# Phase equilibria: solubility limit

**Introduction**

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

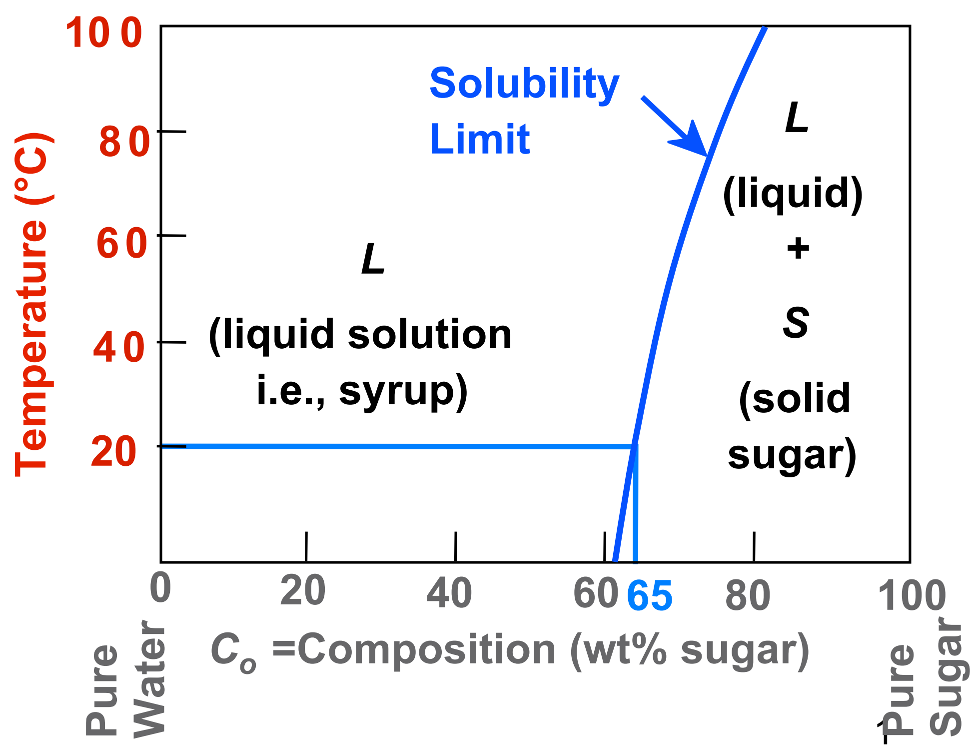
Adapted from Fig. 9.1, *Callister 7e.*

- 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.

