

CHAPTER 9: PHASE DIAGRAMS

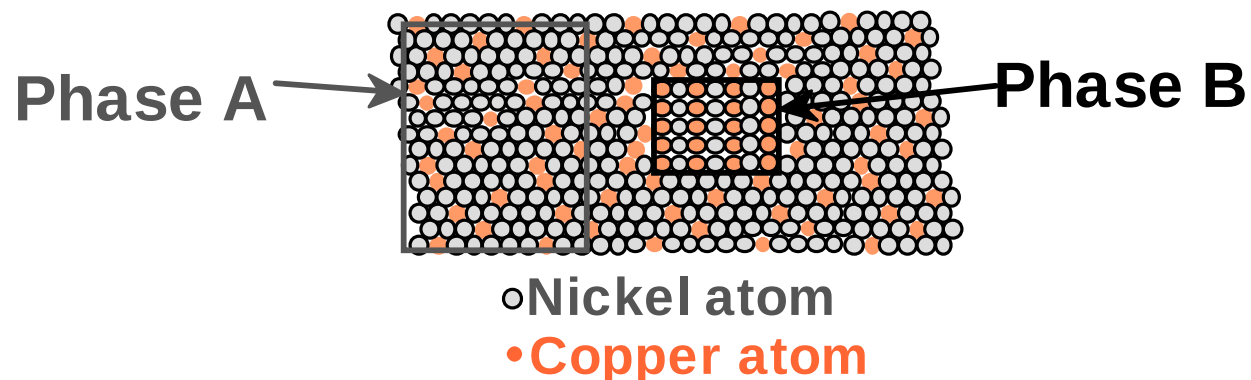
ISSUES TO ADDRESS...

- 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

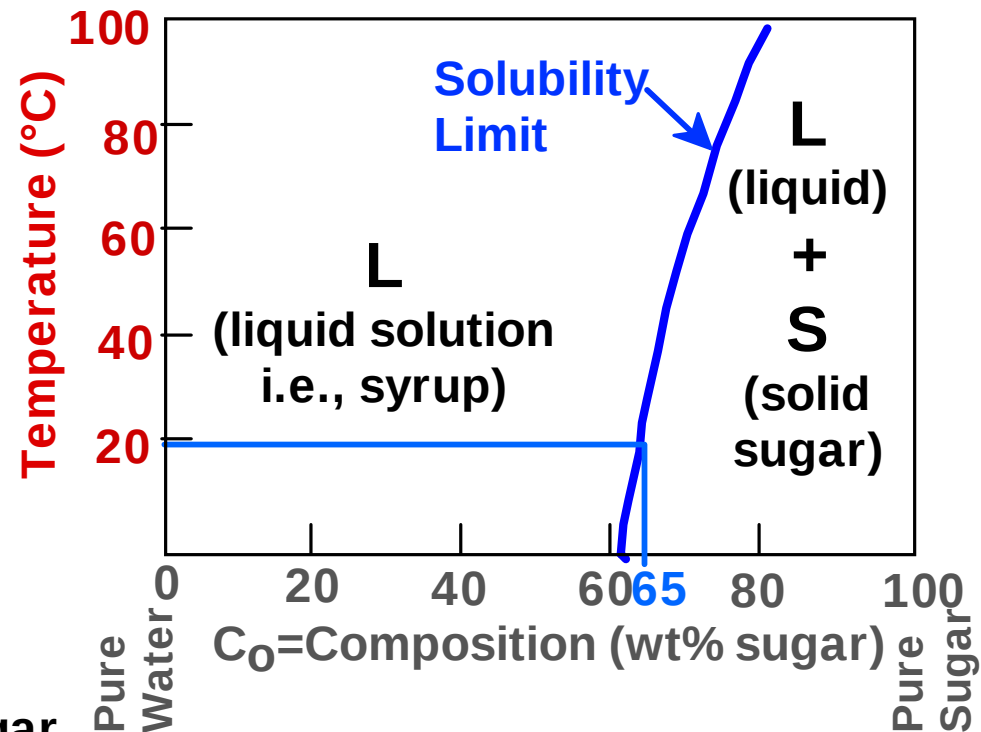
- **Solubility Limit:**
Max concentration for which only a solution occurs.
- **Ex: Phase Diagram: Water-Sugar System**

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

Answer: **65wt% sugar**.

If $C_0 < 65\text{wt\% sugar}$: sugar

If $C_0 > 65\text{wt\% sugar}$: syrup + sugar.



Adapted from Fig. 9.1,
Callister 6e.

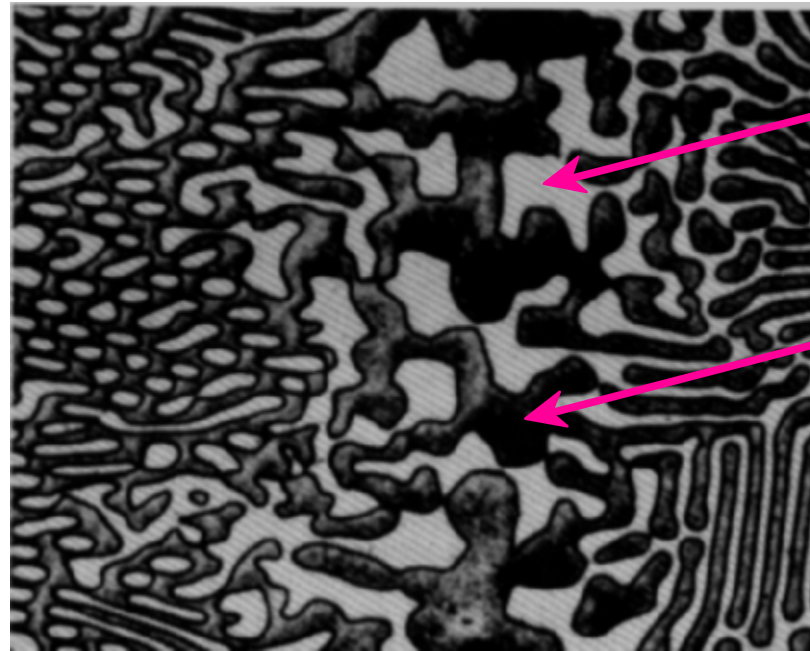
- **Solubility limit increases with T:**
e.g., if $T = 100\text{C}$, solubility limit = 80wt% sugar.

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

Adapted from
Fig. 9.0,
Callister 3e.



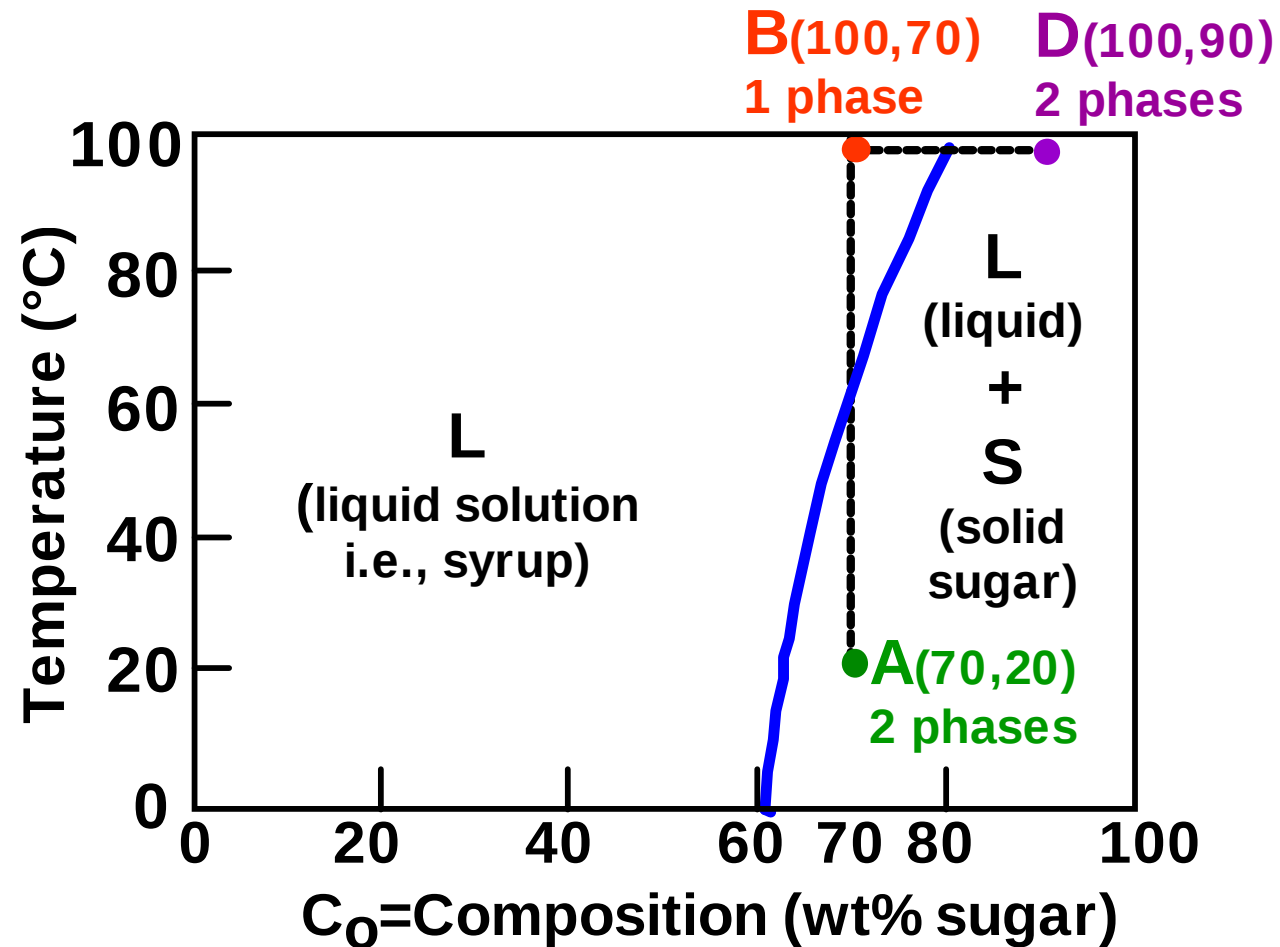
β (lighter
phase)

