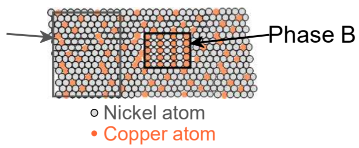
Chapter 9: Phase Diagrams

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?



1

Phase Equilibria: Solubility Limit

Introduction

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

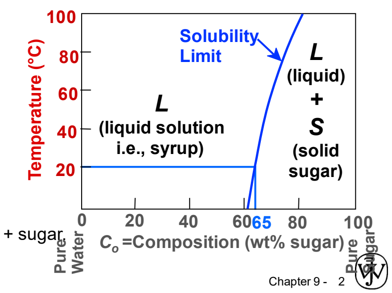
Adapted from Fig. 9.1, *Callister 7e.*

- 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

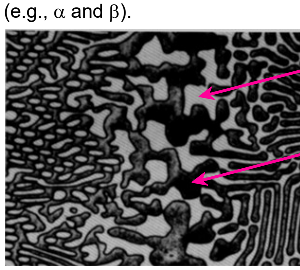


2

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



β (lighter phase)

α (darker phase)

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

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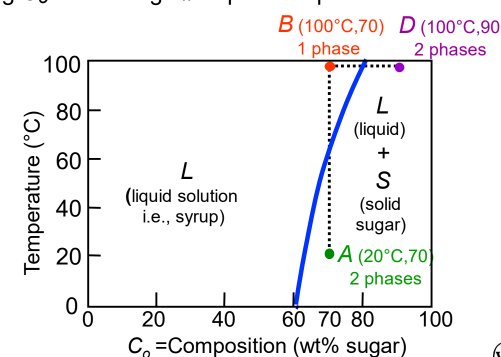
Effect of T & Composition (C_o)

- 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.*

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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.

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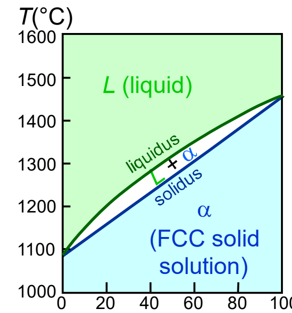
Phase Diagrams

- 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).

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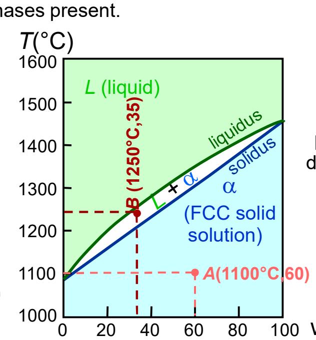
Phase Diagrams:
and types of phases

- 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).

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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)

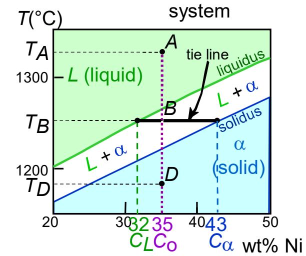
At T_B = 1250°C:

Both α and L

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

$C_\alpha = C_{solidus}$ (= 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.)

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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

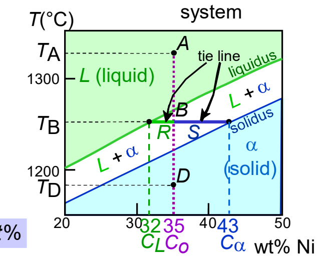
At T_A: Only Liquid (L)
W_L = 100 wt%, W_α = 0

At T_D: Only Solid (α)
W_L = 0, W_α = 100 wt%

At T_B: Both α and L

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

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



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.)

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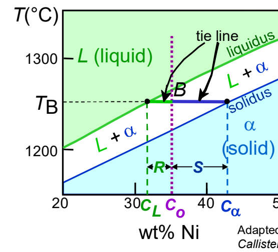
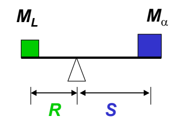
The Lever Rule

- 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)



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

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

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

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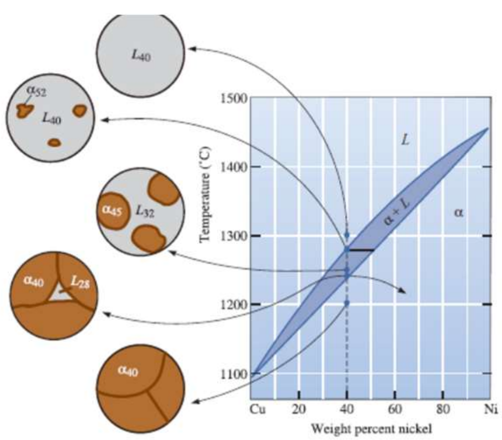

