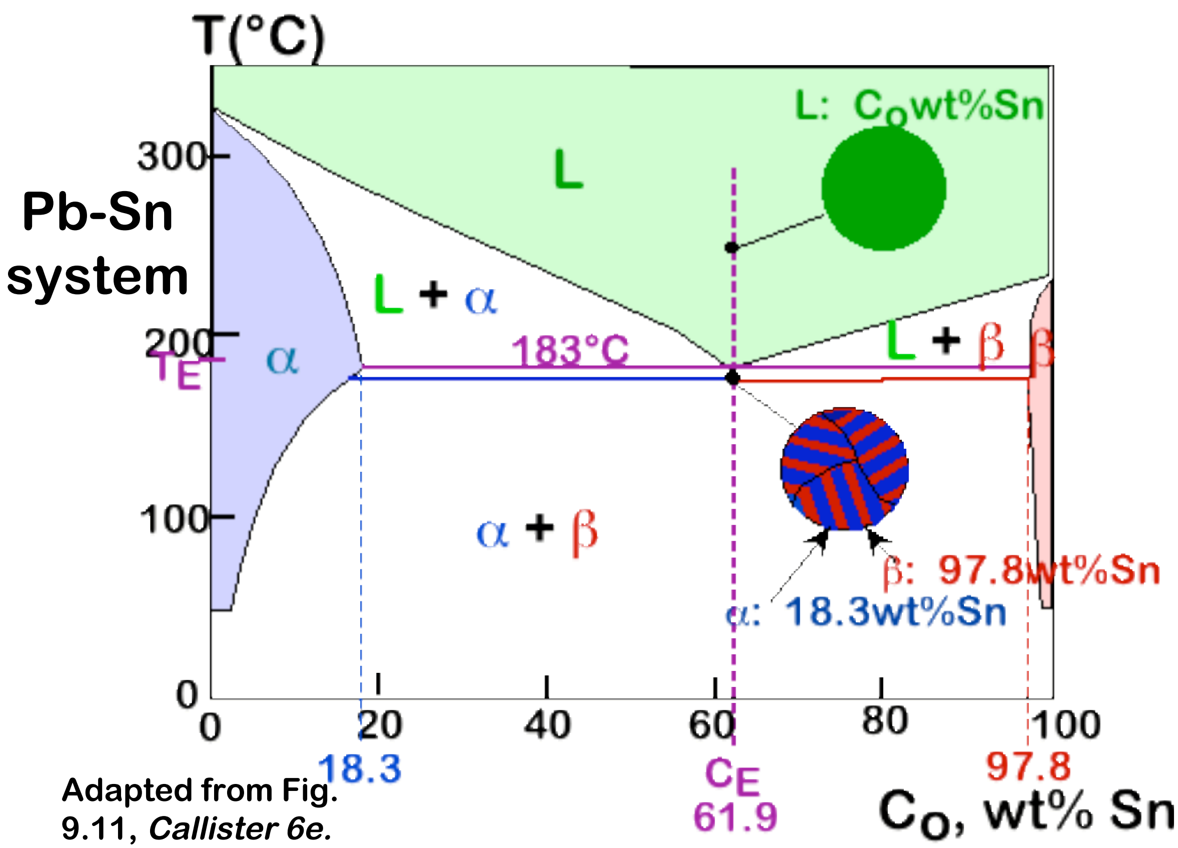
- 2wt%Sn < C_o < 18.3wt%Sn
- Result:
  --α polycrystal with fine β crystals.



Adapted from Fig. 9.10, *Callister 6e.*

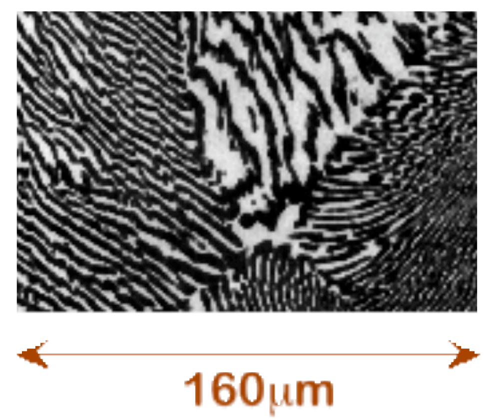
MICROSTRUCTURES IN EUTECTIC SYSTEMS-III

- $C_o = C_E$
- Result: Eutectic microstructure
  --alternating layers of α and β crystals.