α (darker
phase)

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

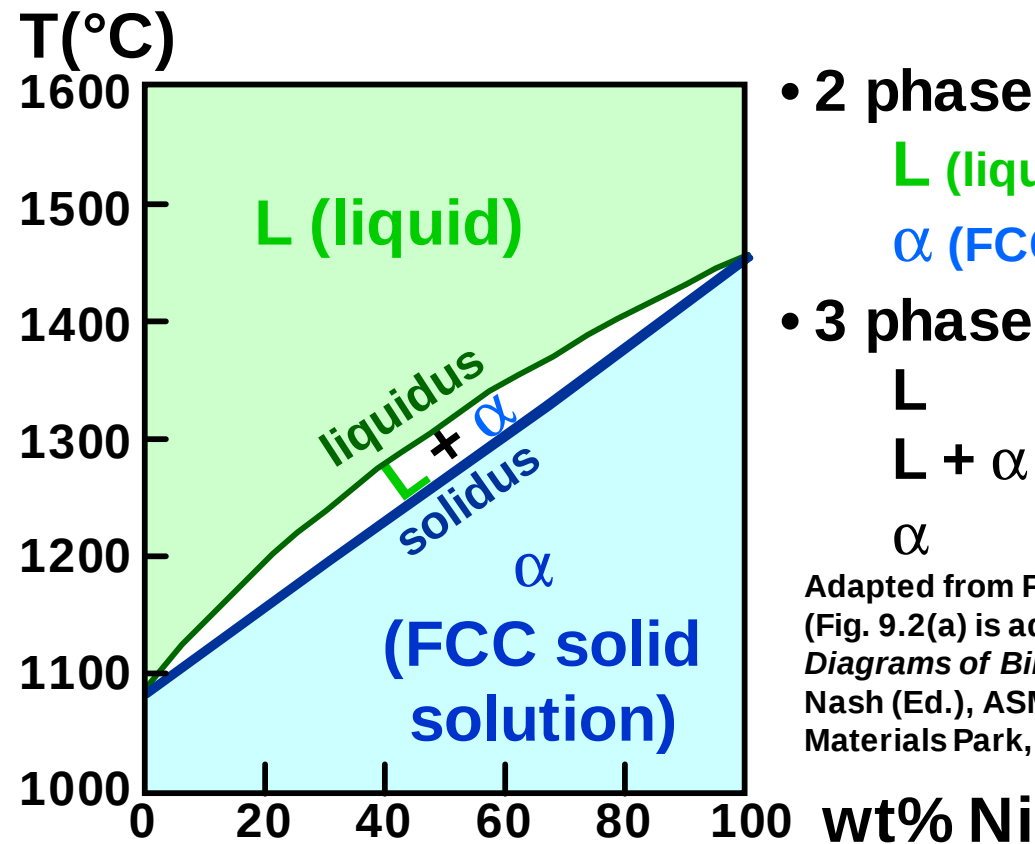


Adapted from
Fig. 9.1,
Callister 6e.

PHASE DIAGRAMS

- Tell us about phases as function of T , C_0 , P .
- For this course:
 - binary systems: just 2 components.
 - independent variables: T and C_0 ($P = 1\text{atm}$ 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

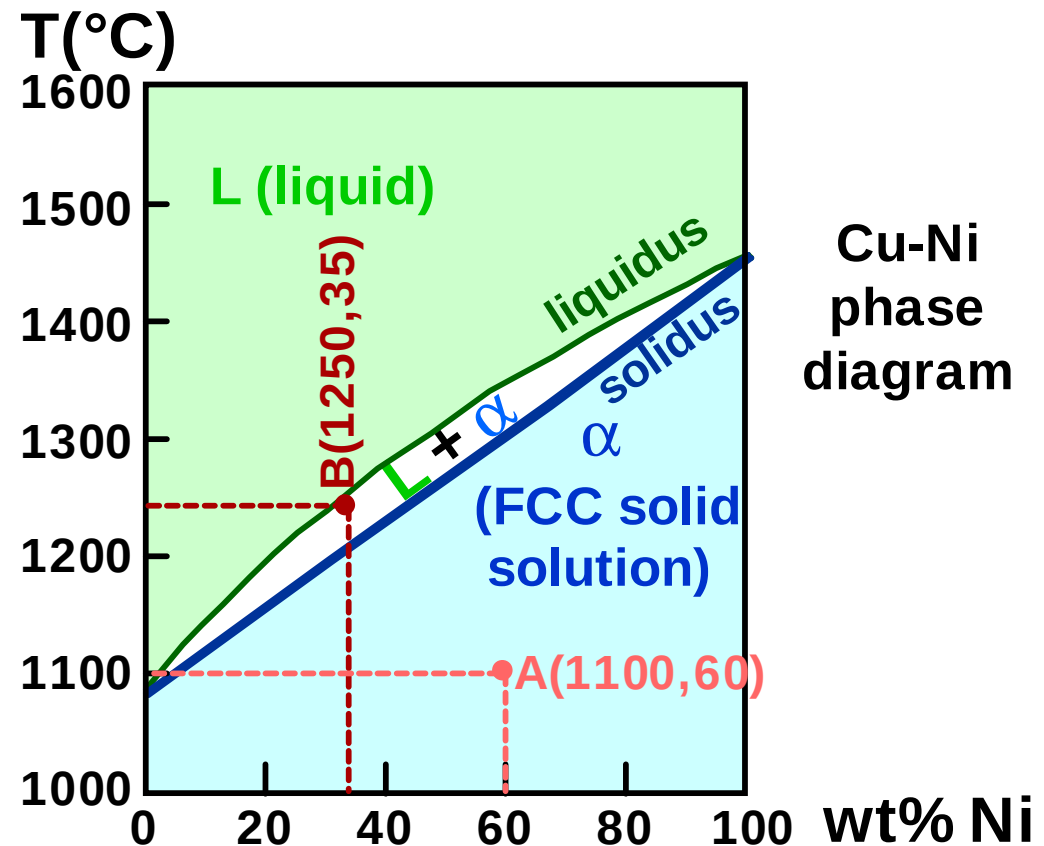
- **Rule 1:** If we know T and C_0 , then we know:
 - the # and types of phases present.

- **Examples:**

A(1100, 60):
1 phase: α

B(1250, 35):
2 phases: $L + \alpha$

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_0 , then we know:
 - the composition of each phase.

- Examples:

$C_0 = 35\text{wt\%Ni}$

At T_A :

Only Liquid (L)

$C_L = C_0 (= 35\text{wt\% Ni})$

At T_D :

Only Solid (α)

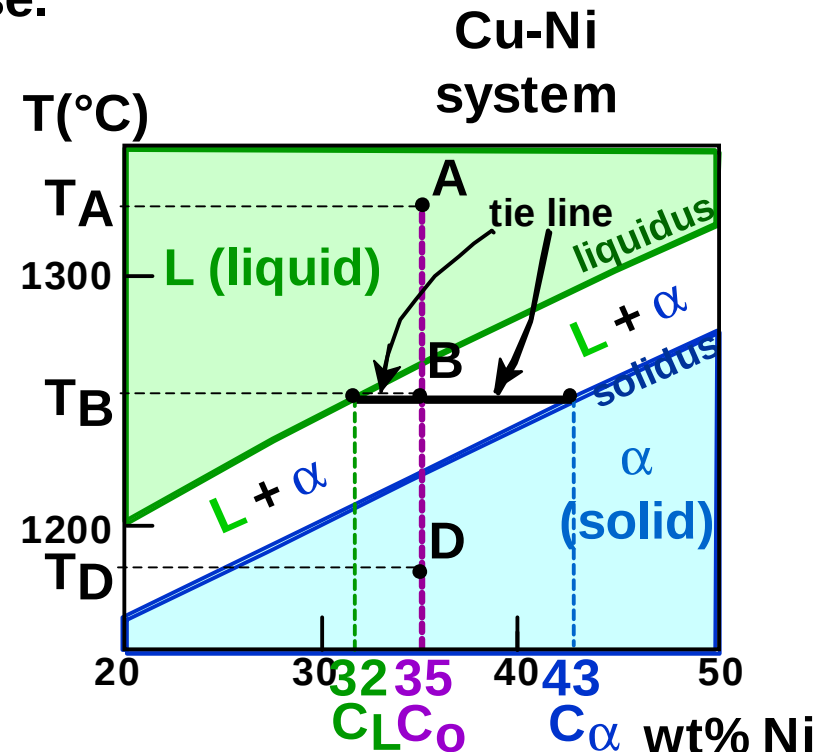
$C_\alpha = C_0 (= 35\text{wt\% Ni})$

At T_B :

Both α and L

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

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



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 C₀, then we know:
--the amount of each phase (given in wt%).