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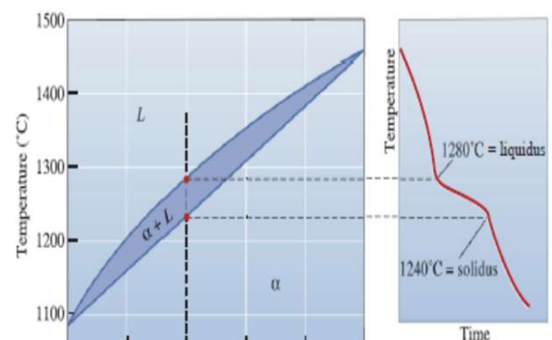

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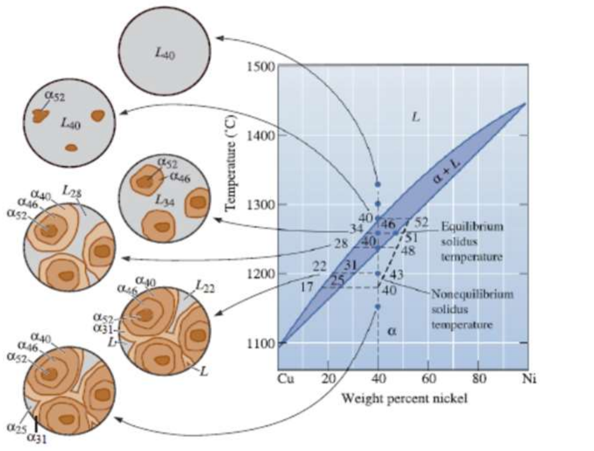

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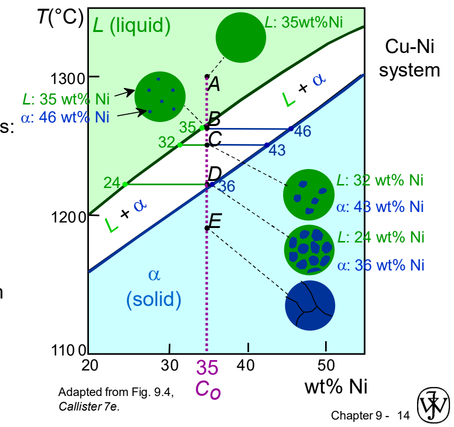
Ex: Cooling in a Cu-Ni Binary

- 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.*

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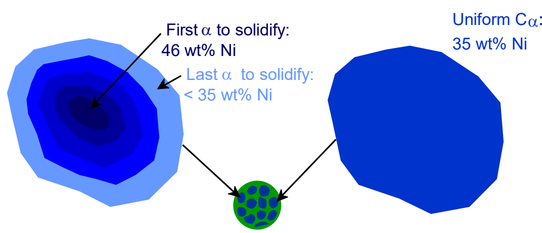
Cored vs Equilibrium Phases

- 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



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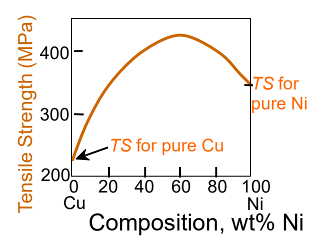
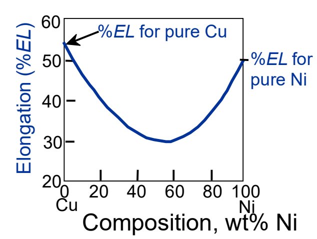
Mechanical Properties: Cu-Ni System

- Effect of solid solution strengthening on:
  - --Tensile strength (*TS*)
  - --Ductility (*%EL*,*%AR*)



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

--Peak as a function of C_o



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

--Min. as a function of C_o

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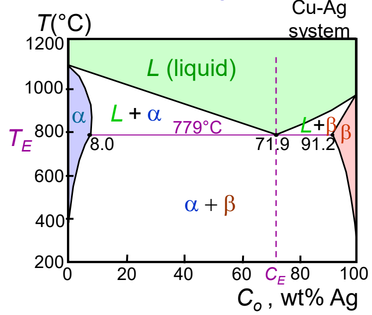
Binary-Eutectic Systems

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.*

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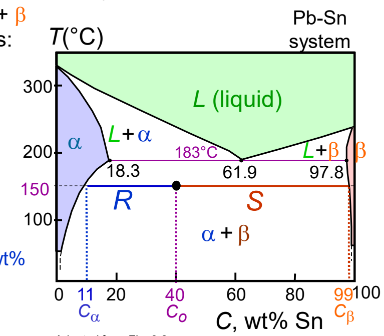
EX: Pb-Sn Eutectic System (1)

- 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.*

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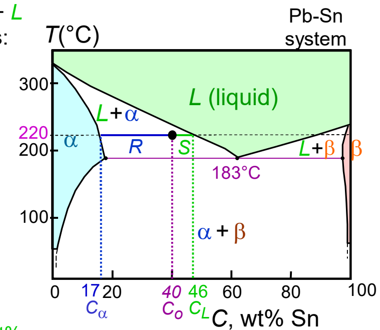
EX: Pb-Sn Eutectic System (2)

- For a 40 wt% Sn-60 wt% Pb alloy at 220°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.*