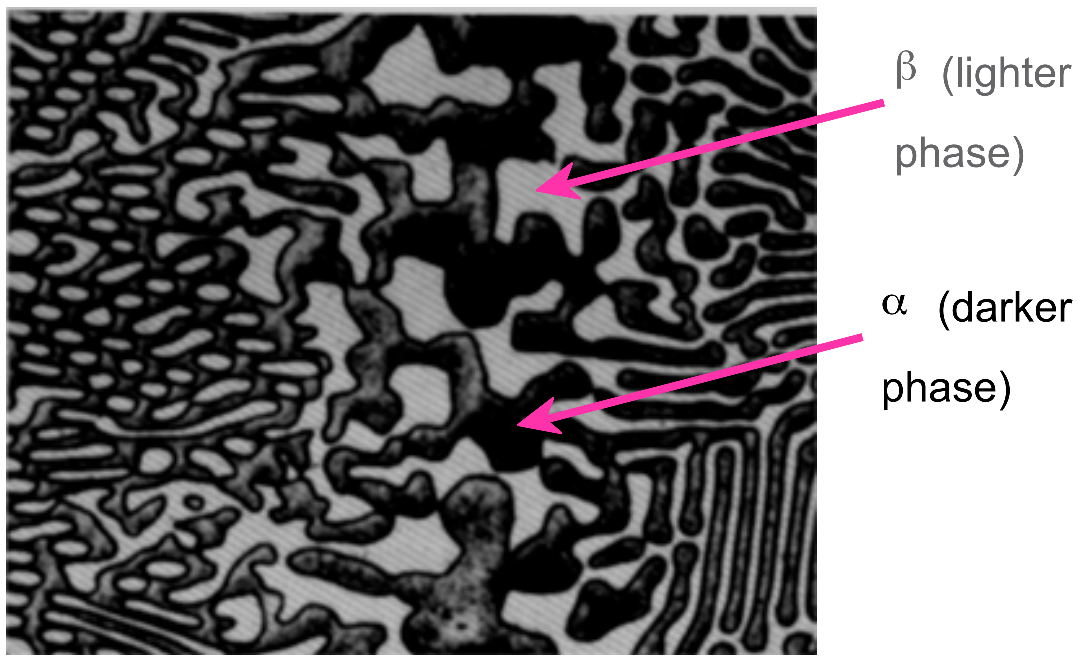
Sucrose/Water Phase Diagram



# 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., $\alpha$ and $\beta$).

Aluminum-Copper Alloy

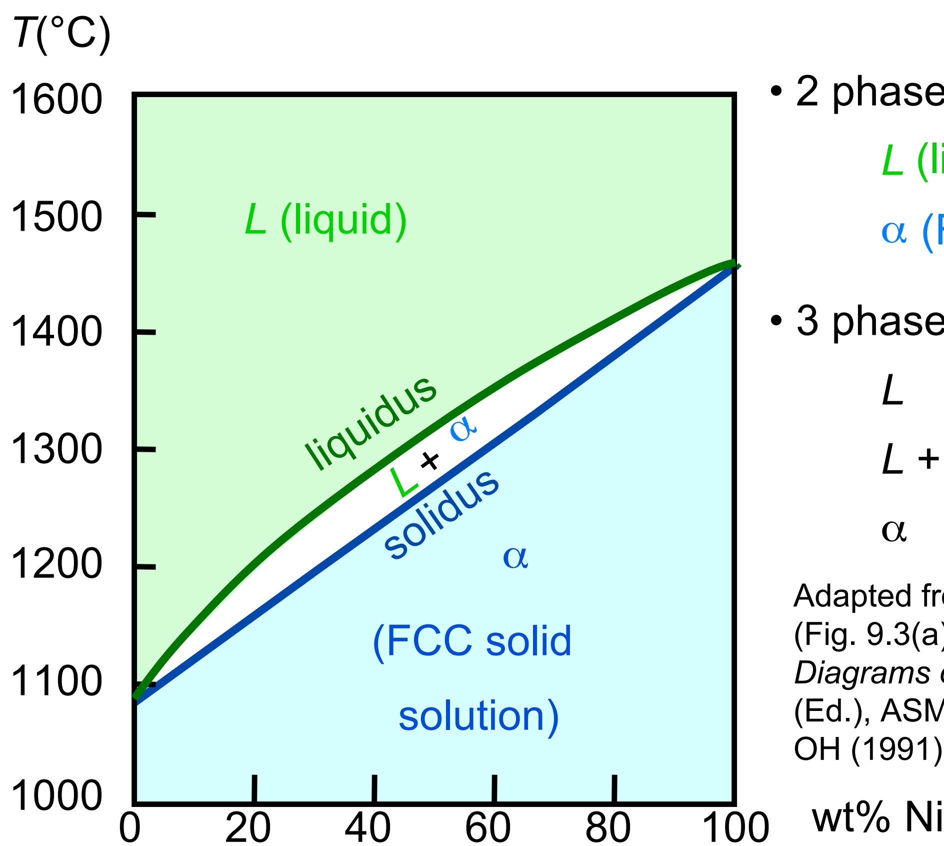



Adapted from chapter-opening photograph, Chapter 9, *Callister 3e.*

# 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 + α
  - α

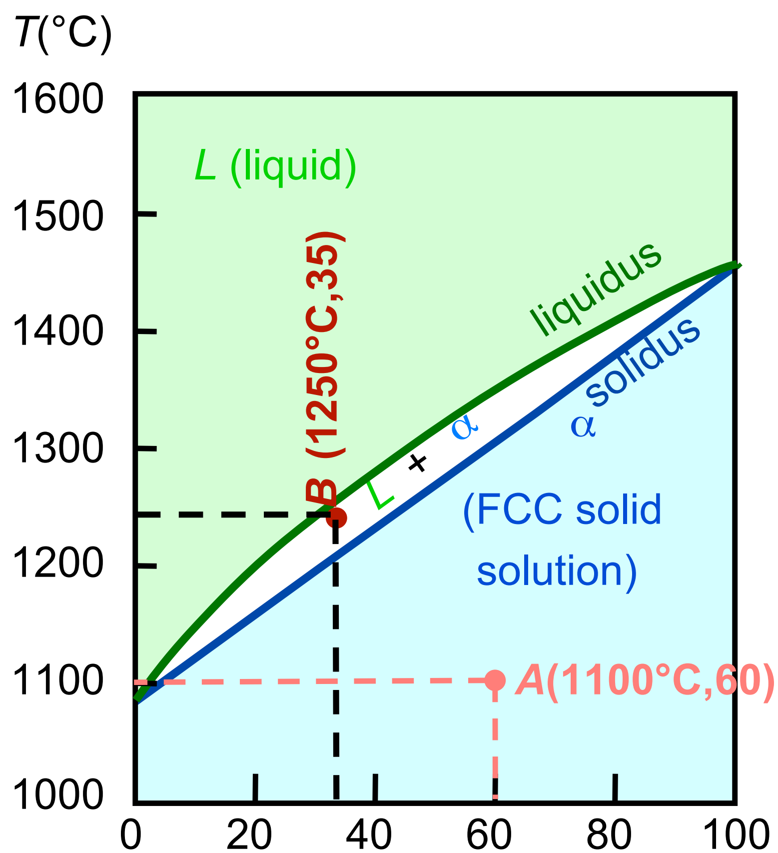
Adapted from Fig. 9.3(a), *Callister 7e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

# Phase diagrams

- 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

- 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 ( $\alpha$ )

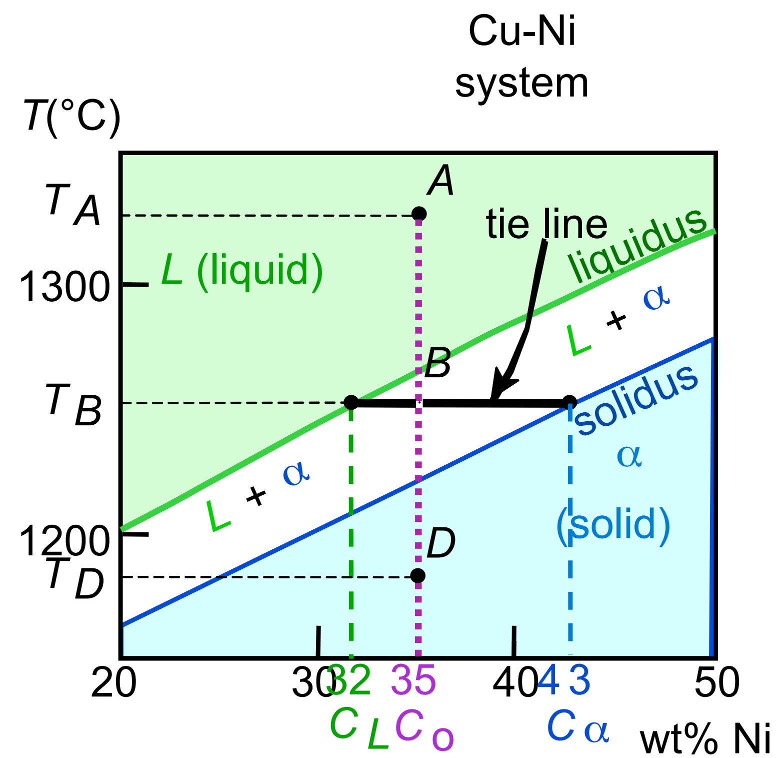
  $C_\alpha = C_o$ ( = 35 wt% Ni)

  At $T_B$ = 1250°C:

  Both $\alpha$ and $L$

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

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




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.)

# Phase diagrams

- 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 ($\alpha$)

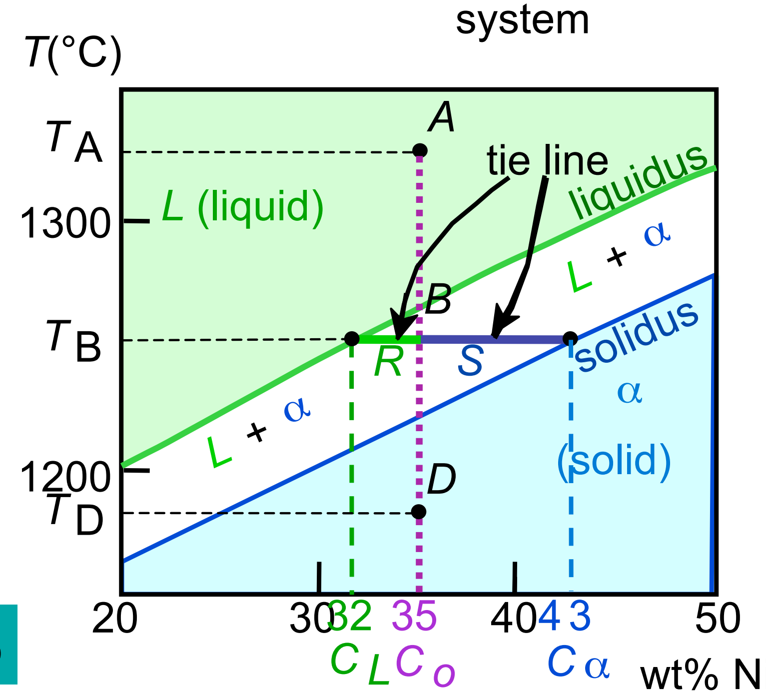
$W_L$ = 0, $W_\alpha$ = 100 wt%

At $T_B$: Both $\alpha$ and $L$

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

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

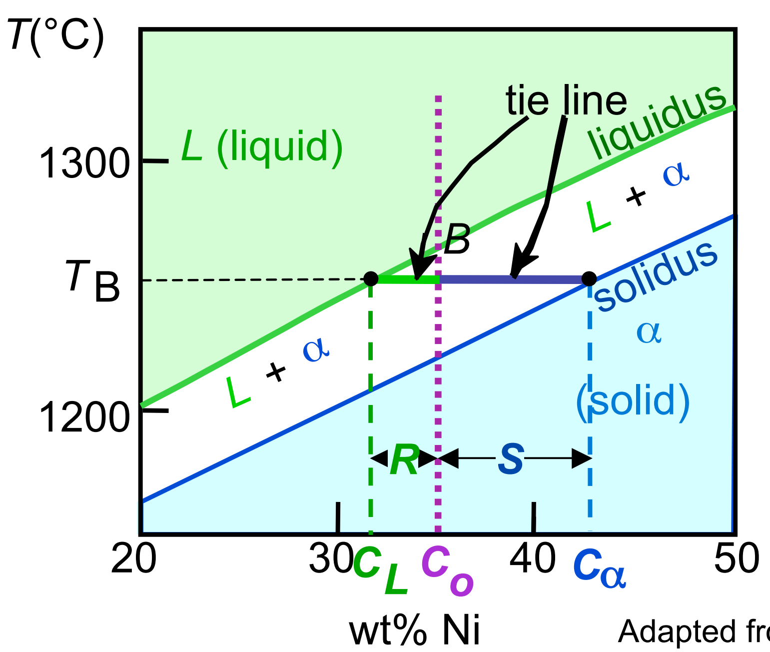
Cu-Ni system




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.)