- Examples:

C₀ = 35wt%Ni

At T_A: Only Liquid (L)

W_L = 100wt%, W_α = 0

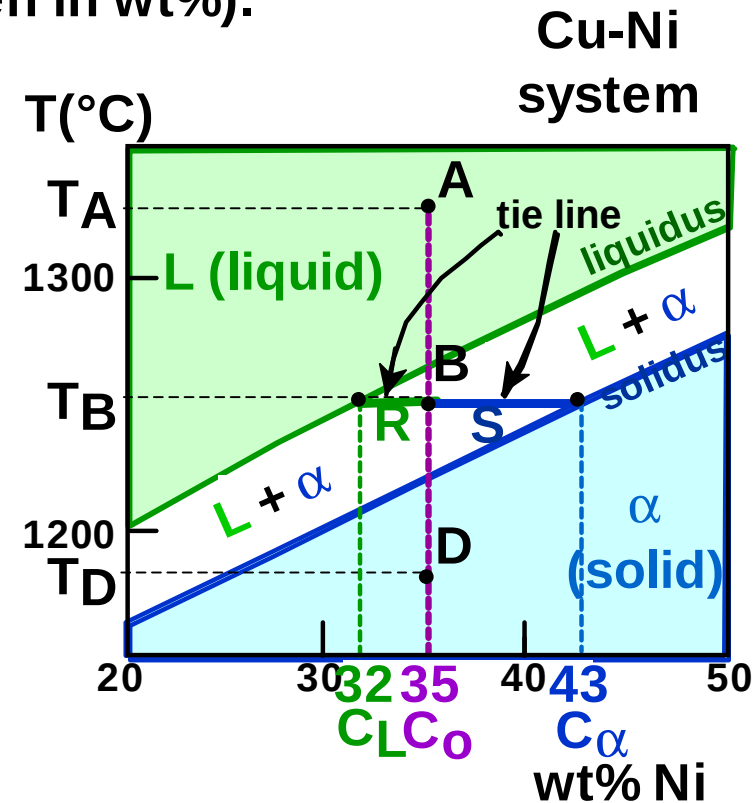
At T_D: Only Solid (α)

W_L = 0, W_α = 100wt%

At T_B: Both α and L

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

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



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.)

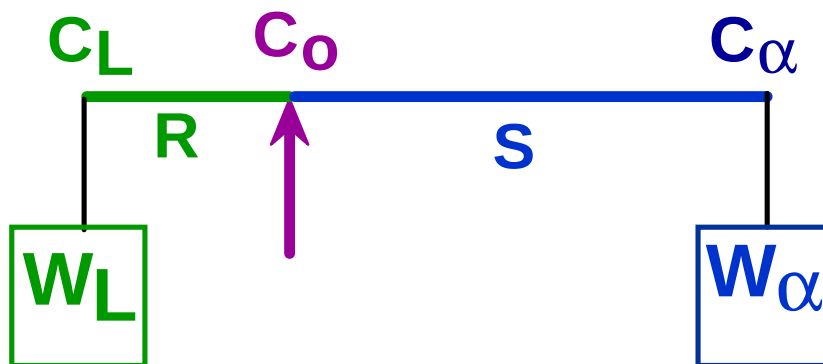
THE LEVER RULE: A PROOF

- 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:

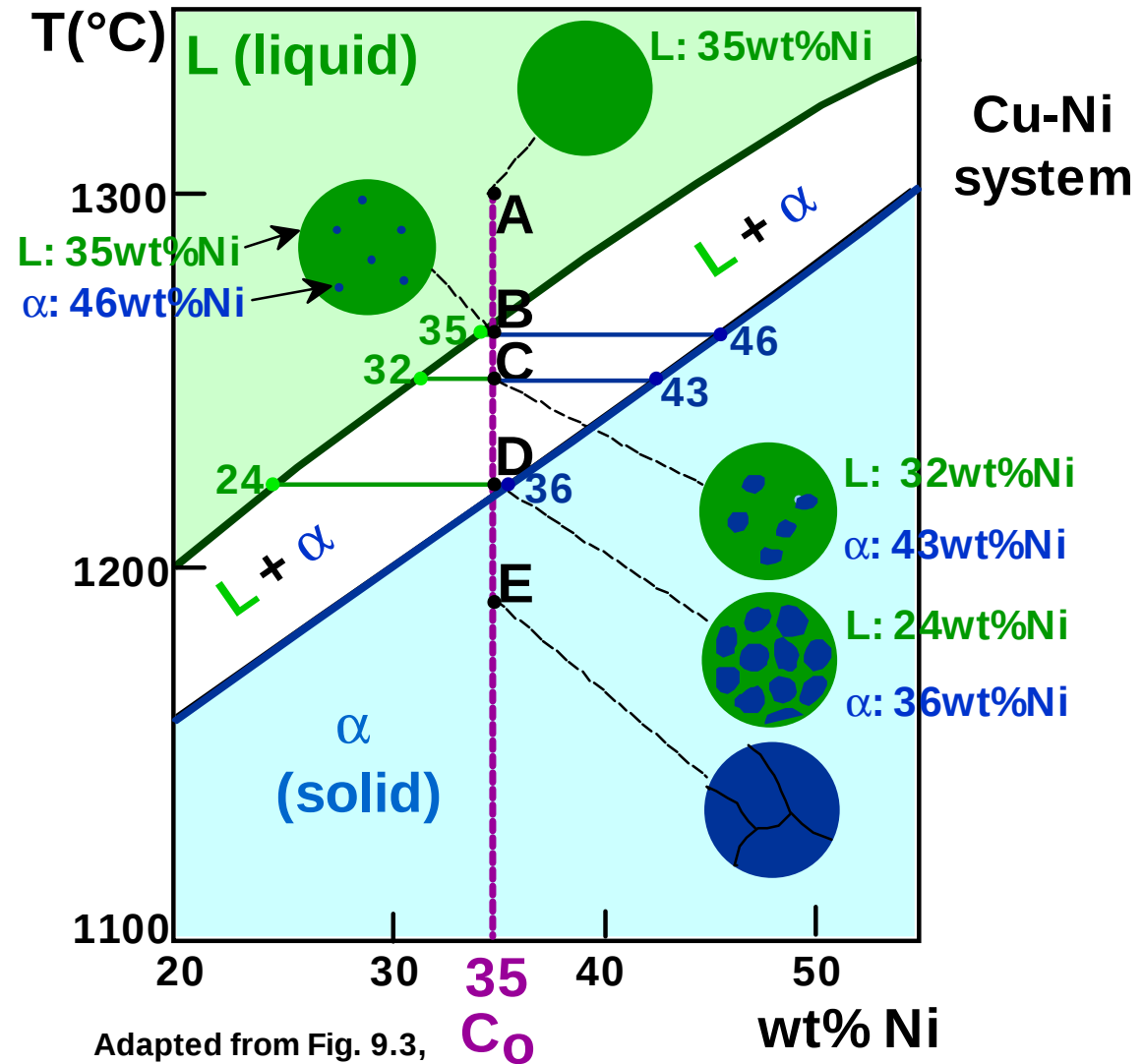
$$W_L R = W_\alpha S$$

$\boxed{1 - W_\alpha}$

solving gives Lever Rule

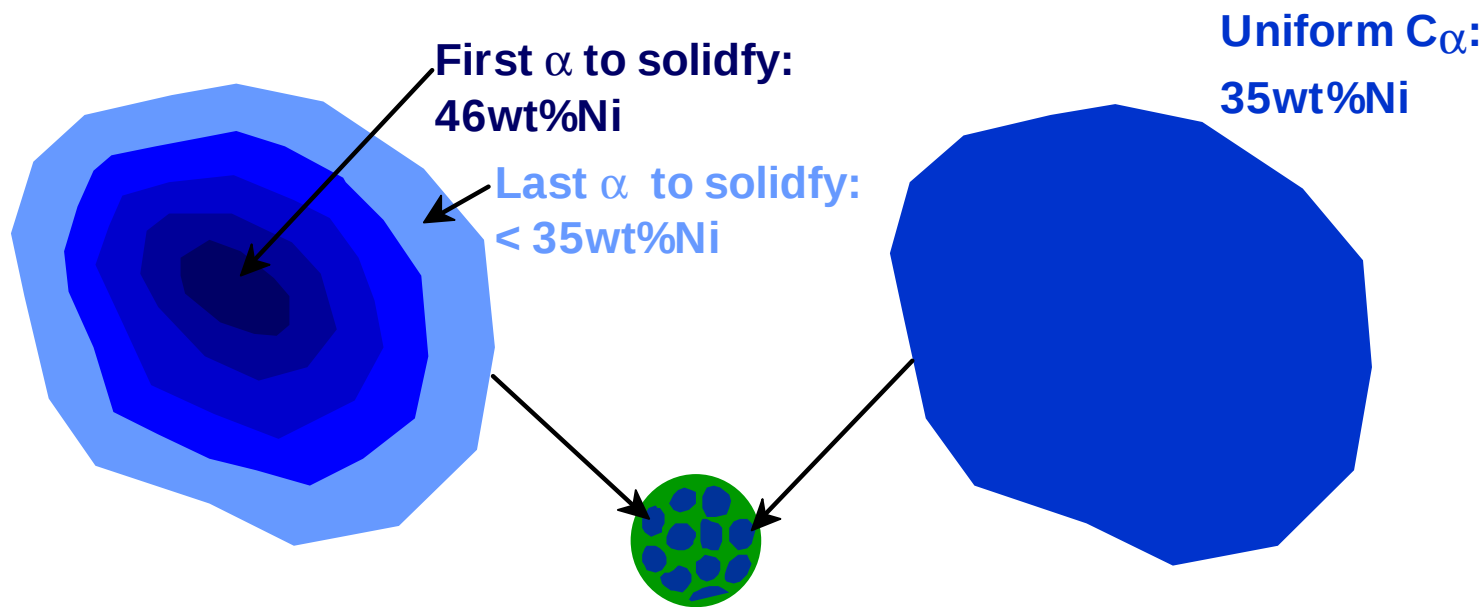
EX: COOLING IN A Cu-Ni BINARY

- 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; α phase field extends from 0 to 100wt% Ni.
- Consider $C_0 = 35\text{wt\%Ni}$.