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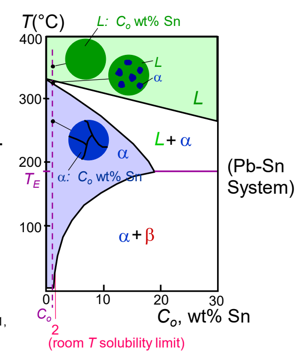
Microstructures in Eutectic Systems: I

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



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

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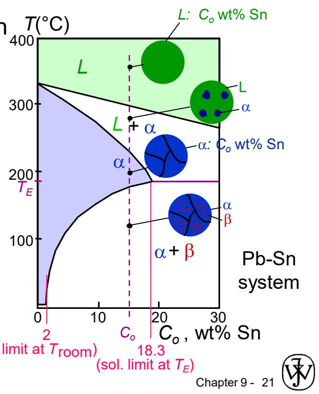
Microstructures in Eutectic Systems: II

- 2 wt% Sn < C_o < 18.3 wt% Sn
- Result:
  - Initially liquid + α
  - then α alone
  - finally two phases
    - α polycrystal
    - fine β-phase inclusions



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

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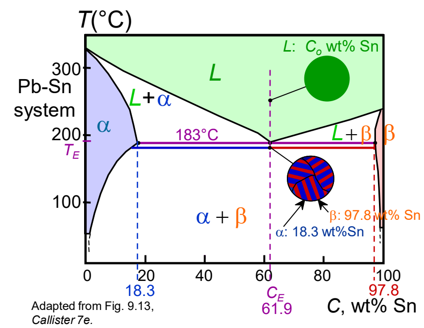
Microstructures in Eutectic Systems: III

- 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

160 μm

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

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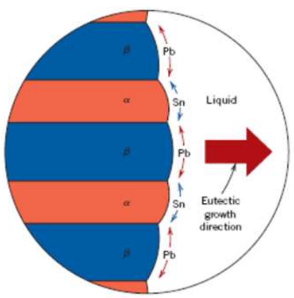
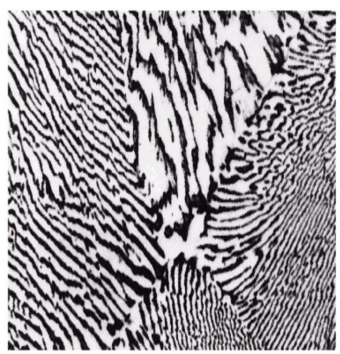
Lamellar Eutectic Structure





Adapted from Figs. 9.14 & 9.15, *Callister 7e.*

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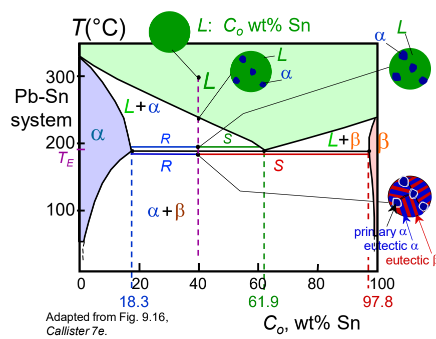
Microstructures in Eutectic Systems: IV

- 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 wt%
  - W_L = (1- W_α) = 50 wt%
- Just below T_E :
  - C_α = 18.3 wt% Sn
  - C_β = 97.8 wt% Sn
  - $W_\alpha = \frac{S}{R+S}$ = 73 wt%
  - W_β = 27 wt%

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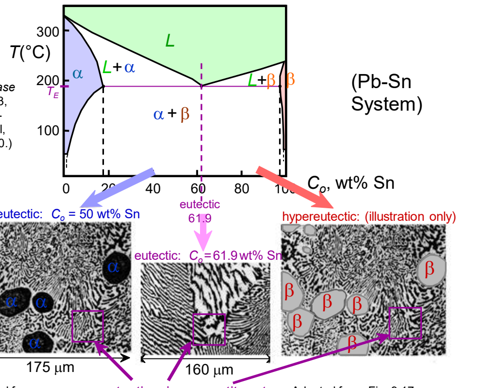
Hypoeutectic & Hypereutectic



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)

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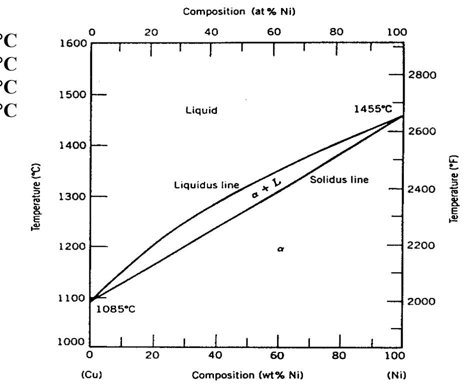
Question 1.