Adapted from Fig. 9.11, *Callister 6e.*

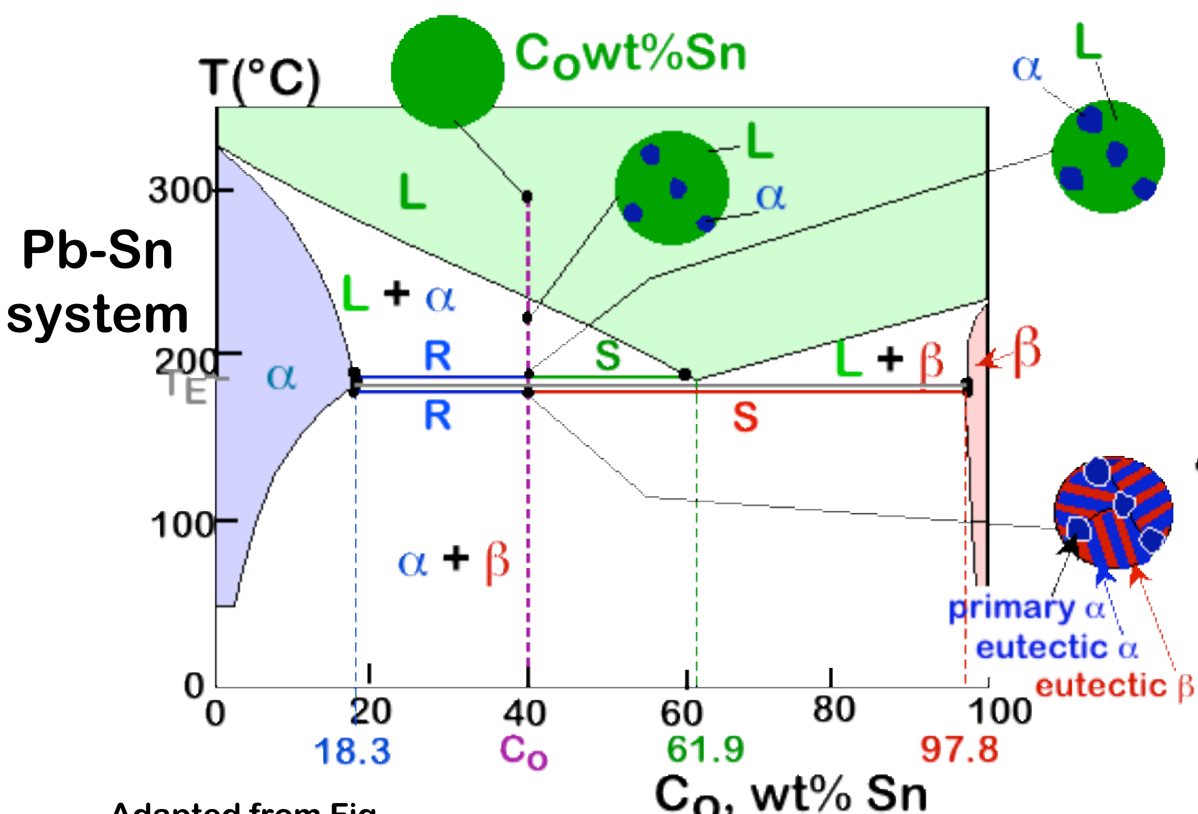
Micrograph of Pb-Sn eutectic microstructure



Adapted from Fig. 9.12, *Callister 6e.* (Fig. 9.12 from *Metals Handbook*, Vol. 9, 9th ed., *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)

MICROSTRUCTURES IN EUTECTIC SYSTEMS-IV

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



Adapted from Fig. 9.14, *Callister 6e.*

- Just above T_E:

  C_α = 18.3wt%Sn

  C_L = 61.9wt%Sn

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

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

- Just below T_E:

  C_α = 18.3wt%Sn

  C_β = 97.8wt%Sn

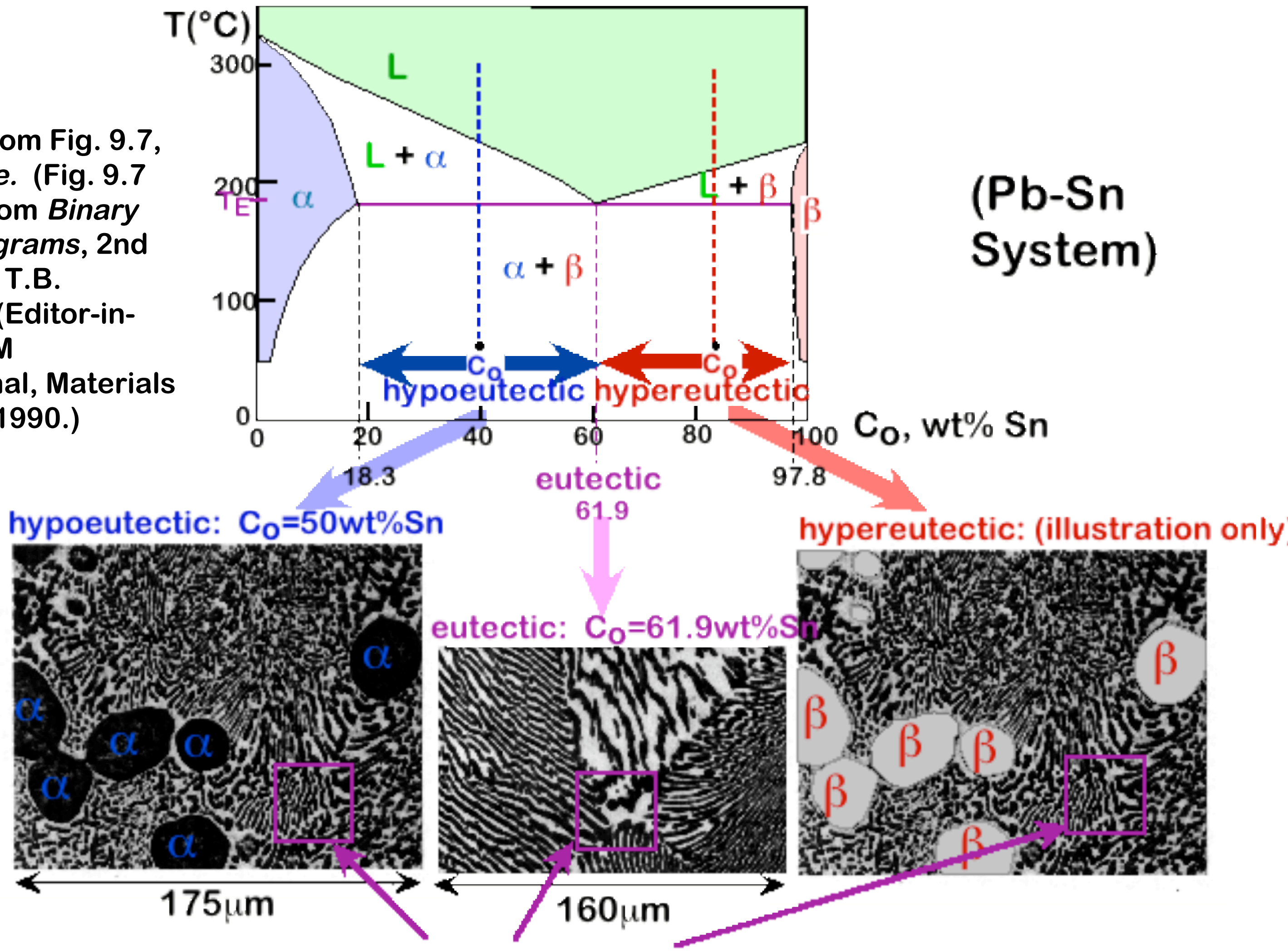
  $$W_\alpha = \frac{S}{R+S} = 73\text{wt\%}$$

  W_β = 27wt%

HYPOEUTECTIC & HYPEREUTECTIC

Adapted from Fig. 9.7, *Callister 6e.* (Fig. 9.7 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

(Figs. 9.12 and 9.15 from *Metals Handbook*, 9th ed., Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)



Adapted from Fig. 9.15, *Callister 6e.*

Adapted from Fig. 9.12, *Callister 6e.*

Adapted from Fig. 9.15, *Callister 6e.* (Illustration only)