CORED VS EQUILIBRIUM PHASES

- C_α changes as we solidify.
- **Cu-Ni case:** First α to solidify has $C_\alpha = 46\text{wt\%Ni}$.
Last α to solidify has $C_\alpha = 35\text{wt\%Ni}$.
- **Fast rate of cooling:**
Cored structure
- **Slow rate of cooling:**
Equilibrium structure



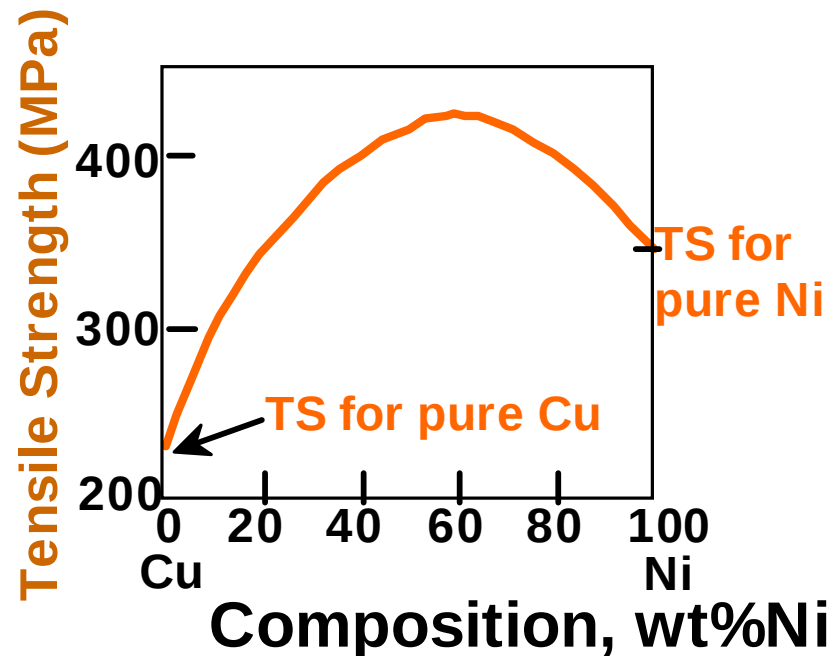
MECHANICAL PROPERTIES: Cu-Ni System

- Effect of solid solution strengthening

on:

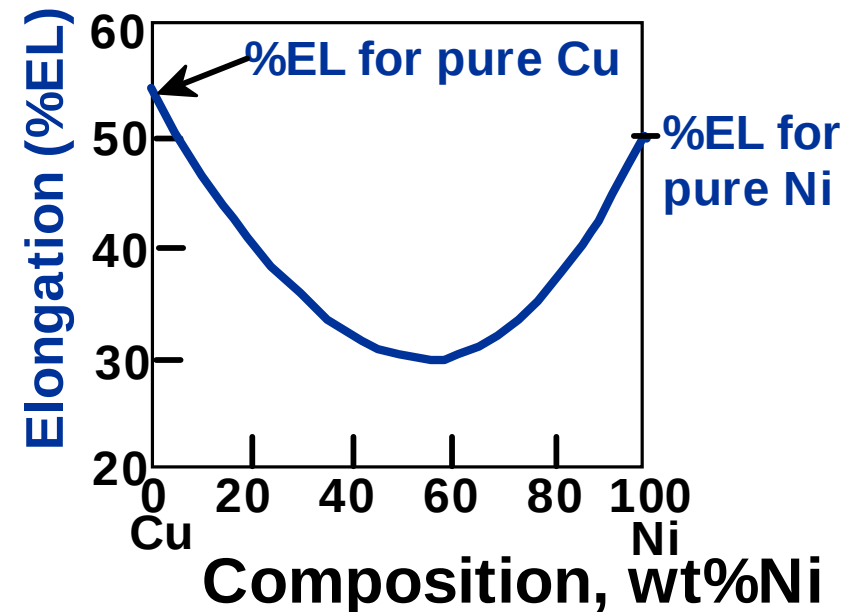
--Tensile strength (TS)

--Ductility (%EL,%AR)



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

--Peak as a function of C_0



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

--Min. as a function of C_0

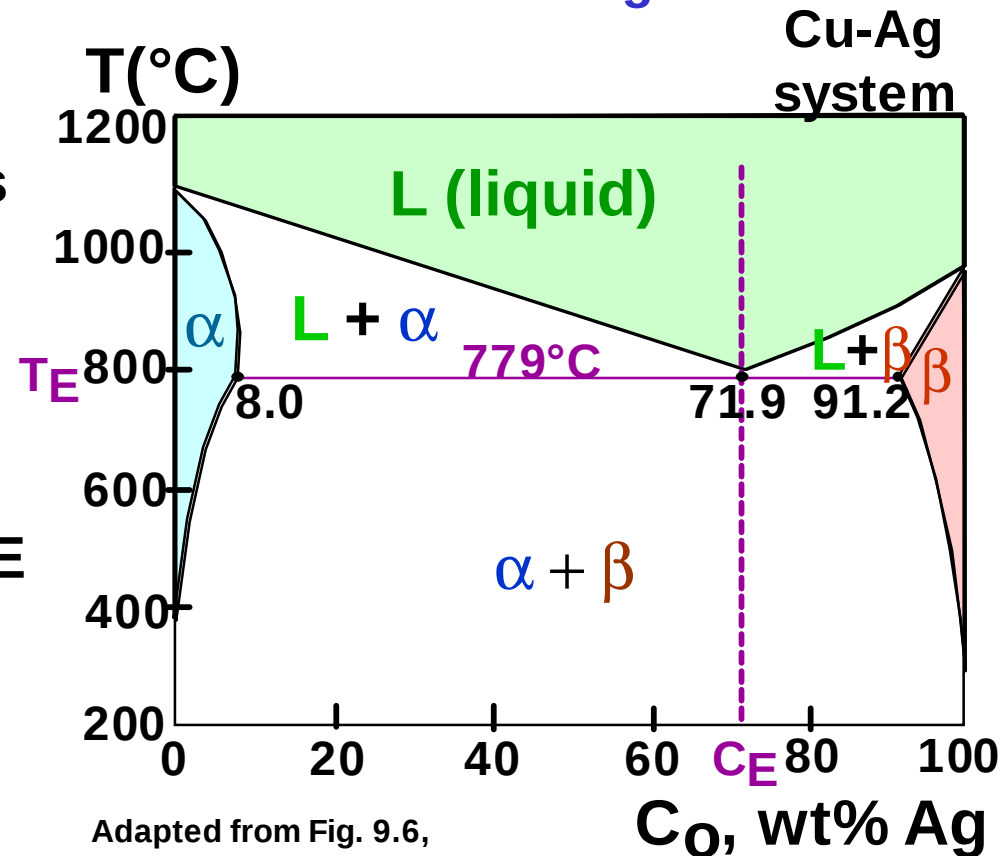
BINARY-EUTECTIC SYSTEMS

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.)

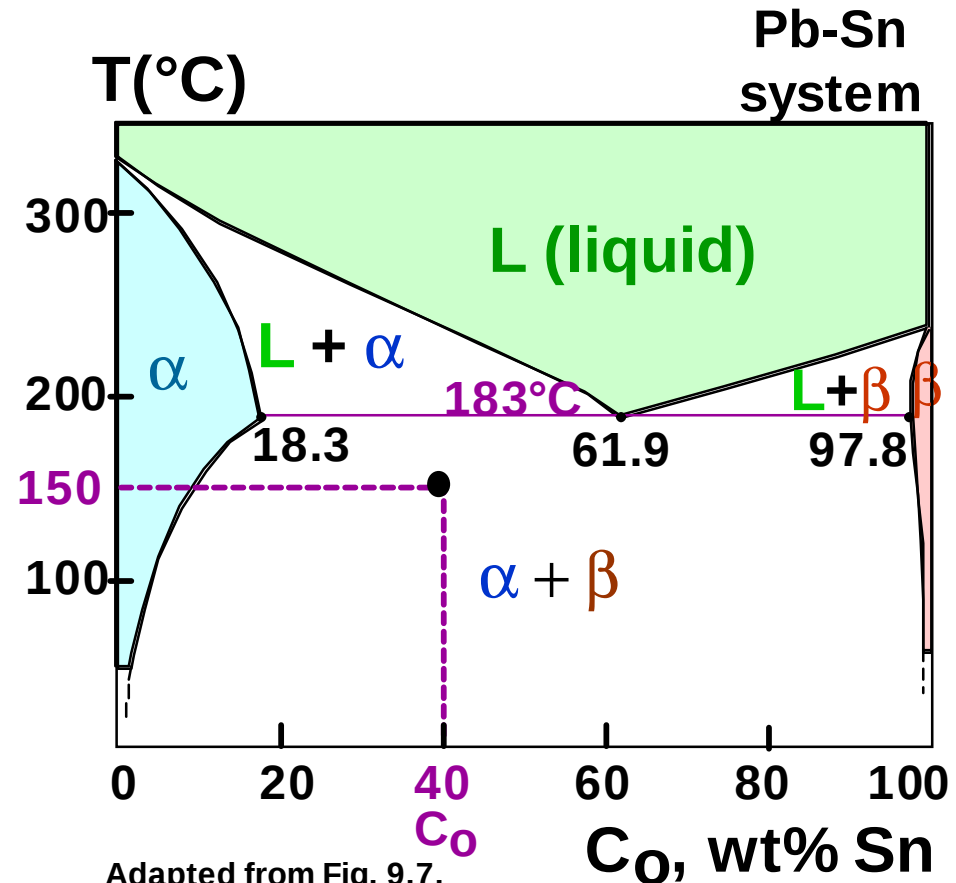
EX: Pb-Sn EUTECTIC SYSTEM (1)