Using the Cu - Ni phase diagram, determine the phases present, the composition of each phase, and the relative proportion of each phase present in:

Cu-70%Ni alloy at 1400°C
Cu-70%Ni alloy at 1300°C
Cu-50%Ni alloy at 1300°C
Cu-20%Ni alloy at 1200°C



Cu 0.128 nm FCC
Ni 0.125 nm FCC

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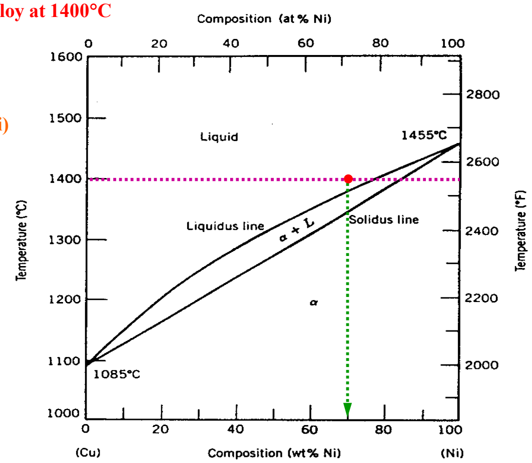
Cu-70%Ni alloy at 1400°C

↓

100%
L (Cu-70%Ni)



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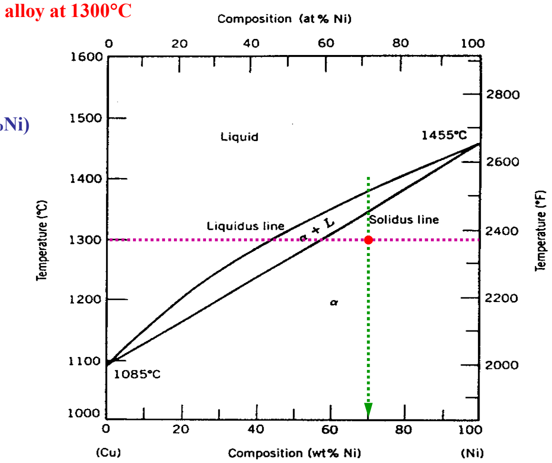
Cu-70%Ni alloy at 1300°C

↓

100%
α (Cu-70%Ni)



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Cu-50%Ni alloy at 1300°C

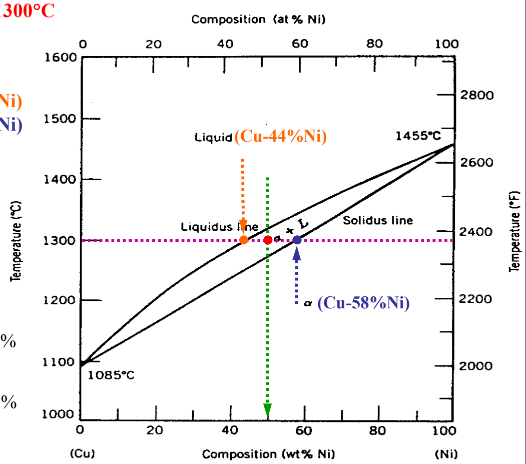
↓

57% L (Cu-44%Ni)
43% α (Cu-58%Ni)

$$L\% = \frac{58-50}{58-44} = 57\%$$

$$\alpha\% = \frac{50-44}{58-44} = 43\%$$

$$L\% + \alpha\% = 100\%$$



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Cu-20%Ni alloy at 1200°C

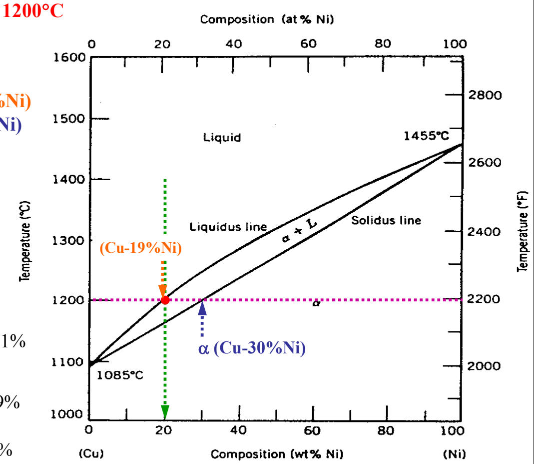
↓

91% L (Cu-19%Ni)
9% α (Cu-30%Ni)

$$L\% = \frac{30-20}{30-19} = 91\%$$

$$\alpha\% = \frac{20-19}{30-19} = 9\%$$

$$L\% + \alpha\% = 100\%$$



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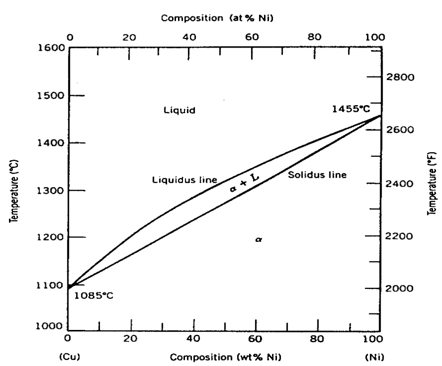
Question 1 _continued

Construct a thermal analysis cooling curve for an alloy containing Cu-50%Ni. Discuss the relationship between the discontinuities on the cooling curve and the respective phase changes that occur.