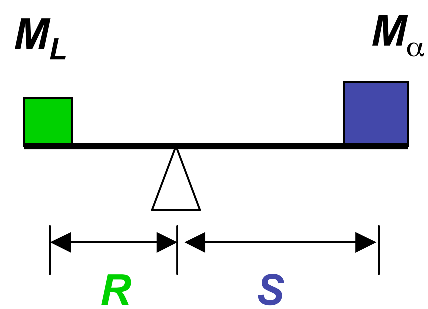
# The lever rule

**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)



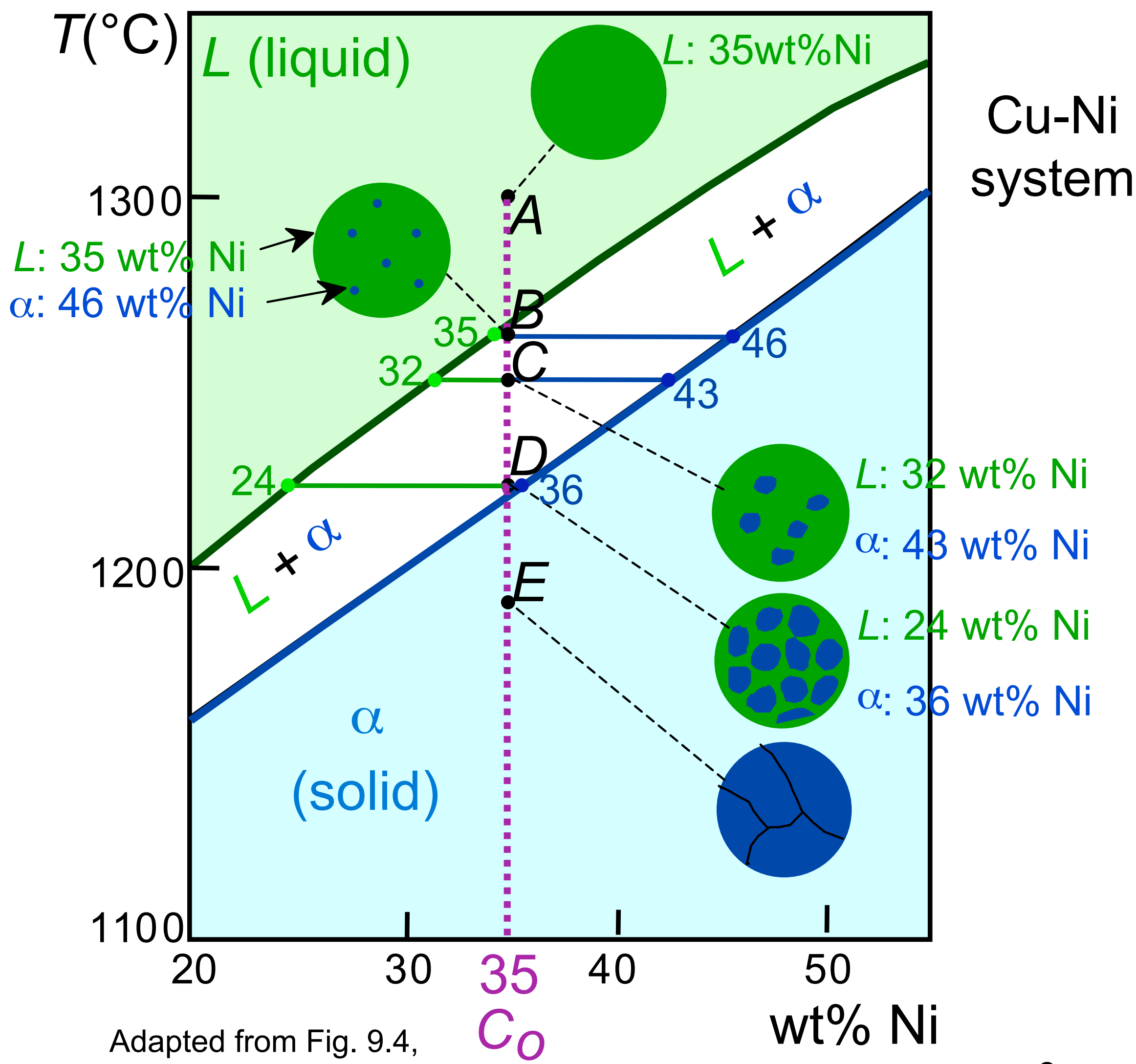

$$M_\alpha \cdot S = M_L \cdot R$$

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

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

# Cooling

- 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.*

# Binary eutectic systems

2 components

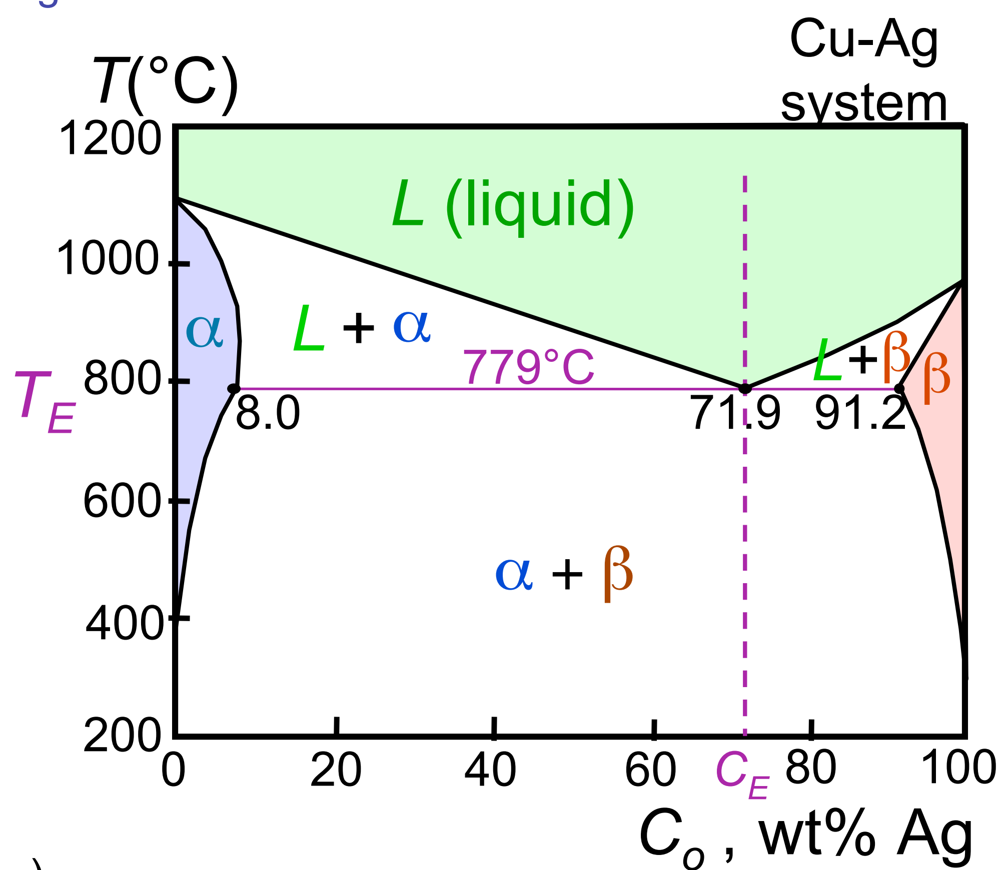
has a special composition with a min. melting T.

Ex.: Cu-Ag system

- 3 single phase regions ($L$, $\alpha$, $\beta$ )
- Limited solubility:
  - $\alpha$ : mostly Cu
  - $\beta$ : 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.*

# Binary eutectic systems

- 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

  $C_\alpha$ = 11 wt% Sn

  $C_\beta$ = 99 wt% Sn

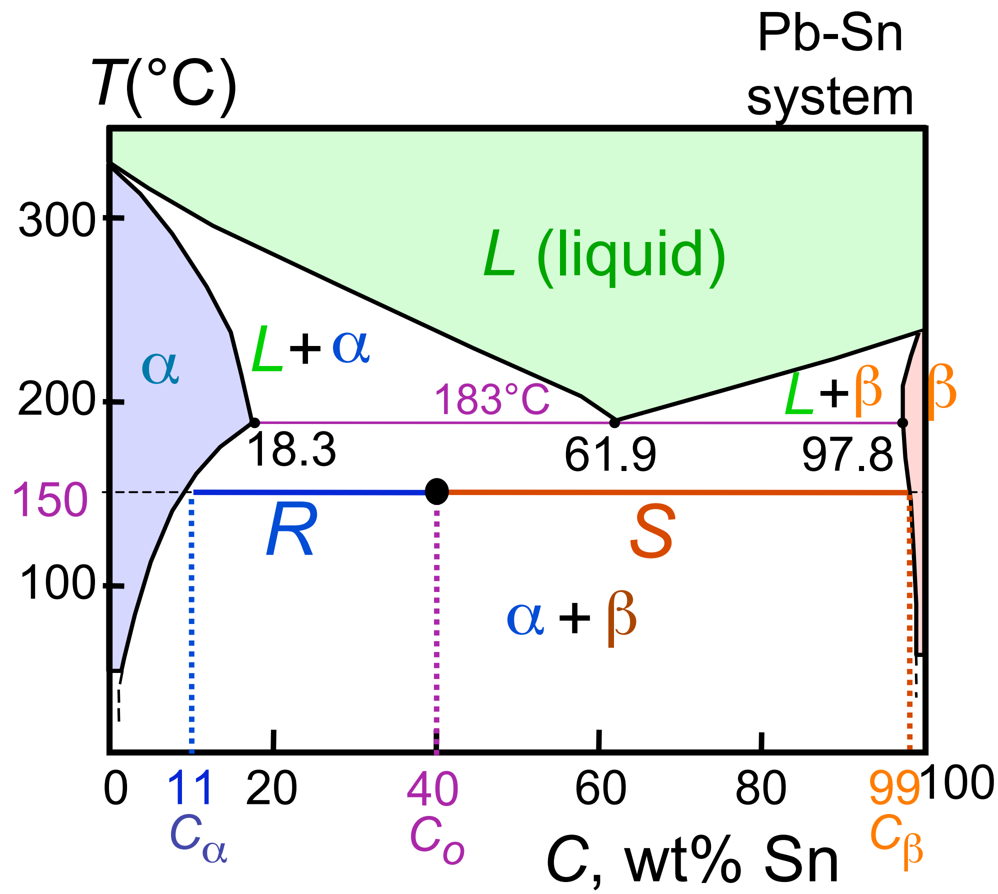
  --the relative amount of each phase:

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

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

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

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




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

# Binary eutectic systems

- 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

  $C_\alpha$ = 17 wt% Sn

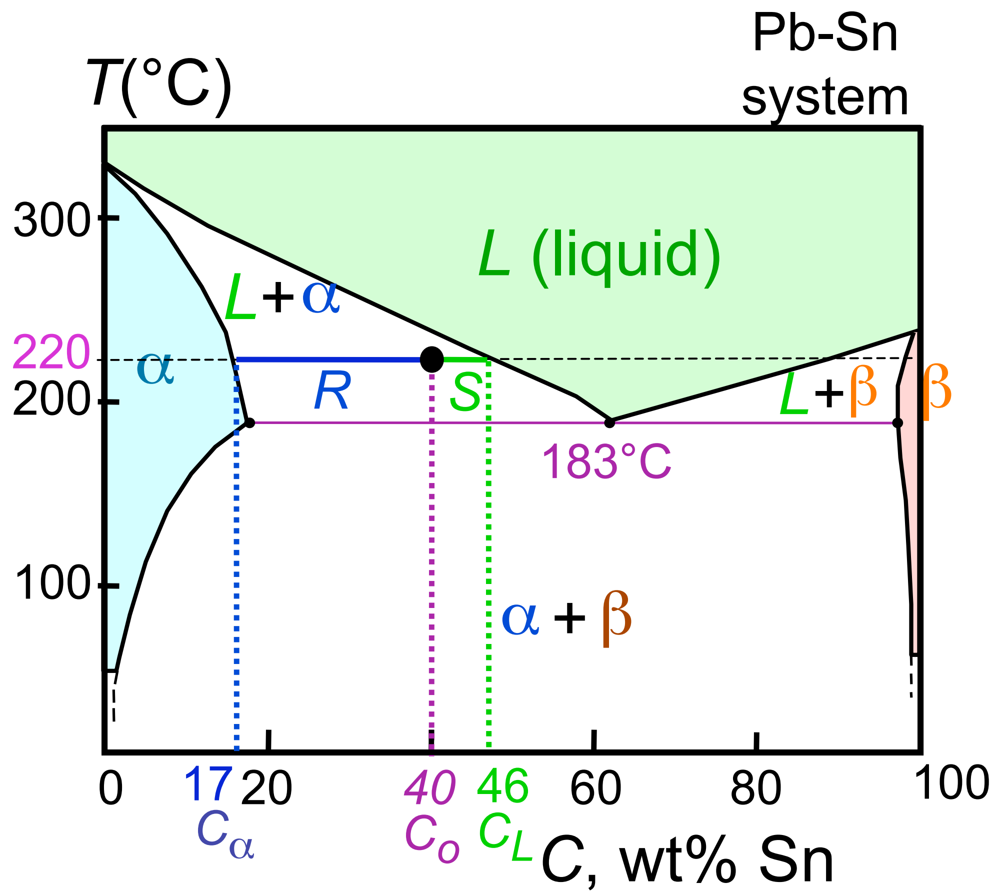
  $C_L$ = 46 wt% Sn

  --the relative amount of each phase:

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

$$= \frac{6}{29} = 21 \text{ wt\%}$$

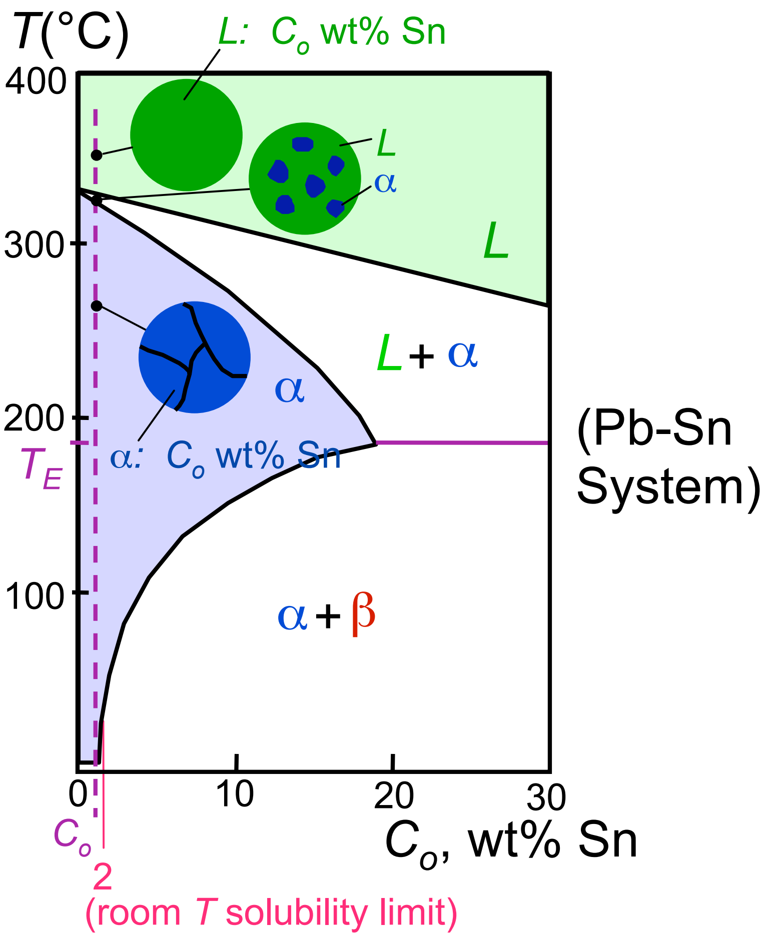
$$W_L = \frac{C_O - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 79 \text{ wt\%}$$




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

# Microstructures in eutectic systems

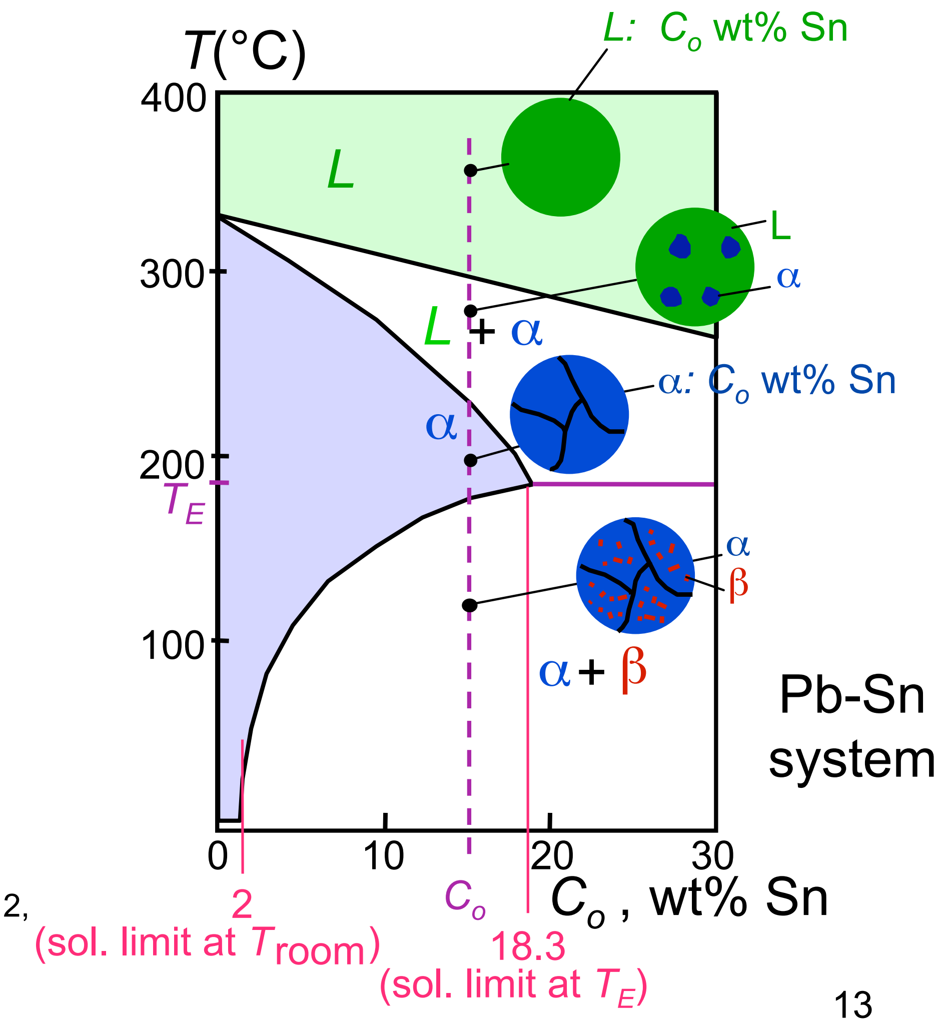
- $C_o$ < 2 wt% Sn
- Result:
  - --at extreme ends
  - --polycrystal of $\alpha$ grains
    - i.e., only one solid phase.