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

--the phases present:

$\alpha + \beta$

--the compositions of the phases:



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: $\alpha + \beta$

--the compositions of the phases:

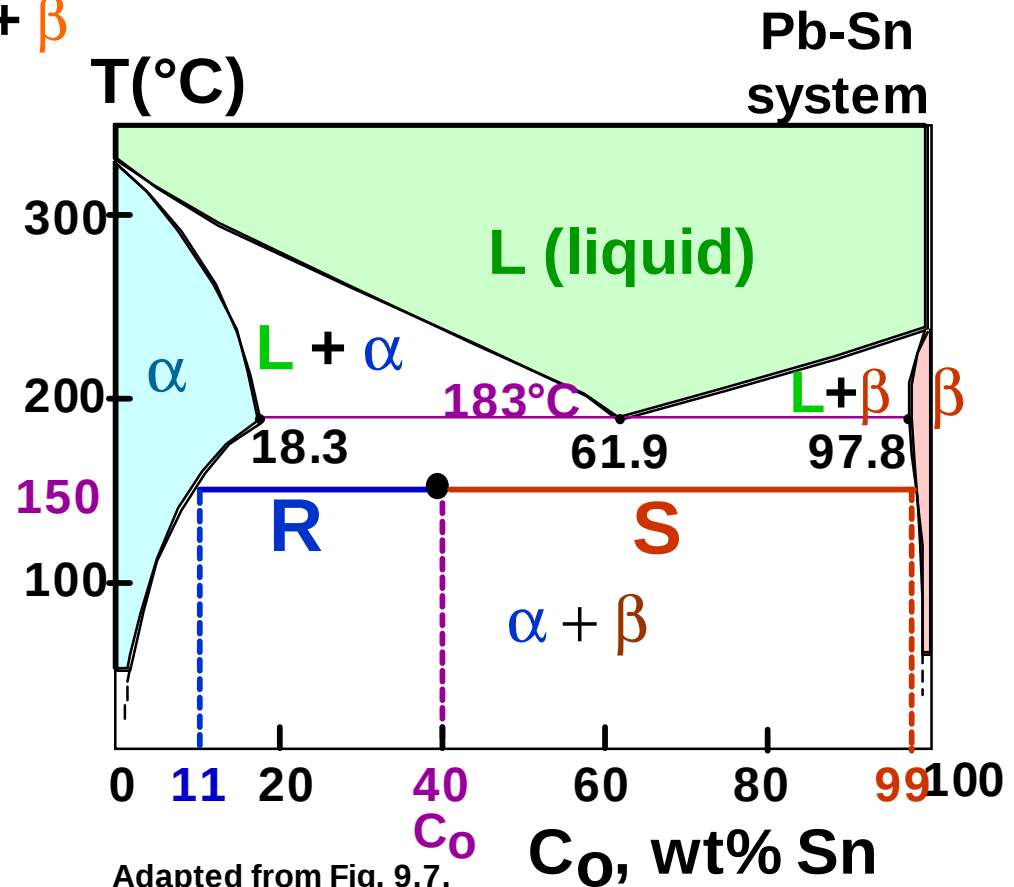
$$C_{\alpha} = 11\text{wt\%Sn}$$

$$C_{\beta} = 99\text{wt\%Sn}$$

--the relative amounts of each phase:

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

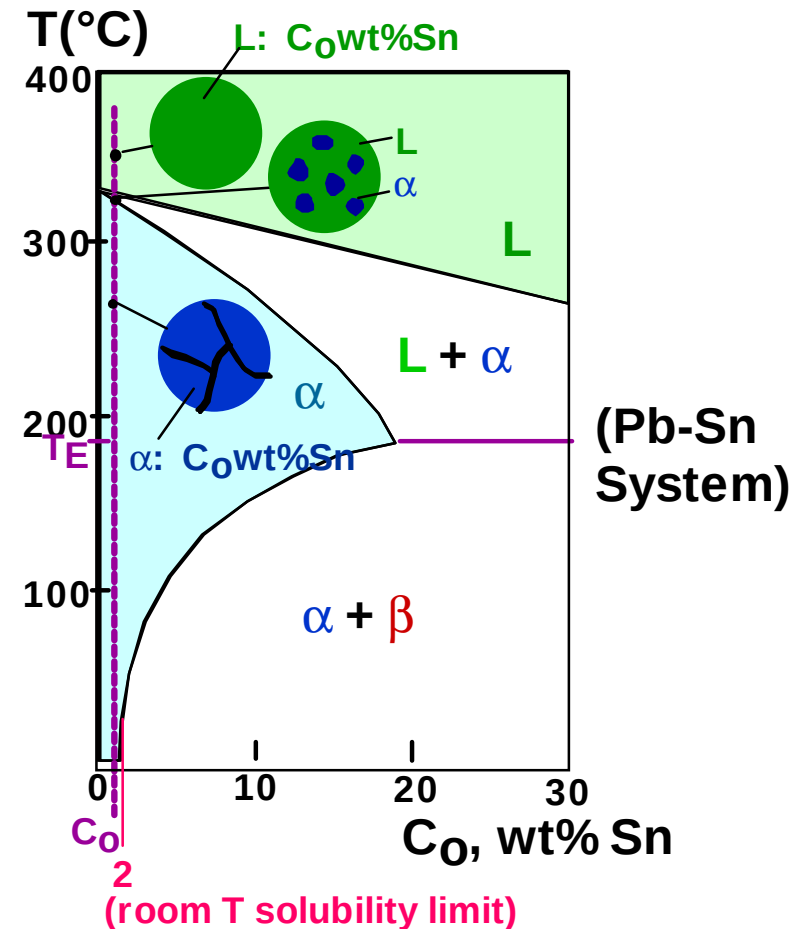
$$W_{\beta} = \frac{29}{88} = 33\text{wt\%}$$



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

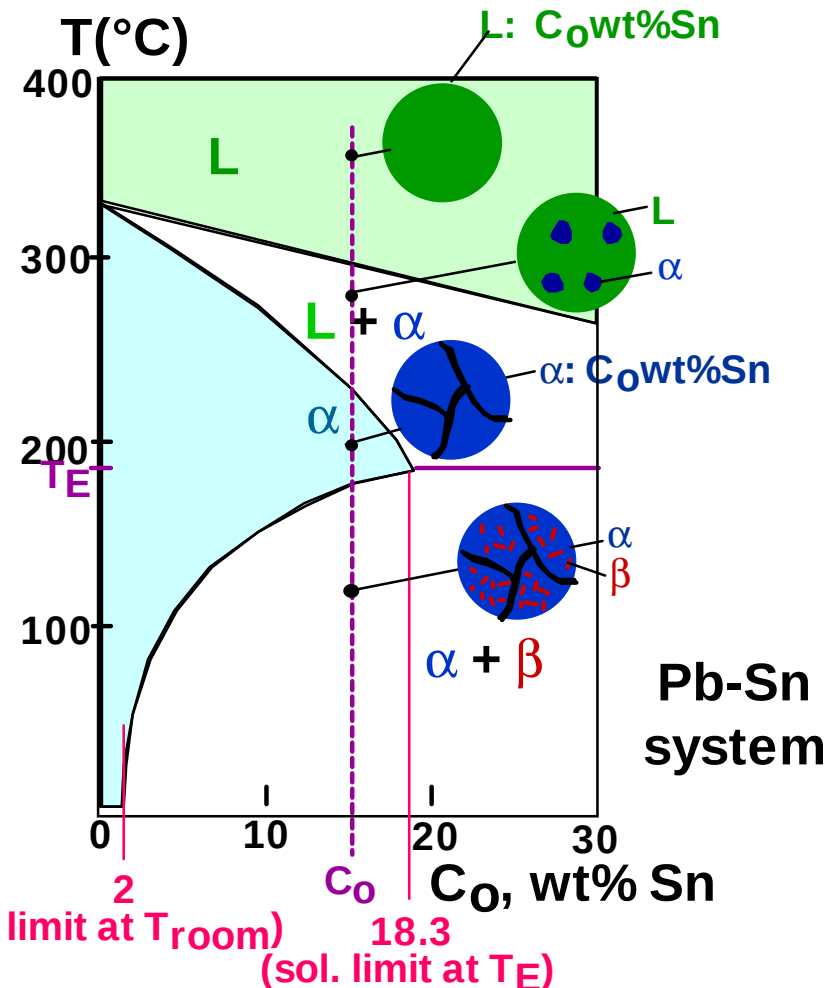
- $C_0 < 2\text{wt\%Sn}$
- Result:
--polycrystal of α grains.