IRON-CARBON (Fe-C) PHASE DIAGRAM

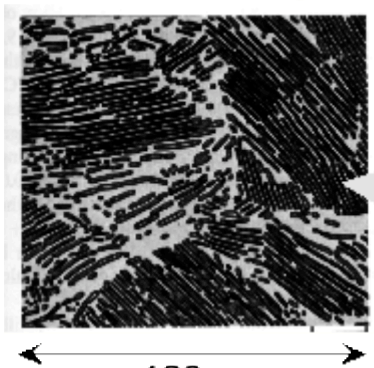
- 2 important points

-Eutectic (A):

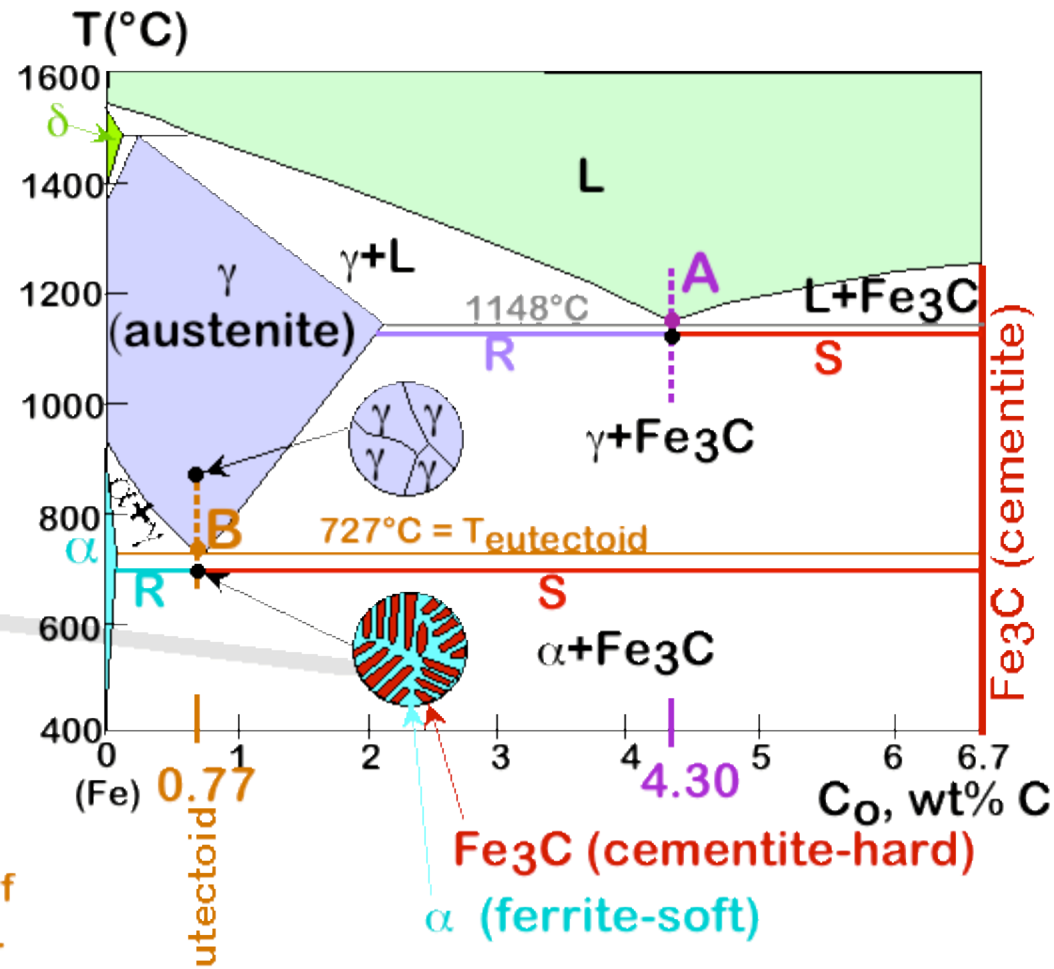
$L \Rightarrow \gamma + Fe_3C$

-Eutectoid (B):