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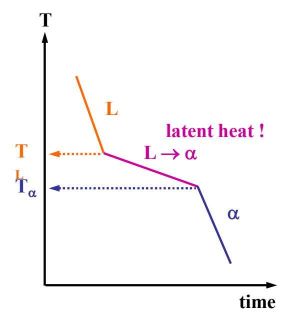
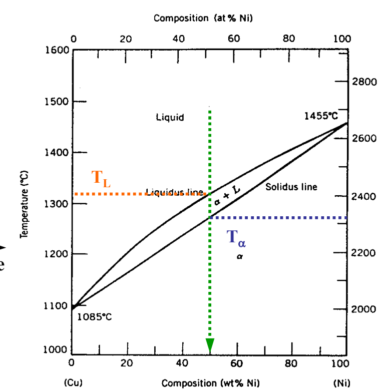
Cu-50%Ni alloy





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Question 2.

With reference to the Pb - Sn phase diagram:

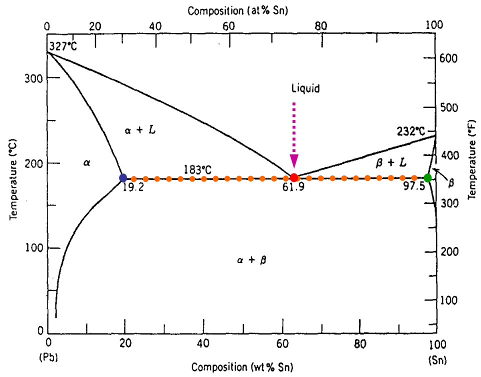
(a) Calculate the relative proportions of the α & β phases present in the eutectic mixture.

$$\alpha^{E}\% = \frac{97.5-61.9}{97.5-19.2} = 45.5\%$$

$$\beta^{E}\% = \frac{61.9-19.2}{97.5-19.2} = 54.5\%$$

or

$$\beta^{E}\% = 1-\alpha^{E}\% = 54.5\%$$



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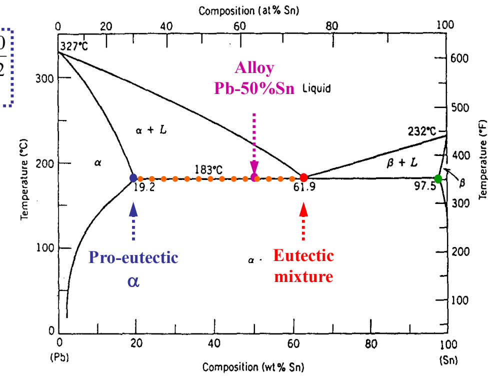
Question 2.

With reference to the Pb - Sn phase diagram:

(b) Calculate the relative proportions of pro-eutectic α and eutectic mixture in an alloy containing 50% Sn at a temperature just below the eutectic temperature.

$$\alpha_{Pro-E}\% = \frac{61.9-50.0}{61.9-19.2} = 27.9\%$$

$$E\% = \frac{50.0-19.2}{61.9-19.2} = 72.1\%$$



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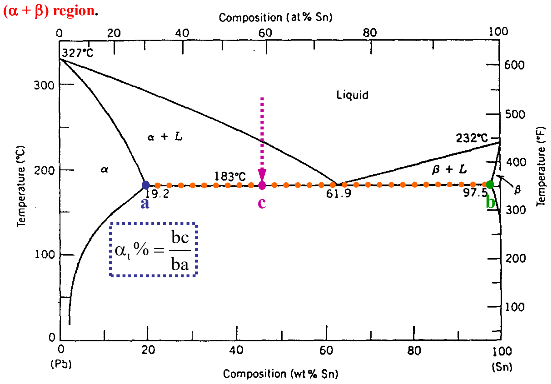
Question 2.

With reference to the Pb - Sn phase diagram:

(c) Show that the total proportion of α obtained by adding together the pro-eutectic α and the α in the eutectic mixture is equal to the α obtained by constructing the tie-line across the (α + β) region.



$$\alpha_{t}\% = \frac{bc}{ba}$$

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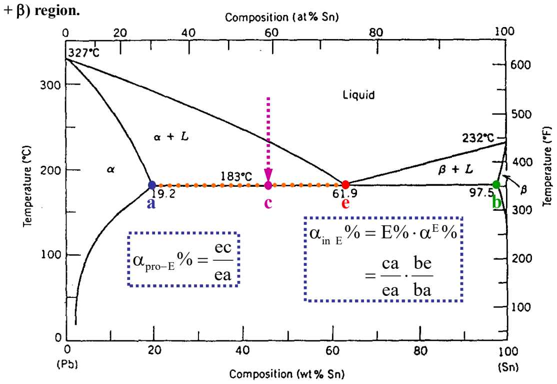
Question 2.