Adapted from Fig. 9.9,
Callister 6e.

MICROSTRUCTURES IN EUTECTIC SYSTEMS-II

- $2\text{wt\%Sn} < C_0 < 18.3\text{wt\%Sn}$
- Result:
-- α polycrystal with fine β crystals.

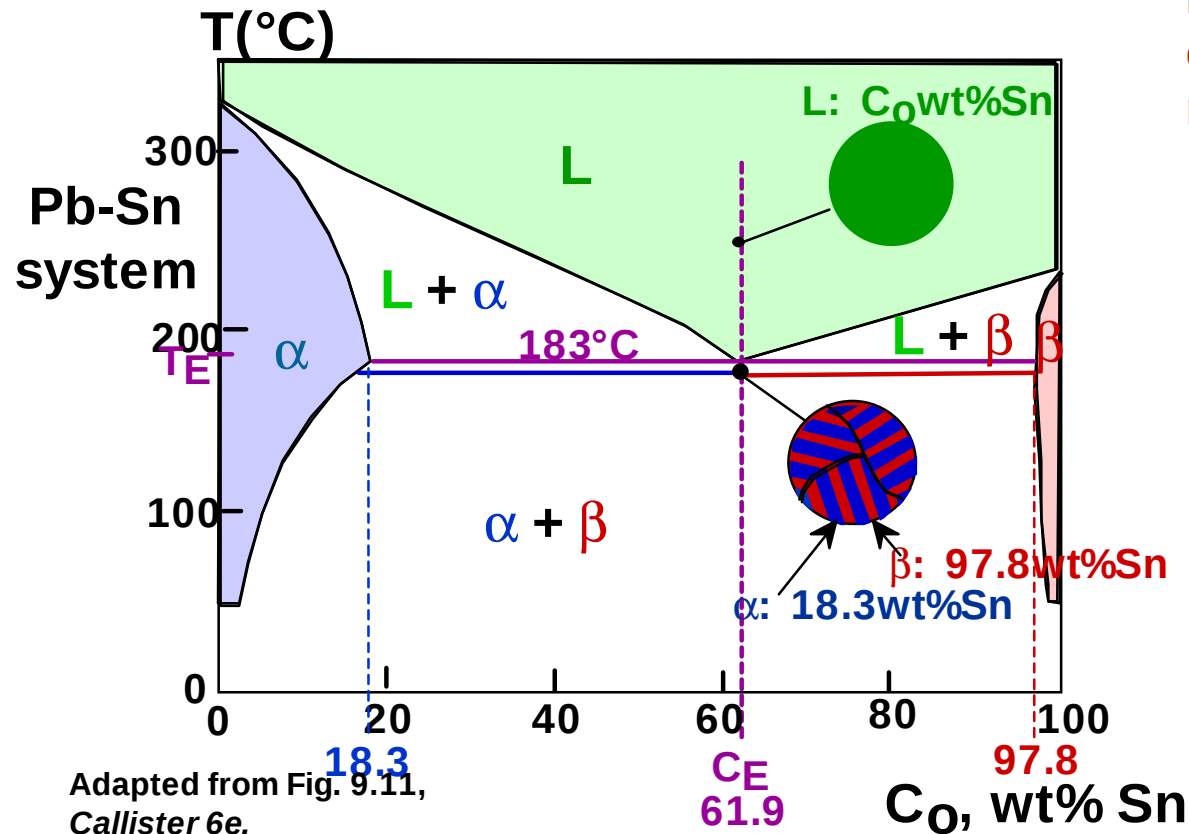


Adapted from Fig. 9.10,
Callister 6e.

(sol. limit at T_{room})
 C_0 18.3
(sol. limit at T_E)

MICROSTRUCTURES IN EUTECTIC SYSTEMS-III

- $C_0 = C_E$
- Result: Eutectic microstructure
--alternating layers of α and β crystals.



Micrograph of Pb-Sn eutectic microstructure

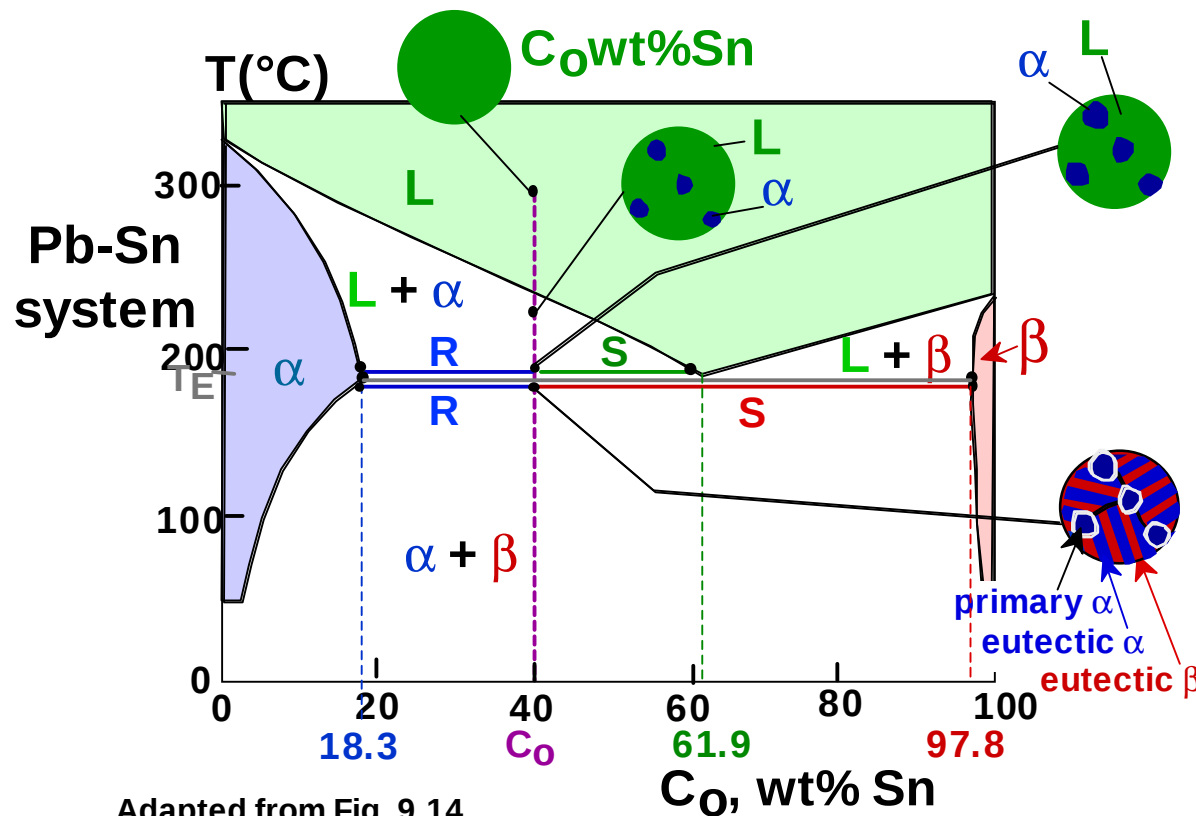


160 μ m

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

- $18.3\text{wt\%Sn} < C_0 < 61.9\text{wt\%Sn}$
- **Result:** α crystals and a eutectic microstructure



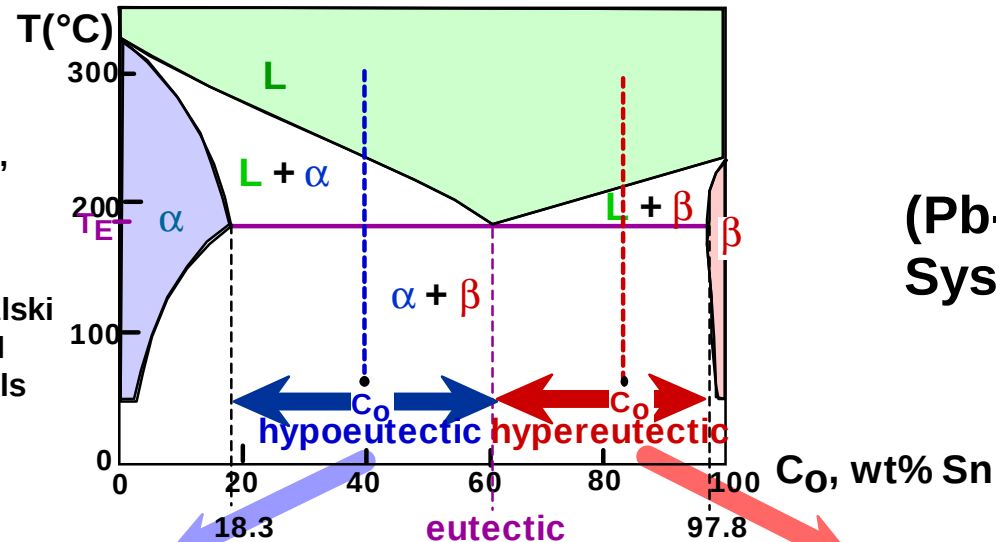
Adapted from Fig. 9.14,
Callister 6e.

- Just above T_E :
 $C_\alpha = 18.3\text{wt\%Sn}$
 $C_L = 61.9\text{wt\%Sn}$
 $W_\alpha = \frac{S}{R+S} = 50\text{wt\%}$
 $W_L = (1-W_\alpha) = 50\text{wt\%}$

- Just below T_E :
 $C_\alpha = 18.3\text{wt\%Sn}$
 $C_\beta = 97.8\text{wt\%Sn}$
 $W_\alpha = \frac{S}{R+S} = 73\text{wt\%}$
 $W_\beta = 27\text{wt\%}$

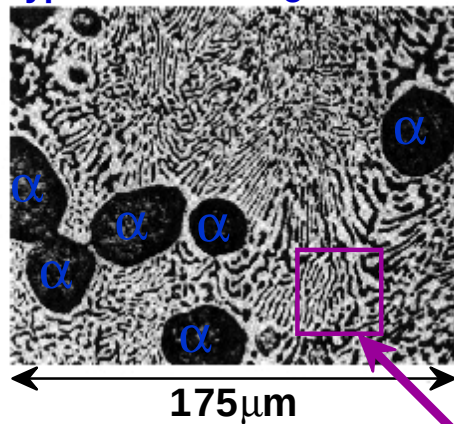
HYPOEUTECTIC & HYPEREUTECTIC

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.)



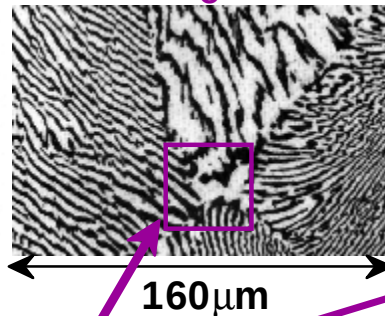
(Figs. 9.12 and 9.15 from *Metals Handbook*, 9th ed., Vol. 9, *Metallography and Microstructures*, American Society for Metals, Materials Park, OH, 1985.)

hypoeutectic: $C_0 = 50$ wt% Sn



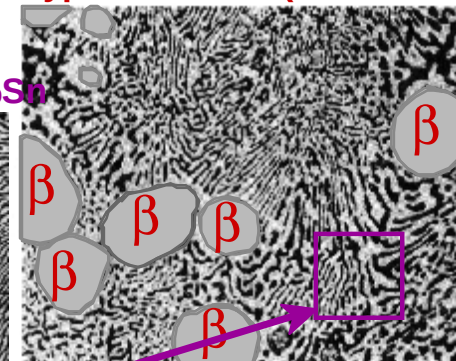
Adapted from Fig. 9.15, Callister 6e.

eutectic: $C_0 = 61.9$ wt% Sn



Adapted from Fig. 9.12, Callister 6e.

hyper-eutectic: (illustration only)



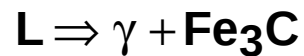
Adapted from Fig. 9.15, Callister 6e. (Illustration only)

eutectic micro-constituent

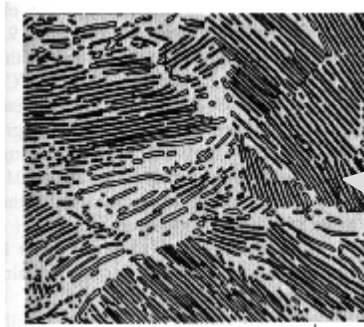
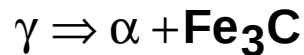
IRON-CARBON (Fe-C) PHASE DIAGRAM

- 2 important points

-Eutectic (A):

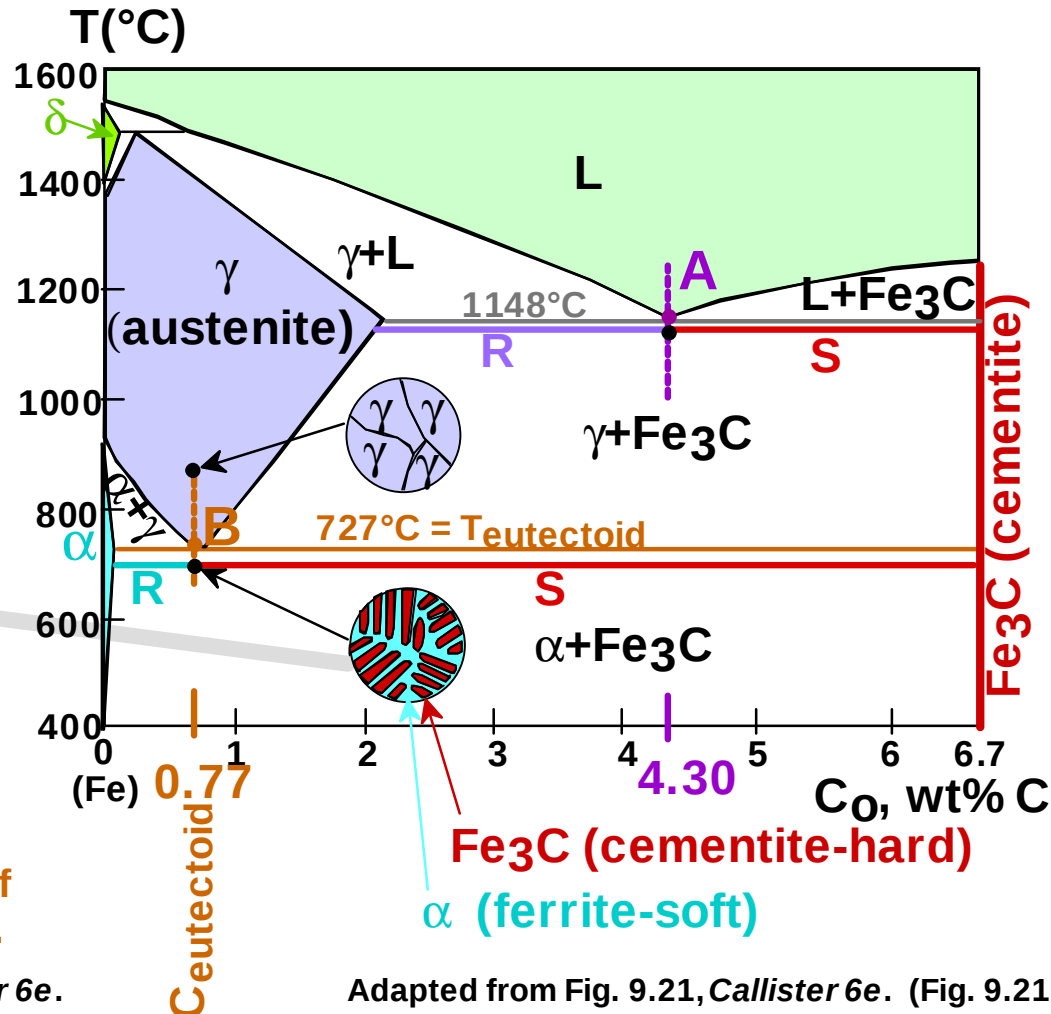


-Eutectoid (B):



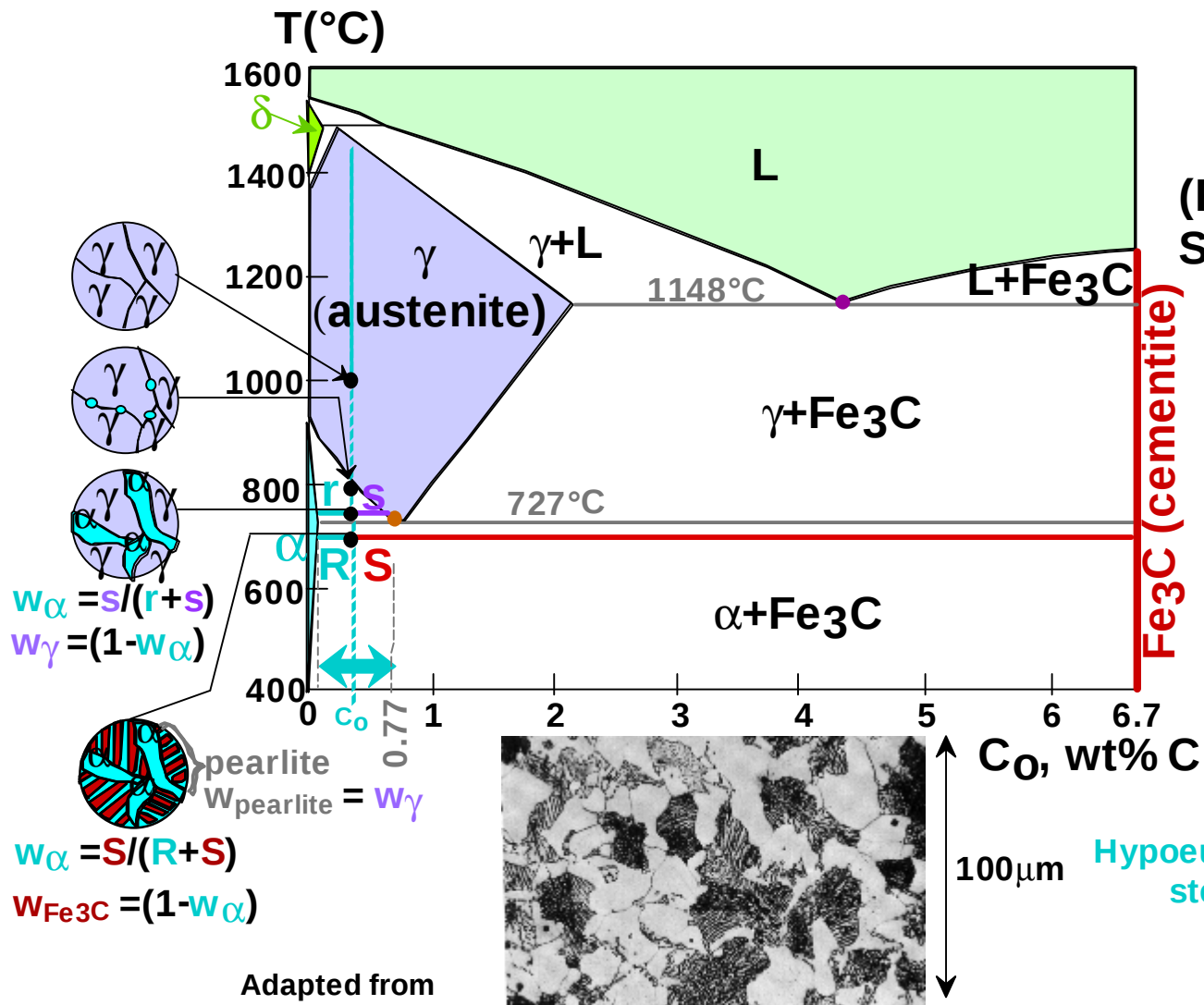
Result: Pearlite = alternating layers of α and Fe_3C phases.

(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.)



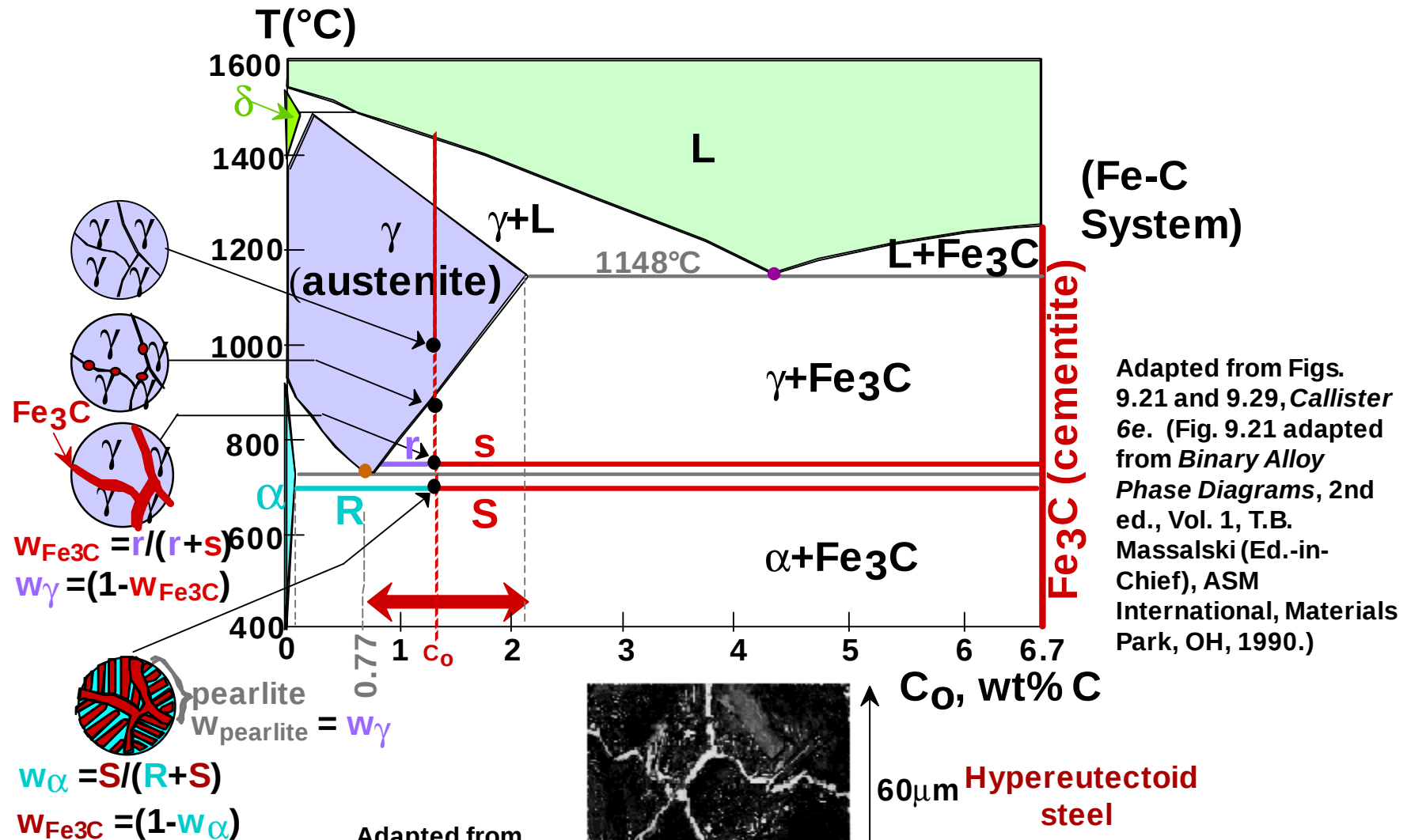
Adapted from Fig. 9.21, Callister 6e. (Fig. 9.21 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)

HYPOEUTECTOID STEEL



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

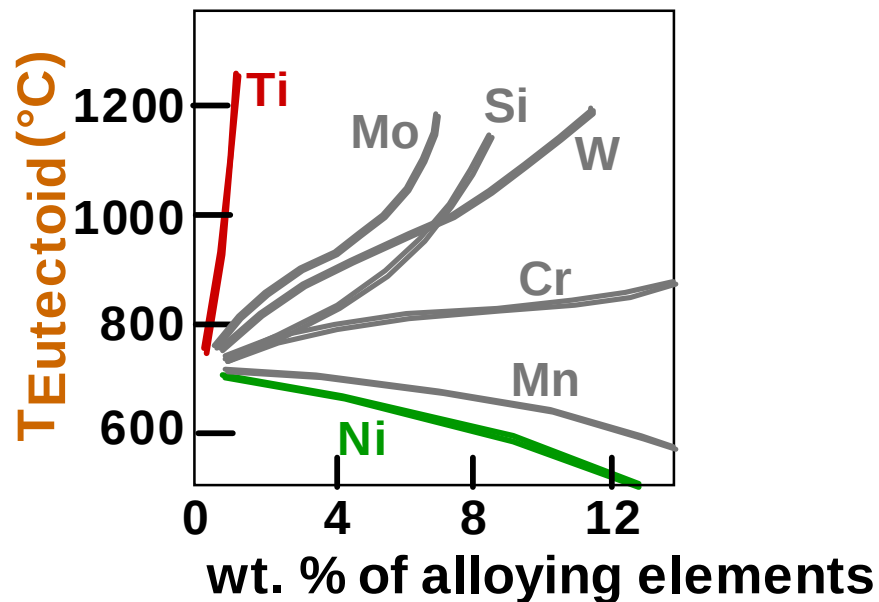
HYPEREUTECTOID STEEL



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

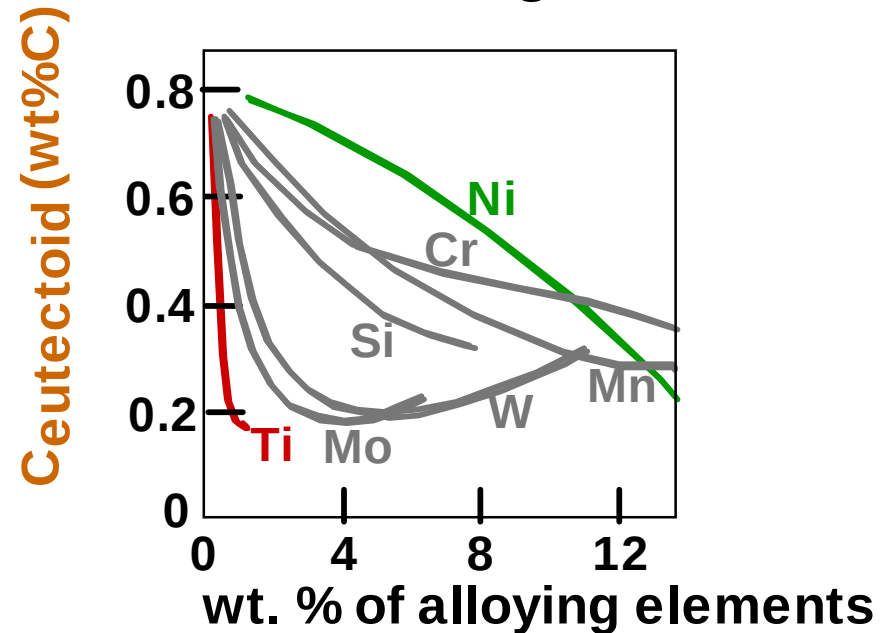
ALLOYING STEEL WITH MORE ELEMENTS

- $T_{\text{Eutectoid}}$ 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.)

- $C_{\text{Eutectoid}}$ 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 phasefor 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.