$\gamma \Rightarrow \alpha + Fe_3C$



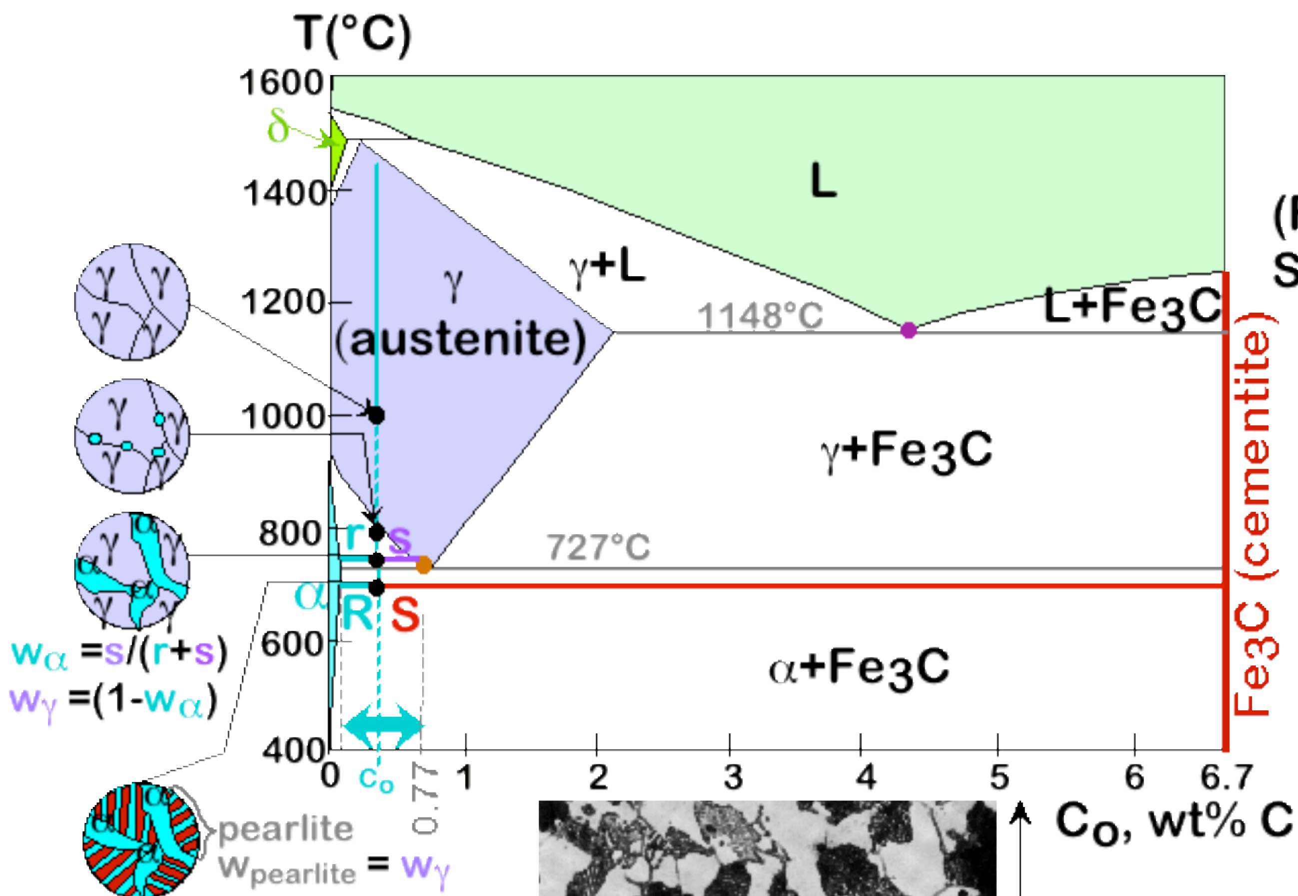
Result: Pearlite = alternating layers of α and Fe_3C phases.



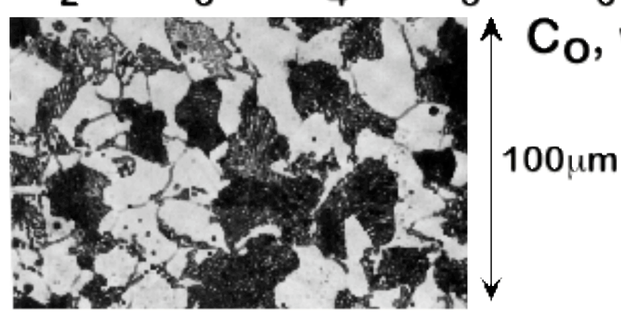
(Adapted from Fig. 9.24, *Callister 6e.* (Fig. 9.24 from *Metals Handbook*, 9th ed., Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)

Adapted from Fig. 9.21,*Callister 6e.* (Fig. 9.21 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