With reference to the Pb - Sn phase diagram:

(c) Show that the total proportion of α obtained by adding together the proeutectic α and the α in the eutectic mixture is equal to the α obtained by constructing the tie-line across the (α + β) region.



$$\alpha_{pro-E}\% = \frac{ec}{ea}$$

$$\alpha_{in\ E}\% = E\% \cdot \alpha^{E}\% = \frac{ca}{ea} \cdot \frac{be}{ba}$$

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MATE 2411 - Tutorial 8.

Question 2.

With reference to the Pb - Sn phase diagram:

(c) Show that the total proportion of α obtained by adding together the proeutectic α and the α in the eutectic mixture is equal to the α obtained by constructing the tie-line across the (α + β) region.

$$\alpha_t\% = \frac{bc}{ba}$$

$$\alpha_t\% = \alpha_{pro-E}\% + \alpha_{in\ E}\%$$
$$= \frac{ec}{ea} + \frac{ca}{ea}\cdot\frac{be}{ba}$$
$$= \frac{ec\cdot ba + ca\cdot be}{ea\cdot ba}$$
$$= \frac{ec\cdot(bc+ca) + ca\cdot be}{ea\cdot ba}$$
$$= \frac{ec\cdot bc + ca\cdot(be+ec)}{ea\cdot ba}$$
$$= \frac{bc\cdot(ec+ca)}{ea\cdot ba} = \frac{bc}{ba}$$

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$$\%\alpha = \frac{97.5-61.9}{97.5-19.2} = 45.5\%$$

$$\%\beta = \frac{61.9-19.2}{97.5-19.2} = 54.5\% \text{ (or 1-45.5\%=54.5\%)}$$

(b) $$\%\alpha \text{ (proeutectic)} = \frac{61.9-50}{61.9-19.2} = 27.9\%$$

$$\%\text{eutectic phase} = \frac{50-19.2}{61.9-19.2} = 72.1\%$$

(c) from (a) and (b)

proeutectic α: $\%\alpha_{pro} = 27.9\%$

α in eutectic mixture: $\%\alpha_{eut} = 72.1\% \times \frac{45.5}{100}$

total proportion of α phase in Pb-50wt%Sn:
$\%\alpha_{tot} = \%\alpha_{pro} + \%\alpha_{eut} = 60.7\%$

alternatively use tie-lie across the α + β region
$$\%\alpha_{tot} = \frac{97.5-50}{97.5-19.2} = 60.7\%$$

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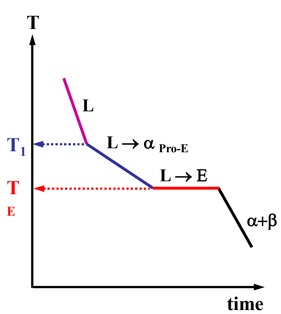
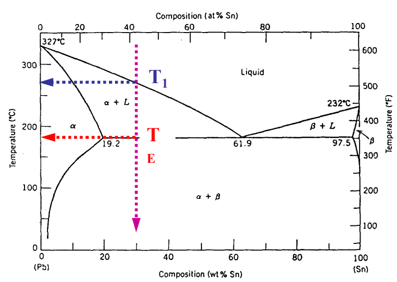
Question 2.

With reference to the Pb - Sn phase diagram:

(d) Construct a thermal analysis cooling curve for an alloy containing 30% Sn. Discuss the relationship between the discontinuities on the cooling curve and the respective phase changes that occur.





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Question 2.

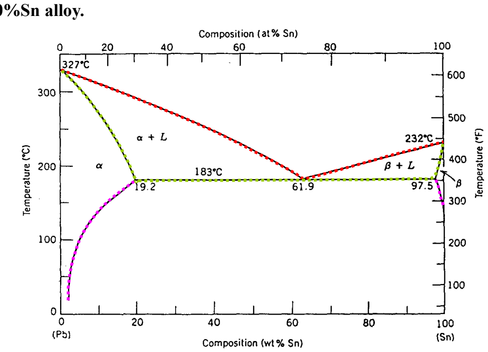
With reference to the Pb - Sn phase diagram:

(e) Highlight the liquidus and solidus lines. Discuss the significance of the regions above the liquidus, below the solidus and between the two lines. Highlight any solvus line. Discuss the significance of this line, taking example of the cooling process of Pb-10%Sn alloy.