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

# Microstructures in eutectic systems

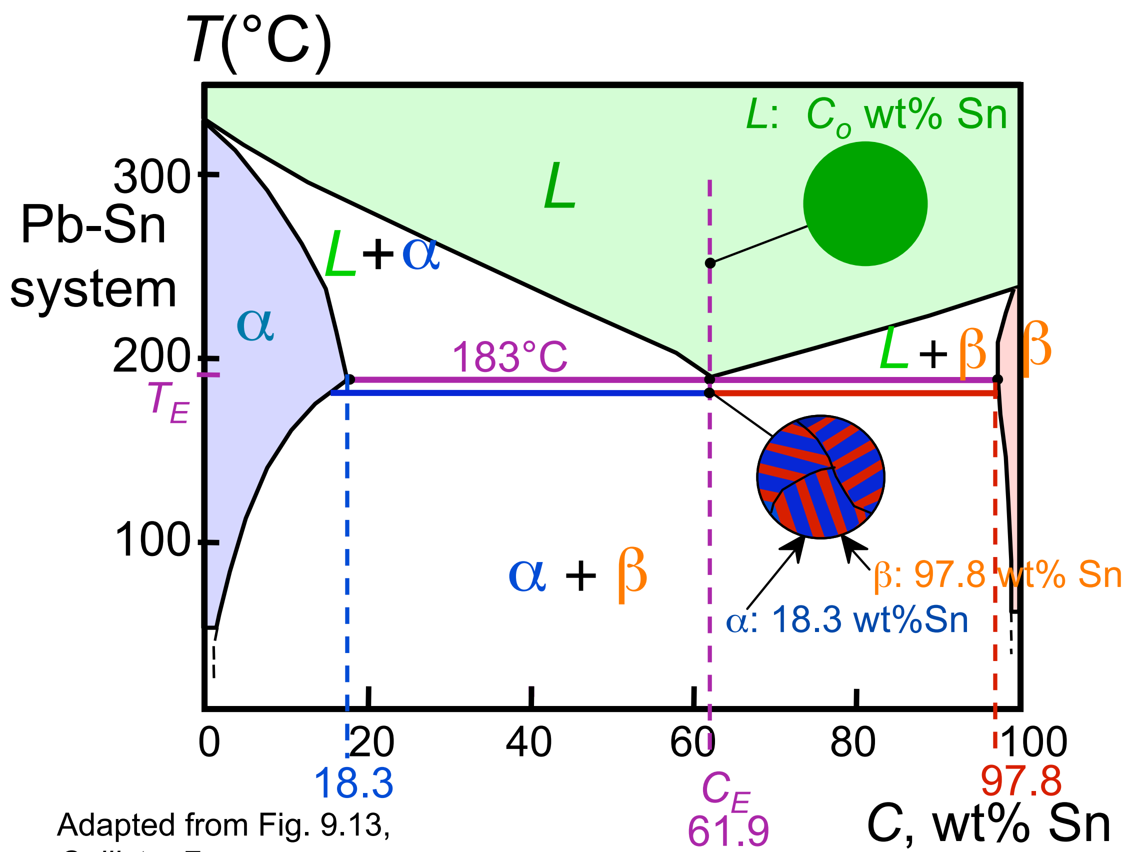
- 2 wt% Sn < $C_o$ < 18.3 wt% Sn
- Result:
  - Initially liquid + $\alpha$
  - then $\alpha$ alone
  - finally two phases
    - $\alpha$ polycrystal
    - fine $\beta$-phase inclusions




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

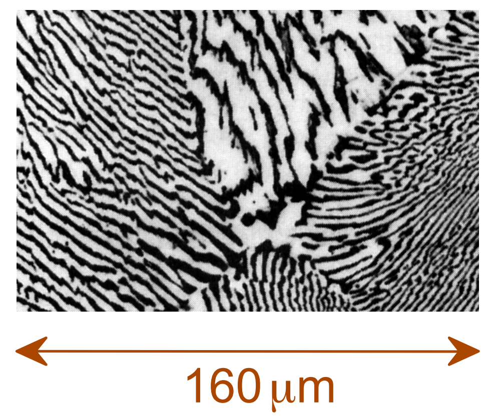
# Microstructures in eutectic systems

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




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

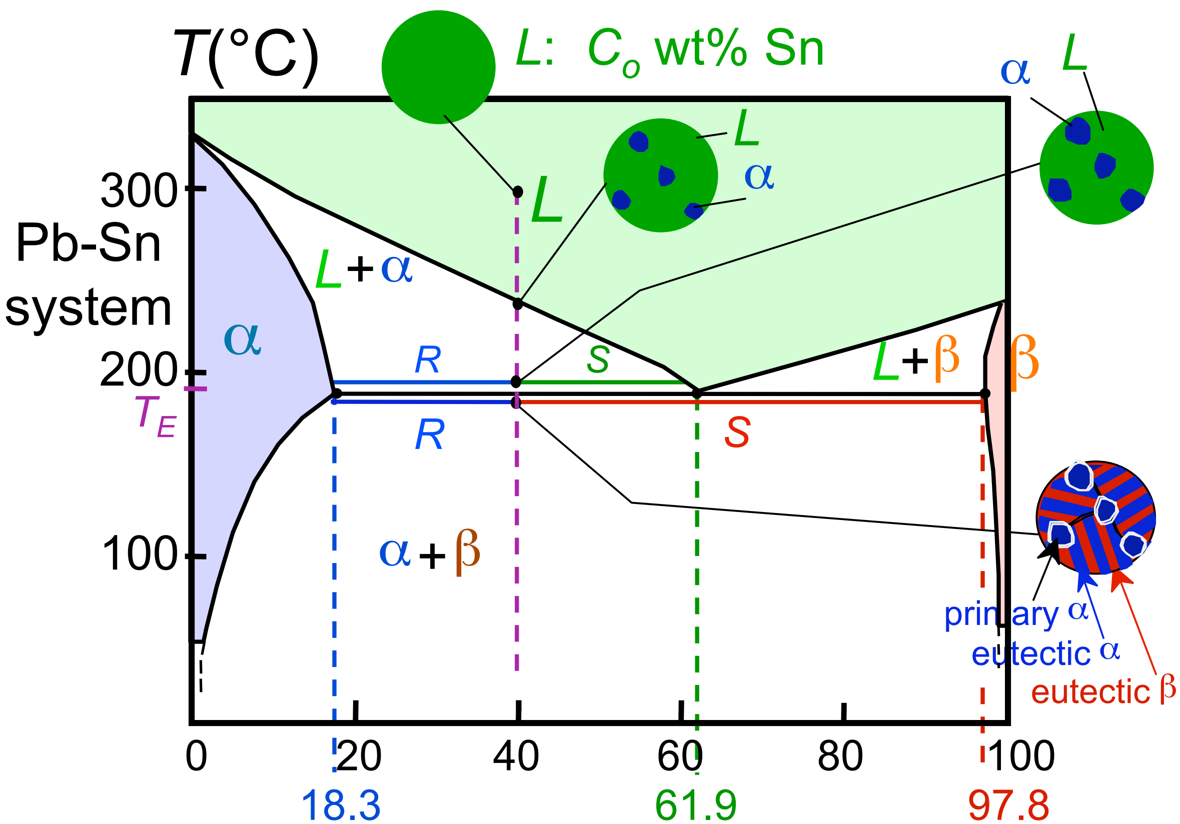
Micrograph of Pb-Sn eutectic microstructure




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

# Microstructures in eutectic systems

- 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 $T_E$:

$C_\alpha$ = 18.3 wt% Sn

$C_L$ = 61.9 wt% Sn

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

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

- Just below $T_E$:

$C_\alpha$ = 18.3 wt% Sn

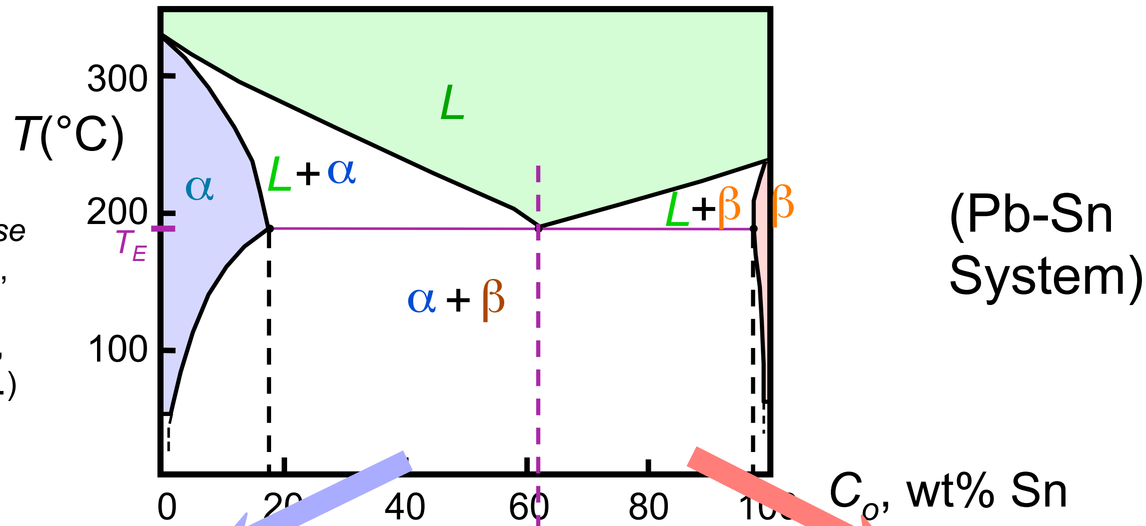
$C_\beta$ = 97.8 wt% Sn

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

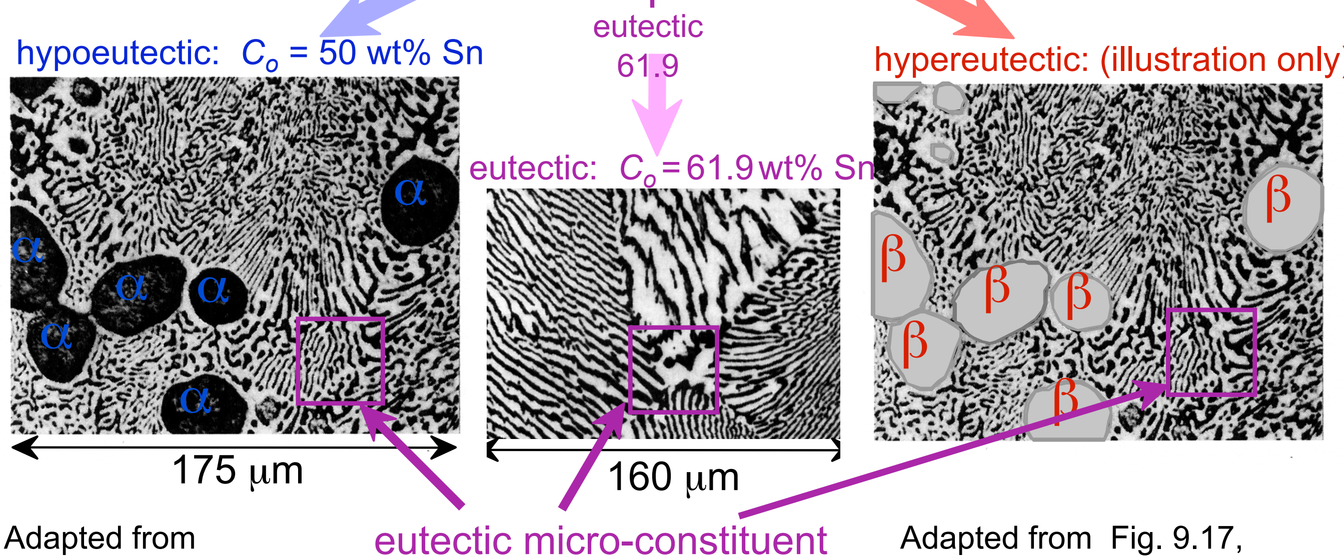
$W_\beta$ = 27 wt%

# Hypoeutectic & hypereutectic

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.)