HYPOEUTECTOID STEEL



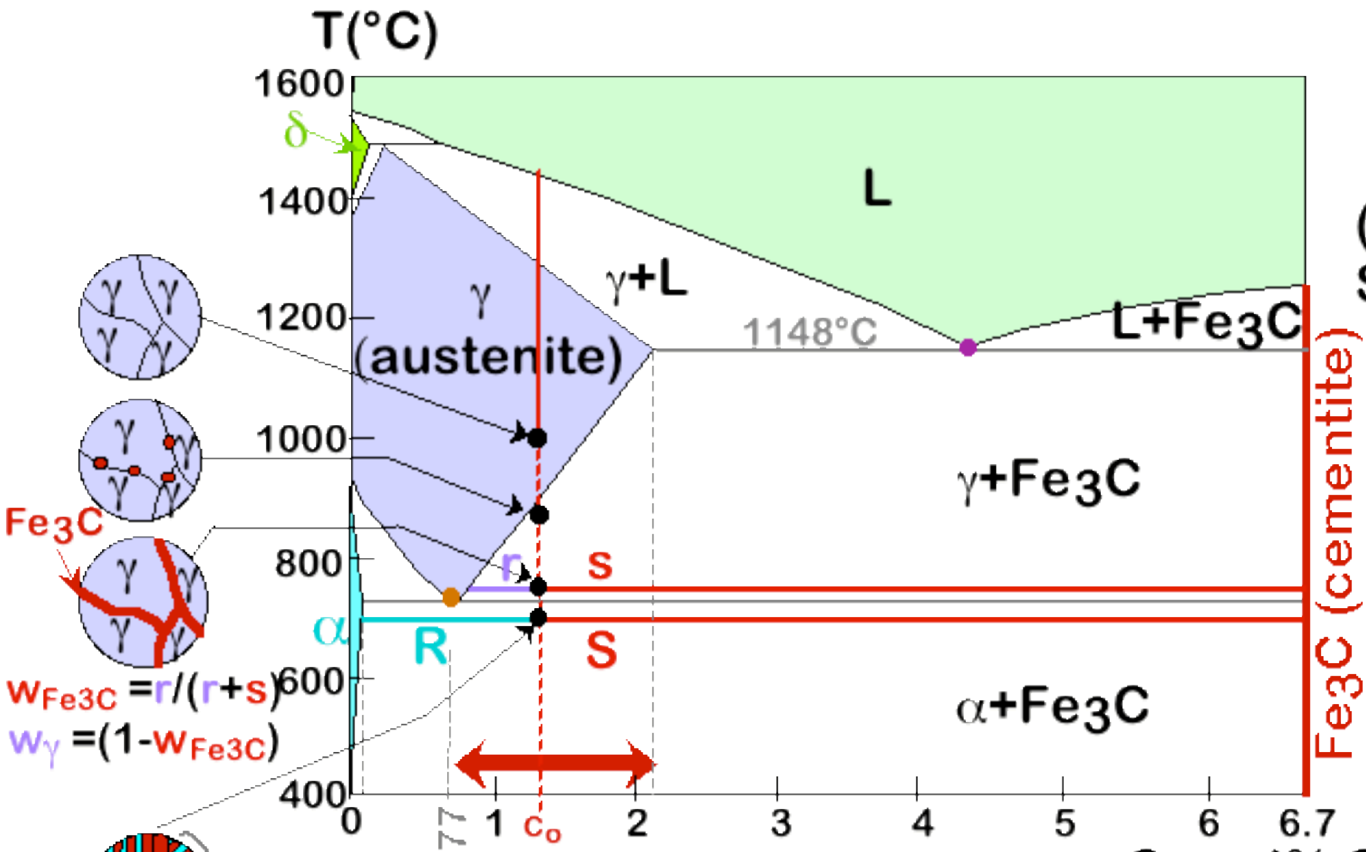
Adapted from Figs. 9.21 and 9.26, *Callister 6e*. (Fig. 9.21 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)



Hypoeutectoid steel

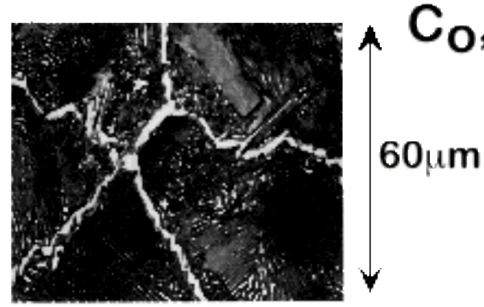
Adapted from Fig. 9.27, *Callister 6e*. (Fig. 9.27 courtesy Republic Steel Corporation.)