Liquidus line

Solidus line

Solvus line



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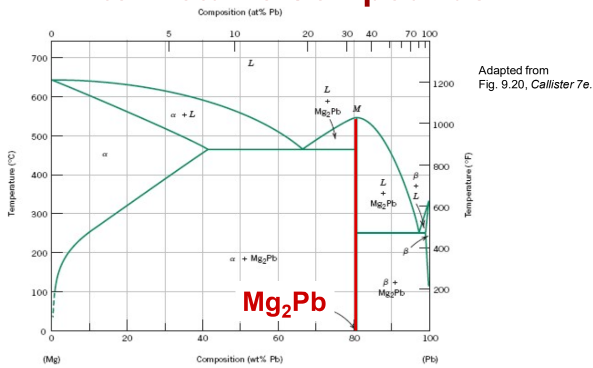
Intermetallic Compounds



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

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

Eutectoid & Peritectic

- Eutectic - liquid in equilibrium with two solids

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

- Eutectoid - solid phase in equation with two solid phases

  $S_2 \rightleftharpoons S_1 + S_3$

  intermetallic compound - cementite

  $\gamma \underset{heat}{\overset{cool}{\rightleftharpoons}} \alpha + Fe_3C$ (727ºC)

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

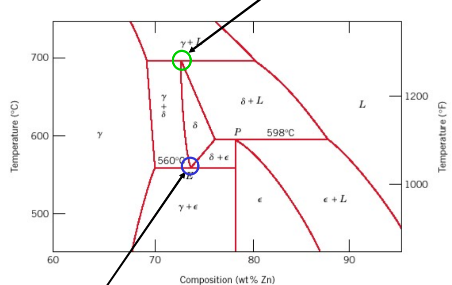
  $S_1 + L \rightleftharpoons S_2$

  $\delta + L \underset{heat}{\overset{cool}{\rightleftharpoons}} \gamma$ (1493ºC)

Eutectoid & Peritectic

Cu-Zn Phase diagram

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



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

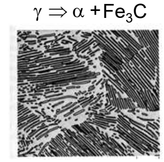
Adapted from Fig. 9.21, *Callister 7e.*

Iron-Carbon (Fe-C) Phase Diagram

- 2 important points

  -Eutectic (*A*): $L \Rightarrow \gamma + Fe_3C$

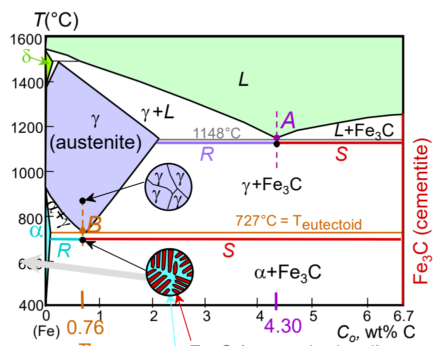
  -Eutectoid (*B*): $\gamma \Rightarrow \alpha + Fe_3C$



120 μm

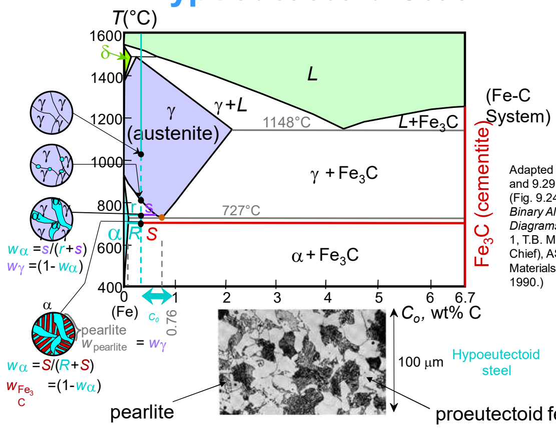
Result: Pearlite = alternating layers of α and Fe_3C phases

(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*.

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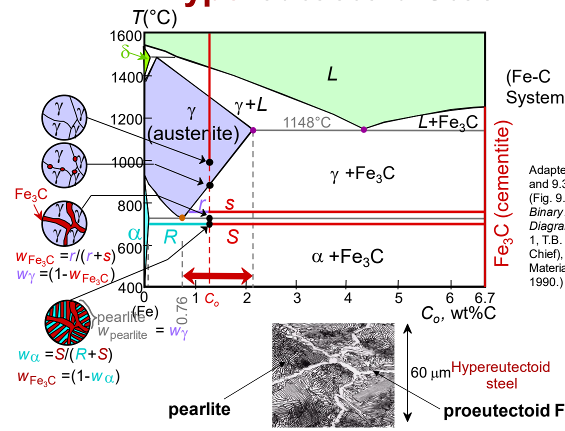
Hypereutectoid Steel



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*.

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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)

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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_α = 0.022 wt% C

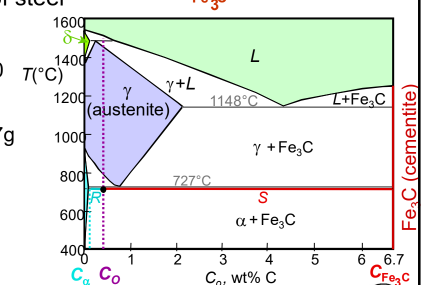
C_{Fe_3C} = 6.70 wt% C

$$\frac{Fe_3C}{Fe_3C+\alpha} = \frac{C_O - C_\alpha}{C_{Fe_3C} - C_\alpha} x100$$

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

$Fe_3C = 5.7$ g

$\alpha = 94.3$ g



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Chapter 9 – Phase Equilibria

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

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

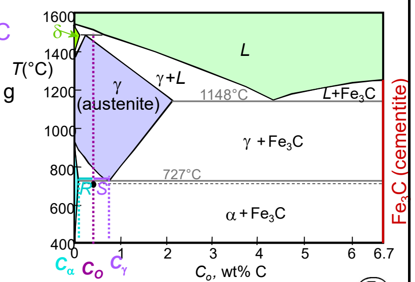
C_o = 0.40 wt% C

C_α = 0.022 wt% C

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

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

pearlite = 51.2 g
proeutectoid α = 48.8 g



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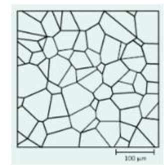
Grain-Size Computations Using ASTM and Intercept Methods

The following is a schematic micrograph that represents the microstructure of some hypothetical metal.



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Determine the following:

(a) Mean intercept length

(b) ASTM grain-size number, G using Equation

$$G = -6.6457 \log \bar{\ell} - 3.298 \quad (\text{for } \bar{\ell} \text{ in mm})$$

$$G = -6.6353 \log \bar{\ell} - 12.6 \quad (\text{for } \bar{\ell} \text{ in in.})$$

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At this point, it is worthwhile to discuss the representation of magnification (i.e., linear magnification) for a micrograph. Sometimes magnification is specified in the micrograph legend (e.g., "60×" for Figure 4.14*b*); this means the micrograph represents a 60 times enlargement of the specimen in real space. *Scale bars* are also used to express degree of magnification. A scale bar is a straight line (typically horizontal), either superimposed on or located near the micrograph image. Associated with the bar is a length, typically expressed in microns; this value represents the distance in magnified space corresponding to the scale line length. For example, in Figure 4.15*b*, a scale bar is located below the bottom right-hand corner of the micrograph; its "100 μm" notation indicates that 100 μm correlates with the scale bar length.

To compute magnification from a scale bar, the following procedure may be used:

1. Measure the length of the scale bar in millimeters using a ruler.
2. Convert this length into microns [i.e., multiply the value in step (1) by 1000 because there are 1000 microns in a millimeter].
3. Magnification M is equal to

$$M = \frac{\text{measured scale length (converted to microns)}}{\text{the number appearing by the scale bar (in microns)}} \quad (4.20)$$

For example, for Figure 4.15*b*, the measured scale length is approximately 10 mm, which is equivalent to (10 mm)(1000 μm/mm) = 10,000 μm. Inasmuch as the scale bar length is 100 μm, the magnification is equal to

$$M = \frac{10{,}000\ \mu m}{100\ \mu m} = 100\times$$

This is the value given in the figure legend.

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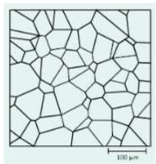
Solution

(a) We first determine the magnification of the micrograph using Equation 4.20. The scale bar length is measured and found to be 16 mm, which is equal to 16,000 μm; and because the scale bar number is 100 μm, the magnification is

$$M = \frac{16{,}000\ \mu\text{m}}{100\ \mu\text{m}} = 160\times$$



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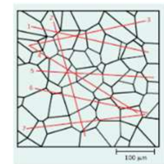
The following sketch is the same micrograph on which have been drawn seven straight lines (in red), which have been numbered.

The length of each line is 50 mm, and thus the total line length (L_T in Equation 4.16) is

$$(7\ \text{lines})(50\ \text{mm/line}) = 350\ \text{mm}$$

Tabulated next is the number of grain-boundary intersections for each line:

Line Number	*Number of Grain-Boundary Intersections*
1	8
2	8
3	8
4	9
5	9
6	9
7	7
Total	58



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Thus, inasmuch as $L_T = 350$ mm, $P = 58$ grain-boundary intersections, and the magnification $M = 160\times$, the mean intercept length $\bar{\ell}$ (in millimeters in real space), Equation 4.16, is equal to

$$\bar{\ell} = \frac{L_T}{PM}$$

$$= \frac{350\ \text{mm}}{(58\ \text{grain boundary intersections})(160\times)} = 0.0377\ \text{mm}$$

(b) The value of G is determined by substitution of this value for $\bar{\ell}$ into Equation 4.19a; therefore,

$$G = -6.6457 \log \bar{\ell} - 3.298$$
$$= (-6.6457) \log(0.0377) - 3.298$$
$$= 6.16$$

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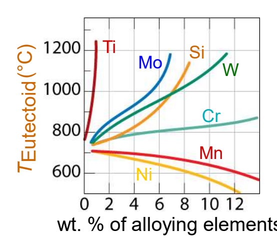
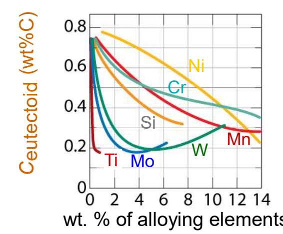
Alloying Steel with More Elements

- $T_{eutectoid}$ 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.)

- $C_{eutectoid}$ 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.)

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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.

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ANNOUNCEMENTS

Reading:

Core Problems:

Self-help Problems:

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