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

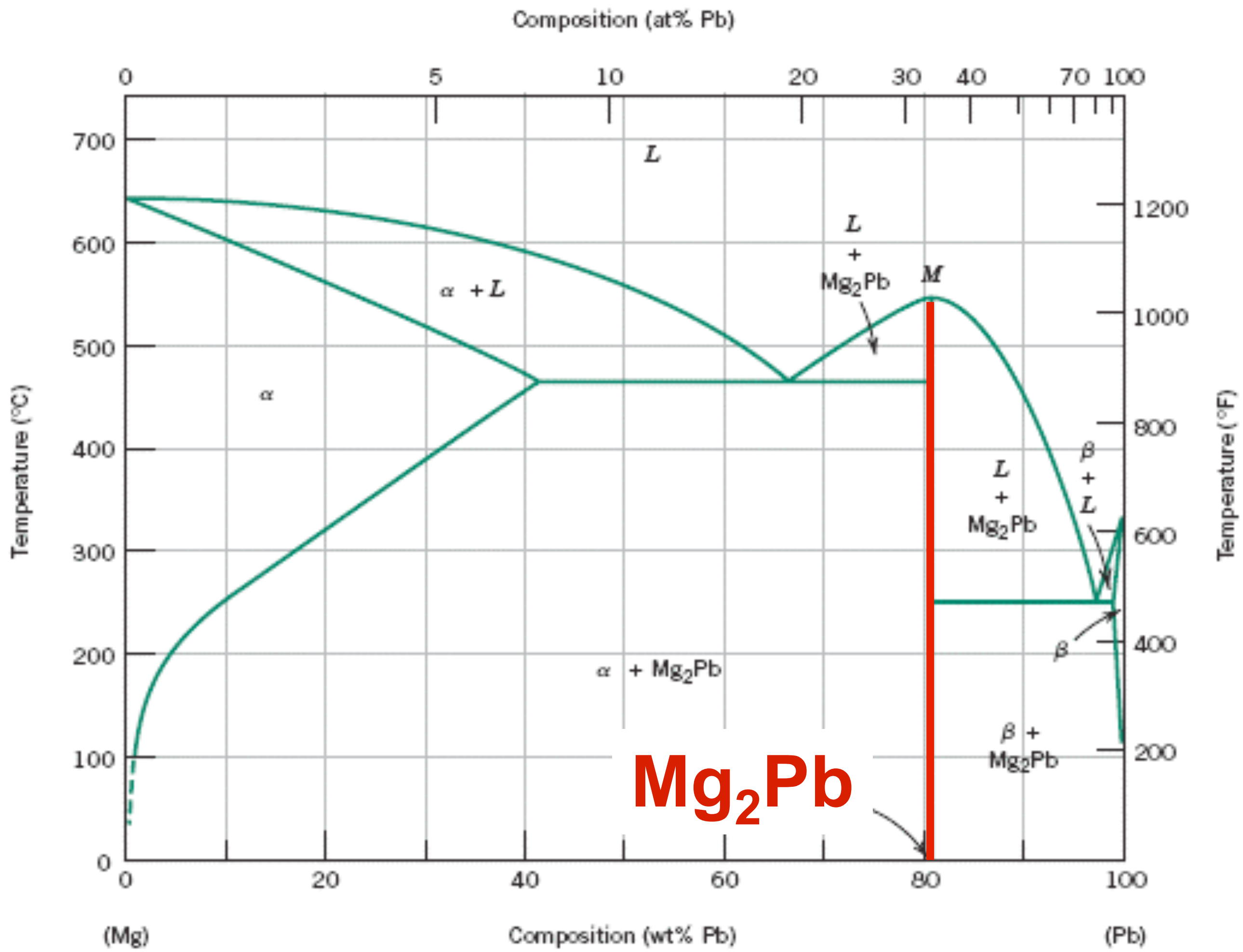



Adapted from Fig. 9.17, *Callister 7e.*

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

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

# Intermetallic compounds



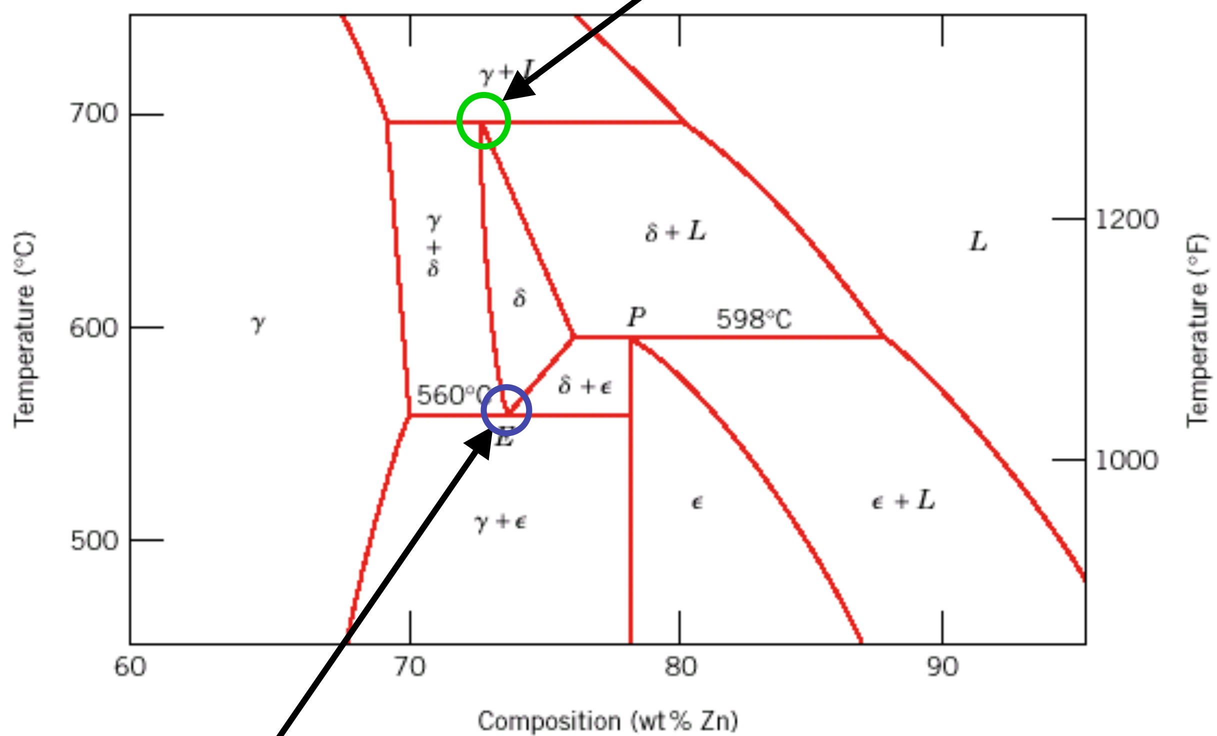

Adapted from
Fig. 9.20, *Callister 7e.*

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

# Peritectic & eutectoid

- Cu-Zn Phase diagram

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




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

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

# Fe-C phase diagram

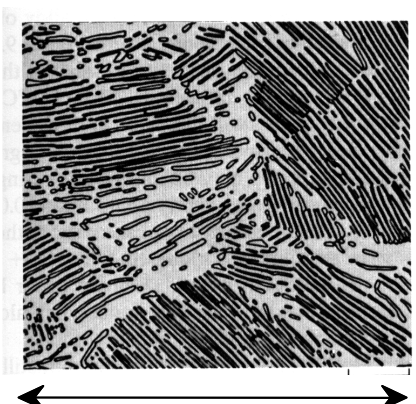
- 2 important points

-Eutectic (*A*):

$L \Rightarrow \gamma + Fe_3C$

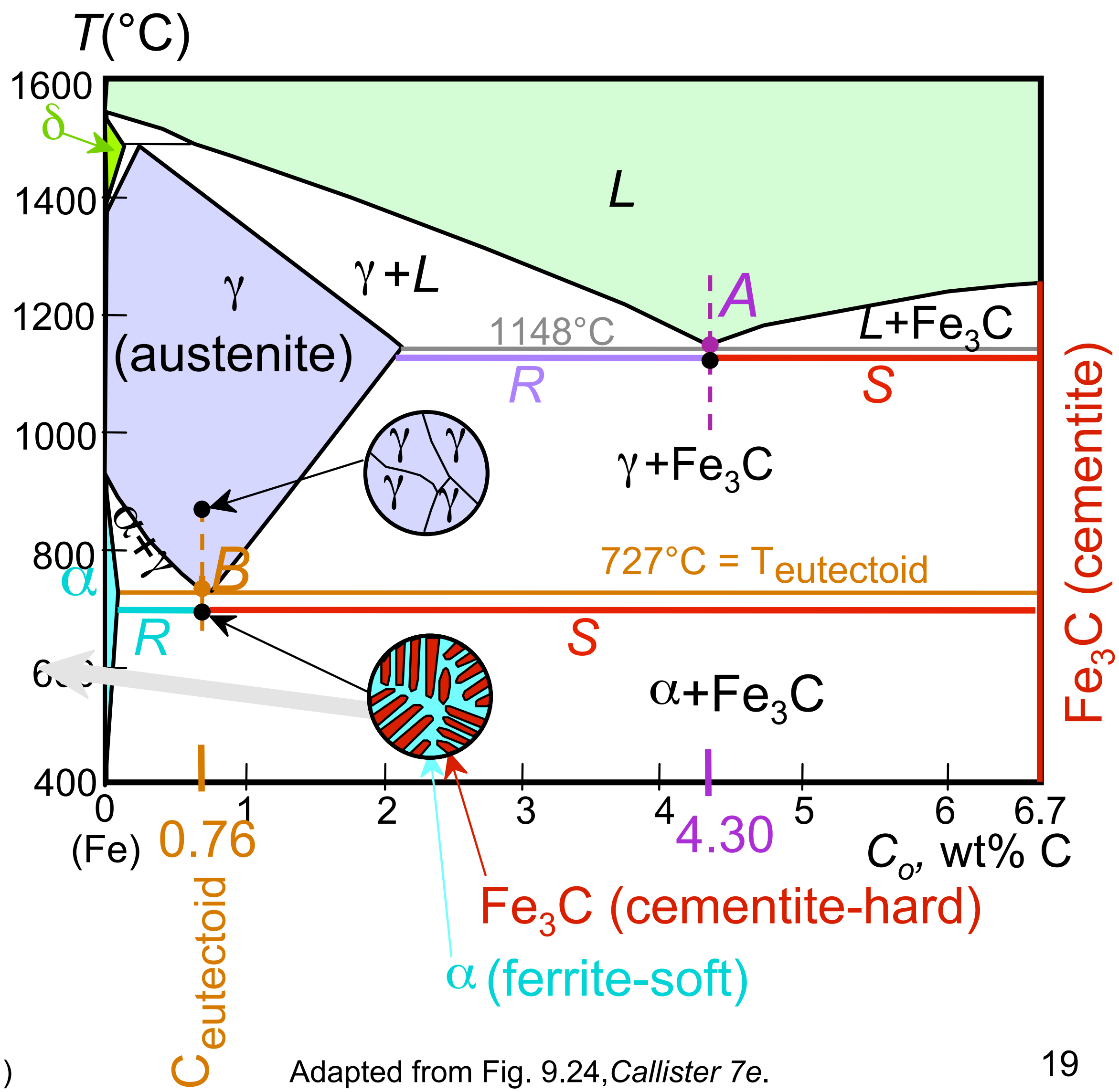
-Eutectoid (*B*):

$\gamma \Rightarrow \alpha + Fe_3C$



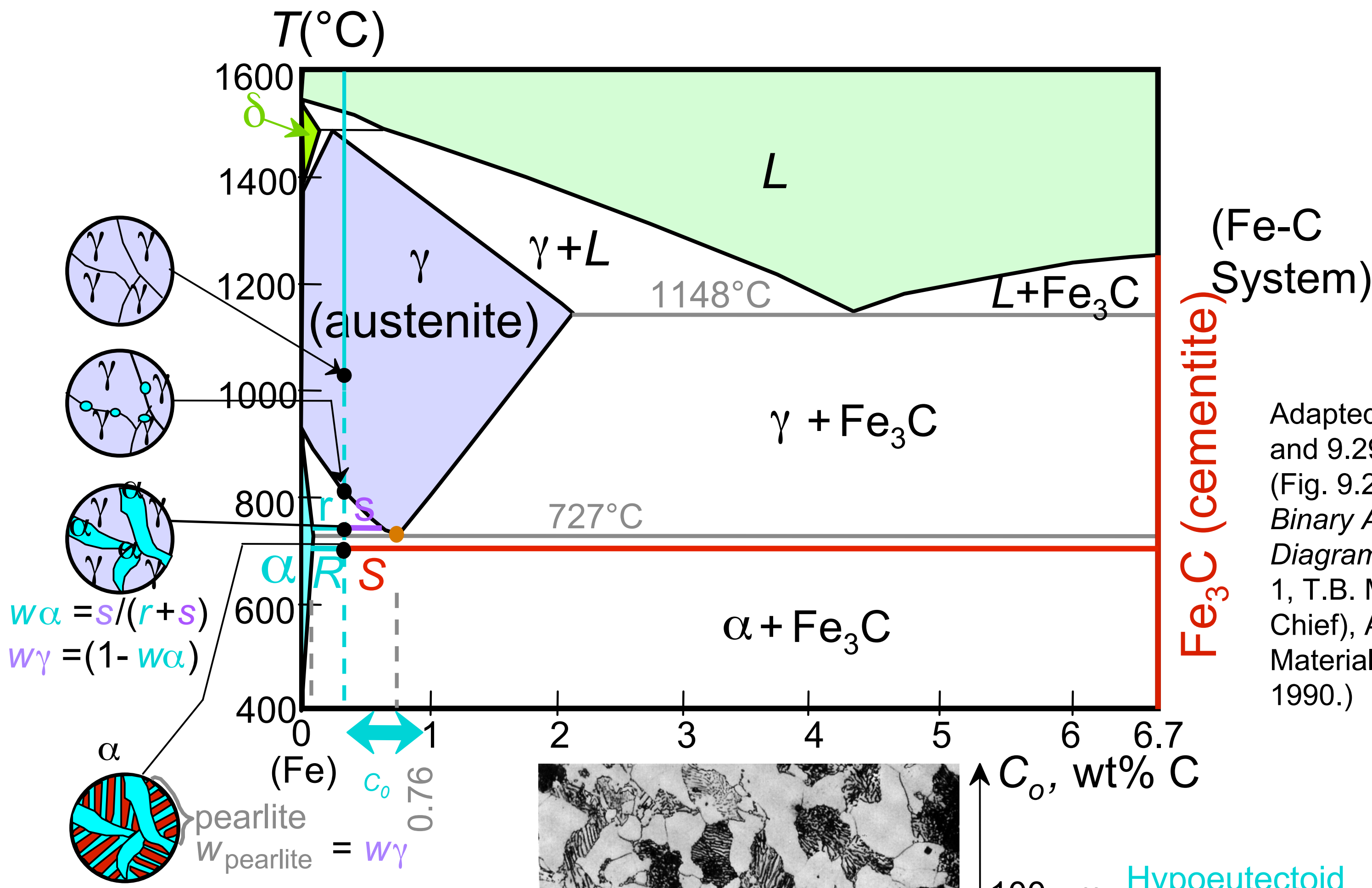

Result: Pearlite = alternating layers of $\alpha$ and $Fe_3C$ phases

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

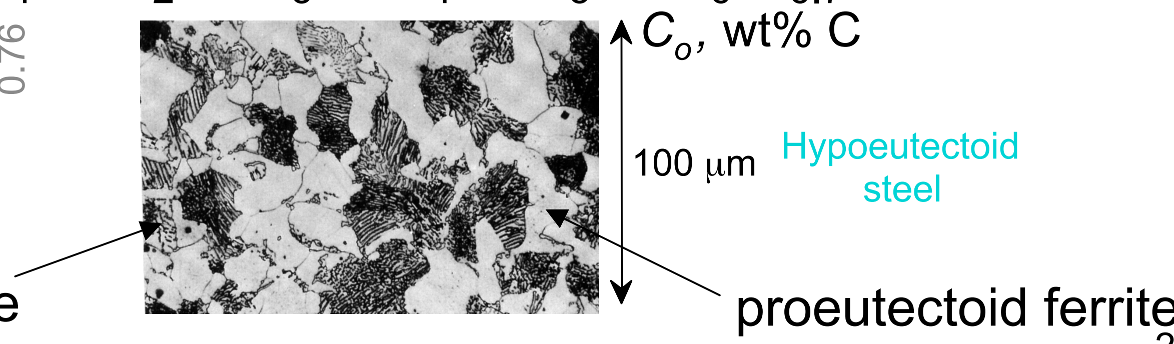



Adapted from Fig. 9.24, *Callister 7e*.

# Hypoeutectoid steel

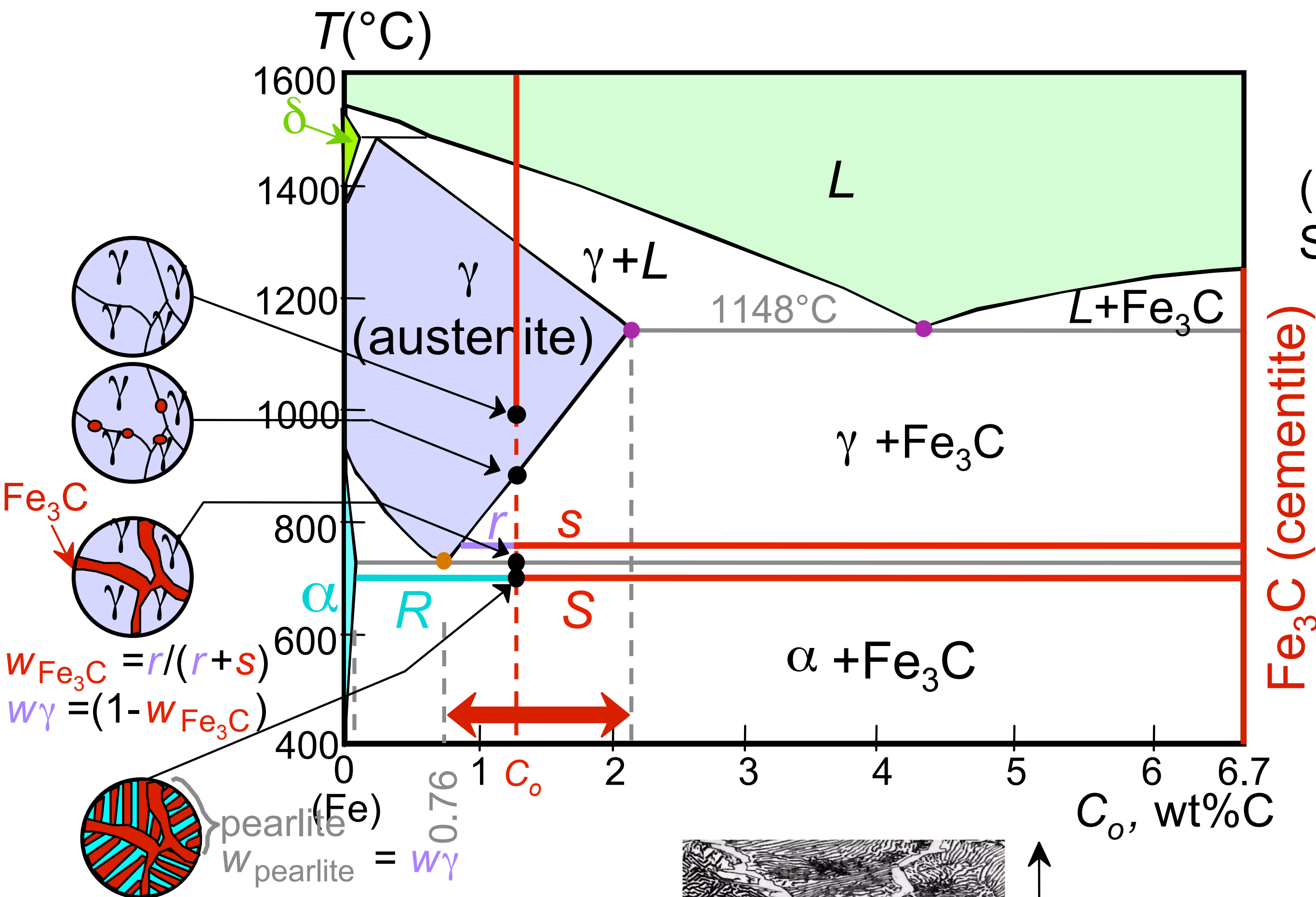



Adapted from Figs. 9.24 and 9.29, *Callister 7e*. (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)




Adapted from Fig. 9.30, *Callister 7e*.

# Hypereutectoid steel




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.)


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