HYPEREUTECTOID STEEL



(Fe-C System)

Adapted from Figs. 9.21 and 9.29, *Callister 6e.* (Fig. 9.21 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

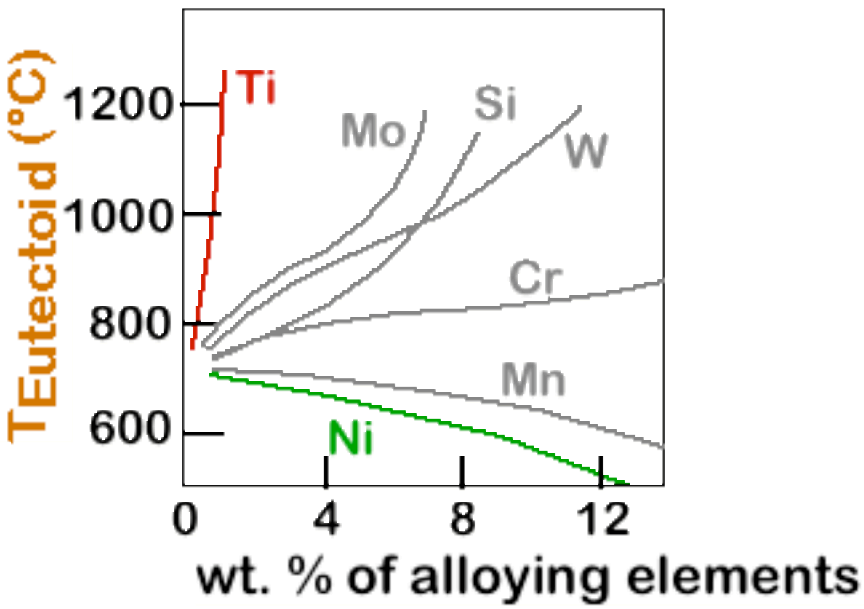


Hypereutectoid steel

Adapted from Fig. 9.30, *Callister 6e.* (Fig. 9.30 copyright 1971 by United States Steel Corporation.)

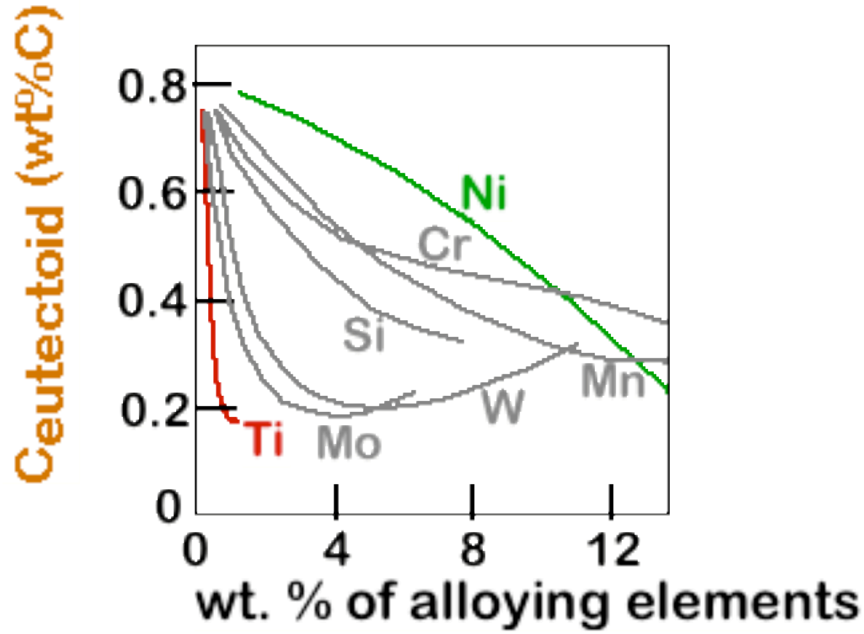
ALLOYING STEEL WITH MORE ELEMENTS

- $T_{eutectoid}$ changes:



Adapted from Fig. 9.31, *Callister 6e*. (Fig. 9.31 from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 127.)

- $C_{eutectoid}$ changes:



Adapted from Fig. 9.32, *Callister 6e*. (Fig. 9.32 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.

ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems: