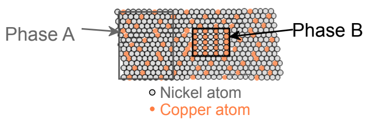
Chapter 9: _______ Diagrams

ISSUES TO ADDRESS...

- When we combine two __________...
  what is the resulting ____________state?
- In particular, if we specify...
  -- the ____________ (e.g., wt% Cu - wt% Ni), and
  -- the temperature (*T*)

then...
  How many __________ form?
  What is the composition of each __________?
  What is the _________ of each phase?



Chapter 9 - 1

____

Phase Equilibria: Solubility Limit

- Solution – solid, liquid, or gas solutions, single phase
- Mixture – ______________________________

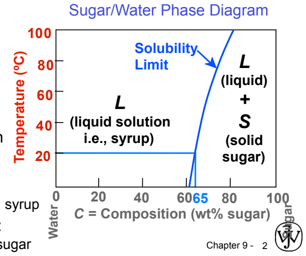
Adapted from Fig. 9.1, *Callister & Rethwisch 8e.*

- Solubility Limit:
  Maximum ____________ for which only a _____________ _________ exists.

Question: What is the __________ limit for sugar in water at 20ºC?

Answer: ___ wt% sugar.
At 20ºC, if *C* < 65 wt% sugar: syrup
At 20ºC, if *C* > 65 wt% sugar: syrup + sugar

Sugar/Water Phase Diagram



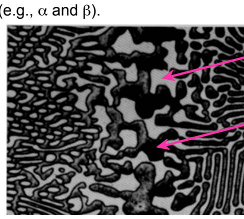
Chapter 9 - 2

____

Components and Phases

- Components:
  ____
  (e.g., Al and Cu)
- Phases:
  The physically and chemically distinct material regions that form (e.g., α and β).

Aluminum-Copper _______



β (lighter ________)

α (darker ________)

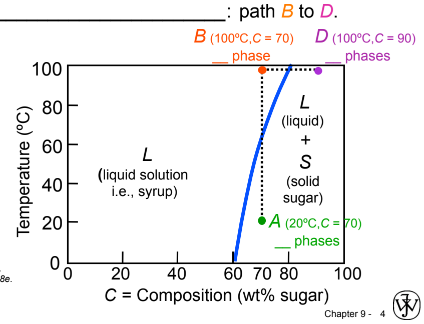
Adapted from chapter-opening photograph, Chapter 9, *Callister, Materials Science & Engineering: An Introduction, 3e.*

Chapter 9 - 3

Effect of Temperature & Composition

- Altering ______________________: path *A* to *B*.
- Altering ______________________: path *B* to *D*.

water-sugar system



Adapted from Fig. 9.1, *Callister & Rethwisch 8e.*

Chapter 9 - 4

Criteria for Solid Solubility

_____________ (e.g., Ni-Cu solution)

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

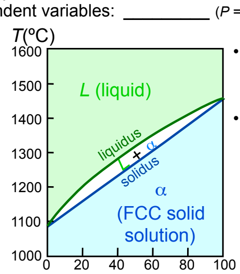
- Both have the same ____________________ and have similar ________________ and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.
- ____________________ in one another for all proportions.

Chapter 9 - 5

Phase Diagrams

- Indicate phases as a function of *T*, *C*, and *P*.
- For this course:
  - binary systems: __________________.
  - independent variables: ________ (*P* = 1 atm is almost always used).

Phase Diagram for Cu-Ni system



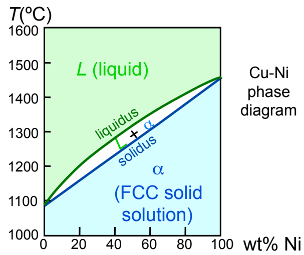
- 2 phases:
  - ____________
  - ____________
- 3 different phase fields:
  - ______
  - ______
  - ______

Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Chapter 9 - 6

Isomorphous Binary Phase Diagram

- Phase diagram: Cu-Ni system.
- System is:
  -- ____________ *i.e.*, 2 components: Cu and Ni.
  -- ____________ *i.e.*, complete _________ of one component in another; α phase field extends from 0 to 100 wt% Ni.

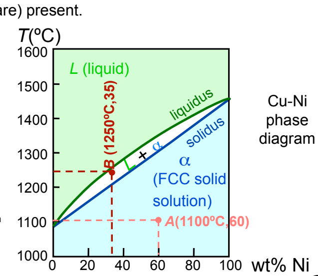


Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Chapter 9 - 7

Phase Diagrams: Determination of phase(s) present

- Rule 1: If we know ___________, then we know:
  -- which phase(s) is (are) present.
- Examples:
  A(1100ºC, 60 wt% Ni): ______________
  B(1250ºC, 35 wt% Ni): ______________

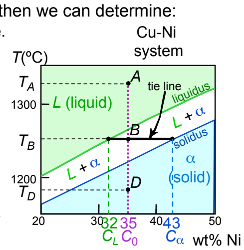


Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Chapter 9 - 8

Phase Diagrams: Determination of phase compositions

- Rule 2: If we know T and C_0, then we can determine:
  -- the composition of each phase.
- Examples:
  Consider C_0 = 35 wt% Ni
  At T_A = 1320ºC:
  ____
  C_L ______________
  At T_D = 1190ºC:
  ____
  C_α ______________
  At T_B = 1250ºC:
  ____
  $C_L = C_{liquidus}$ (= ___ wt% Ni)
  $C_\alpha = C_{solidus}$ (= ___ wt% Ni)



Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

Chapter 9 - 9

Phase Diagrams:
Determination of phase weight fractions

- Rule 3: If we know T and C_0, then can determine:
  -- the _______________ of each phase.
- Examples:

Consider C_0 = 35 wt% Ni

At T_A : Only Liquid (L) present

W_L = _____, W_α = _____

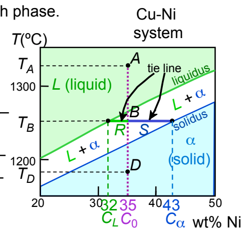
At T_D : Only Solid (α) present

____

At T_B : __________________

$$W_L = \frac{S}{R+S} = \frac{43-35}{43-32} = 0.73$$

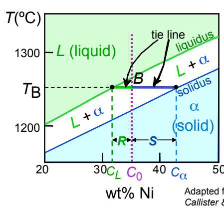
$$W_\alpha = \frac{R}{R+S} = 0.27$$



Adapted from Fig. 9.3(a), *Callister & Rethwisch 8e.* (Fig. 9.3(a) is adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash (Ed.), ASM International, Materials Park, OH (1991).

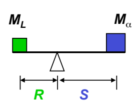
The Lever Rule

- _________ – connects the phases in equilibrium with each other – also sometimes called an ___________



Adapted from Fig. 9.3(b), *Callister & Rethwisch 8e.*

What fraction of each phase?
Think of the tie line as a lever (teeter-totter)



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

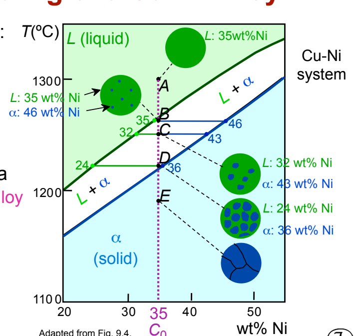
$$W_L = \frac{M_L}{M_L + M_\alpha} = \frac{S}{R+S} =$$

$$W_\alpha = \frac{R}{R+S} =$$

Ex: Cooling of a Cu-Ni Alloy

- Phase ________: Cu-Ni system.
- Consider

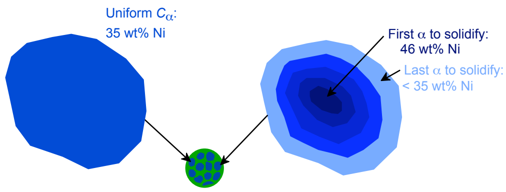
  ____________ changes that accompany the ___________ of a C_0 = 35 wt% Ni alloy



Adapted from Fig. 9.4, *Callister & Rethwisch 8e.*

Cored vs Equilibrium Structures

- ______________________
- Cu-Ni _____: First α to solidify has C_α = ____ wt% Ni.
  Last α to solidify has C_α = ____ wt% Ni.
- ______rate of cooling: Equilibrium structure
- _____ rate of cooling: Cored structure

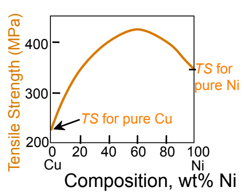


Chapter 9 - 13

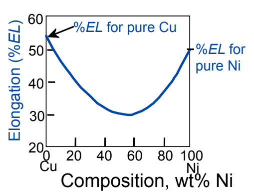
Mechanical Properties: Cu-Ni System

- Effect of _______________________ on:

-- Tensile _________ (*TS*) -- Ductility (%*EL*)



Adapted from Fig. 9.6(a), *Callister & Rethwisch 8e.*



Adapted from Fig. 9.6(b), *Callister & Rethwisch 8e.*

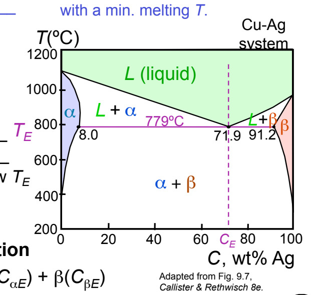
Chapter 9 - 14

Binary-Eutectic Systems

has a special composition with a min. melting *T*.

Ex.: Cu-Ag system

- 3 single phase regions (L, α, β)
- Limited solubility:
  ____
  ____
- T_E : No _______ below T_E
- C_E : Composition at temperature T_E
- ____________ **reaction**



Adapted from Fig. 9.7, *Callister & Rethwisch 8e.*

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

$$L(71.9 \text{ wt\% Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0 \text{ wt\% Ag}) + \beta(91.2 \text{ wt\% Ag})$$

9 - 15

EX 1: Pb-Sn Eutectic System

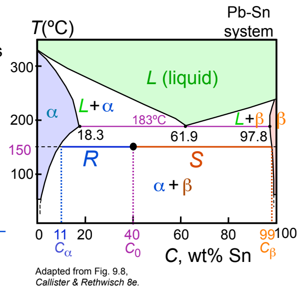
- For a 40 wt% Sn-60 wt% Pb alloy at 150ºC, determine:
  - -- the phases present
  - **Answer:** $\alpha + \beta$
  - -- the phase compositions
  - **Answer:** C_α = __ wt% Sn
  - C_β = __ wt% Sn
  - -- the relative amount of each phase
  - **Answer:**

$$W_\alpha = \frac{S}{\_\_\_\_} = \frac{C_\beta - C_0}{C_\beta - C_\alpha}$$

$$= \frac{99 - 40}{99 - 11} = \frac{59}{\_\_} = \_\_\_\_\_$$

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

$$= \frac{40 - 11}{99 - 11} = \frac{29}{\_\_} = \_\_\_\_\_$$



Adapted from Fig. 9.8, *Callister & Rethwisch 8e.*

Chapter 9 - 16

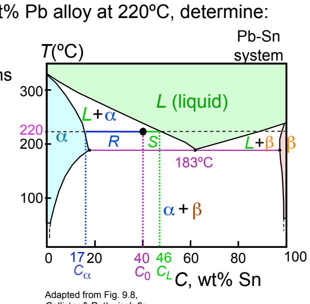
EX 2: Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 220ºC, determine:
  - -- the phases present:
  - **Answer:** $\alpha + L$
  - -- the phase compositions
  - **Answer:** C_α = __ wt% Sn
  - C_L = __ wt% Sn
  - -- the relative amount of each phase
  - **Answer:**

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17}$$

$$= \frac{6}{\_\_} = \_\_\_\_\_$$

$$W_L = \frac{C_0 - C_\alpha}{C_L - C_\alpha} = \frac{23}{\_\_} = \_\_\_\_\_$$

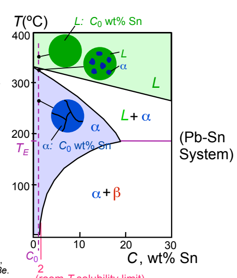


Adapted from Fig. 9.8, *Callister & Rethwisch 8e.*

Chapter 9 - 17

Microstructural Developments in Eutectic Systems I

- For alloys for which C_o < 2 wt% Sn
- Result: at room temperature
  - -- ____________ with grains of ___________ having ___________ C_o

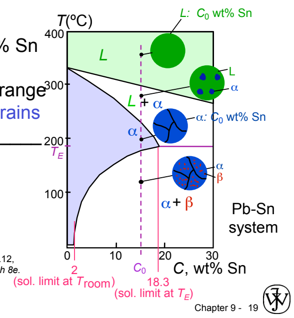


Adapted from Fig. 9.11, *Callister & Rethwisch 8e.*

Chapter 9 - 18

Microstructural Developments in Eutectic Systems II

- For alloys for which
  2 wt% Sn < C_o < 18.3 wt% Sn
- Result:
  at ___________ in α + β range
  --polycrystalline with __ grains
  and small __-phase ________

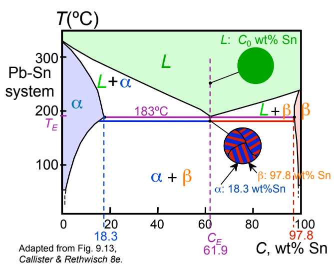


Adapted from Fig. 9.12, *Callister & Rethwisch 8e.*

Chapter 9 - 19

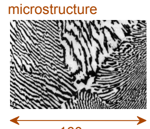
Microstructural Developments in Eutectic Systems III

- For alloy of composition C_o = C_E
- Result: Eutectic microstructure (_______ structure)
  --alternating layers (__________) of α and β phases.



Adapted from Fig. 9.13, *Callister & Rethwisch 8e.*

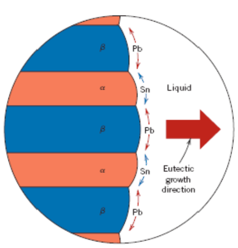
Micrograph of Pb-Sn eutectic microstructure

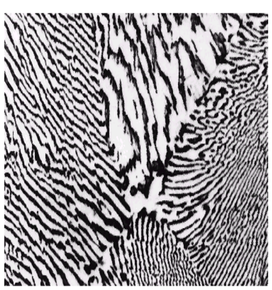


Adapted from Fig. 9.14, *Callister & Rethwisch 8e.*

Chapter 9 - 20

Lamellar Eutectic Structure



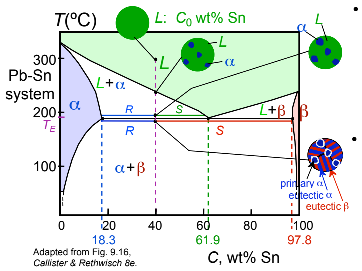


Adapted from Figs. 9.14 & 9.15, *Callister & Rethwisch 8e.*

Chapter 9 - 21

Microstructural Developments in Eutectic Systems IV

- For ______ for which 18.3 wt% Sn < C_0 < 61.9 wt% Sn
- Result: α phase particles and a ________ microconstituent



- Just above T_E:
  - C_α = ____ wt% Sn
  - C_L = ____ wt% Sn
  - $W_\alpha = \frac{S}{R+S}$ = 0.50
  - $W_L = (1 - W_\alpha)$ = 0.50
- Just below T_E:
  - C_α = _____ wt% Sn
  - C_β = _____ wt% Sn
  - $W_\alpha = \frac{S}{R+S}$ = 0.73
  - W_β = 0.27

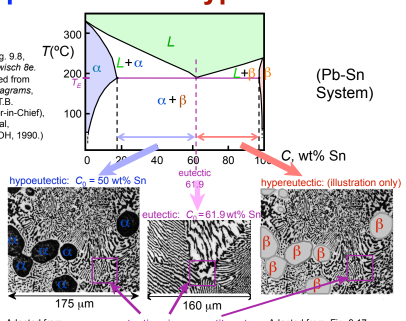
Adapted from Fig. 9.16, *Callister & Rethwisch 8e.*

Hypoeutectic & Hypereutectic

Adapted from Fig. 9.8, *Callister & Rethwisch 8e.* (Fig. 10.8 adapted from *Binary Phase Diagrams*, 2nd ed., Vol. 3, T.B. Massalski (Editor-in-Chief), ASM International, Materials Park, OH, 1990.)

(Pb-Sn System)

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

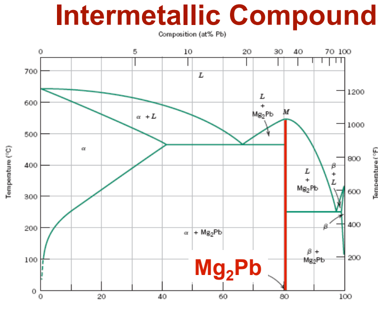


Adapted from Fig. 9.17, *Callister & Rethwisch 8e.*

Adapted from Fig. 9.14, *Callister & Rethwisch 8e.*

Adapted from Fig. 9.17, *Callister & Rethwisch 8e.* (Illustration only)

Intermetallic Compounds



Adapted from Fig. 9.20, *Callister & Rethwisch 8e.*

Note: intermetallic compound exists as a ____ on the diagram - not an ______ - because of stoichiometry (i.e. composition of a ____________ is a fixed value).

Eutectic, Eutectoid, & Peritectic

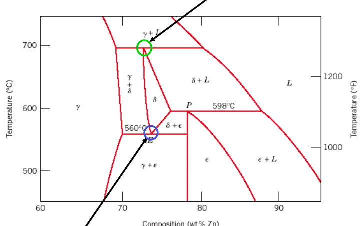
- Eutectic - liquid transforms to two solid phases
  $L \underset{heat}{\overset{cool}{\rightleftharpoons}} \alpha + \beta$ (For Pb-Sn, 183ºC, 61.9 wt% Sn)
- _______ – one solid phase __________ to two other solid phases
  $S_2 \rightleftharpoons S_1 + S_3$ ______ compound - cementite
  $\gamma \underset{heat}{\overset{cool}{\rightleftharpoons}} \alpha + Fe_3C$ (For Fe-C, 727ºC, 0.76 wt% C)
- ________ - liquid and one solid phase transform to a second solid phase
  $S_1 + L \rightleftharpoons S_2$
  $\delta + L \underset{heat}{\overset{cool}{\rightleftharpoons}} \gamma$ (For Fe-C, 1493ºC, 0.16 wt% C)

Chapter 9 - 25

Eutectoid & Peritectic

Cu-Zn Phase diagram

_______transformation $\gamma + L \rightleftharpoons \delta$



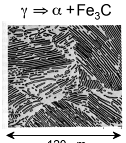
Adapted from Fig. 9.21, *Callister & Rethwisch 8e.*

_______transformation $\delta \rightleftharpoons \gamma + \varepsilon$

Chapter 9 - 26

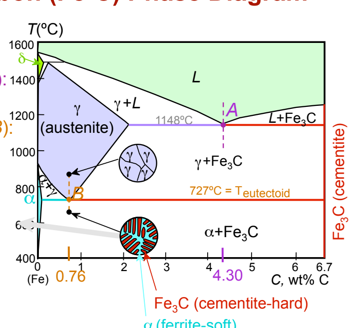
Iron-Carbon (Fe-C) Phase Diagram

- 2 important points
  - _________ (A): $L \Rightarrow \gamma + Fe_3C$
  - _________ (B): $\gamma \Rightarrow \alpha + Fe_3C$



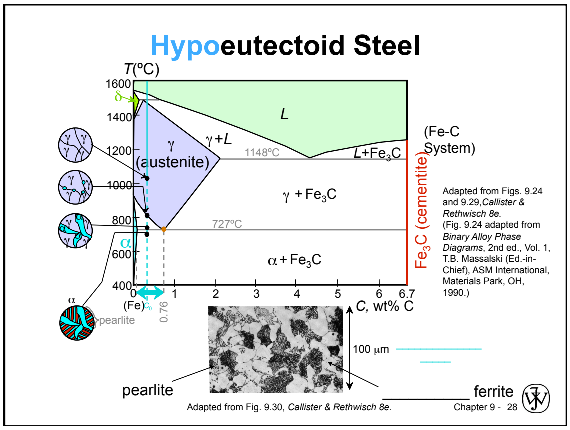
Result: _______ = alternating layers of α and Fe_3C phases

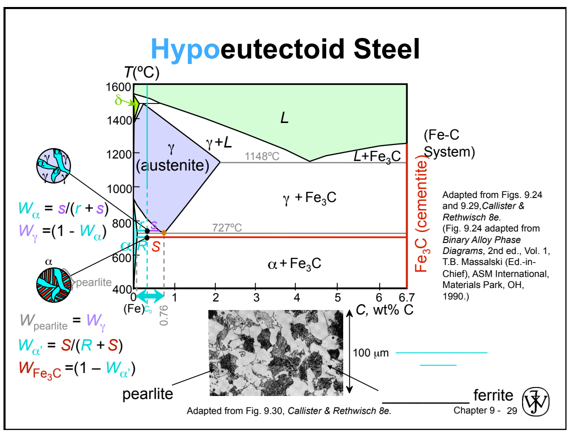
(Adapted from Fig. 9.27, *Callister & Rethwisch 8e.*)

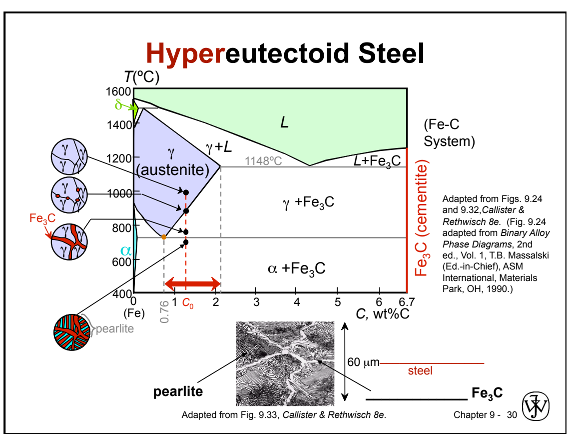


Adapted from Fig. 9.24, *Callister & Rethwisch 8e.*

Chapter 9 - 27


Hypoeutectoid Steel
T(°C)
1600
1400
1200
1000
800
600
400
δ
L
γ+L
γ
(austenite)
1148°C
L+Fe3C
γ + Fe3C
727°C
α
α + Fe3C
(Fe-C System)
Fe3C (cementite)
0 (Fe)
0.76
1 2 3 4 5 6 6.7
C, wt% C
pearlite
100 µm
ferrite
pearlite
Adapted from Figs. 9.24 and 9.29, Callister & Rethwisch 8e. (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 & Rethwisch 8e.
Chapter 9 - 28


Hypoeutectoid Steel
T(°C)
1600
1400
1200
1000
800
600
400
δ
L
γ+L
γ
(austenite)
1148°C
L+Fe3C
γ + Fe3C
727°C
r s
R S
α + Fe3C
(Fe-C System)
Fe3C (cementite)
Wα = s/(r + s)
Wγ = (1 - Wα)
pearlite
Wpearlite = Wγ
Wα' = S/(R + S)
WFe3C = (1 – Wα')
0 (Fe)
0.76
1 2 3 4 5 6 6.7
C, wt% C
100 µm
ferrite
pearlite
Adapted from Figs. 9.24 and 9.29, Callister & Rethwisch 8e. (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 & Rethwisch 8e.
Chapter 9 - 29


Hypereutectoid Steel
T(°C)
1600
1400
1200
1000
800
600
400
δ
L
γ+L
γ
(austenite)
1148°C
L+Fe3C
γ + Fe3C
Fe3C
α
α + Fe3C
(Fe-C System)
Fe3C (cementite)
pearlite
0 (Fe)
0.76
1 C0 2 3 4 5 6 6.7
C, wt%C
60 µm
steel
pearlite
Fe3C
Adapted from Figs. 9.24 and 9.32, Callister & Rethwisch 8e. (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 & Rethwisch 8e.
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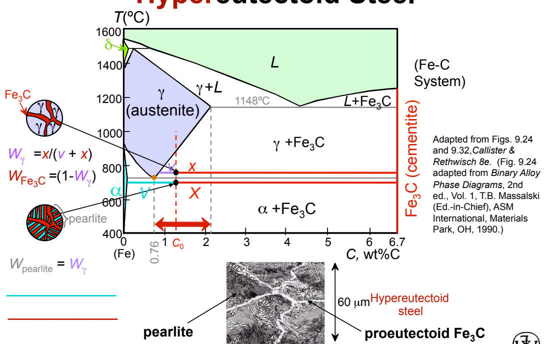
Hypereutectoid Steel



Adapted from Figs. 9.24 and 9.32, *Callister & Rethwisch 8e.* (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 & Rethwisch 8e.*

Example Problem

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

a) The compositions of Fe_3C and ferrite (α).

b) The amount of cementite (in grams) that forms in 100 g of steel.

c) The amounts of pearlite and proeutectoid ferrite (α) in the 100 g.

Solution to Example Problem

a) Using the *RS* tie line just below the ____________

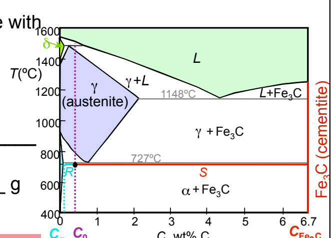
C_α = ______ wt% C

C_{Fe_3C} = ____ wt% C

b) Using the ______ rule with the tie line shown

$$W_{Fe_3C} = \frac{R}{R+S} = \frac{C_o - C_\alpha}{C_{Fe_3C} - C_\alpha}$$

$$= \frac{0.40 - 0.022}{6.70 - 0.022} = \_\_\_\_\_\_$$



Amount of Fe_3C in _______ g

= (100 g)W_{Fe_3C}

= (100 g)(0.057) = ____

Solution to Example Problem (cont.)

c) Using the *VX* tie line just above the eutectoid and realizing that

C_0 = 0.40 wt% C
C_α = 0.022 wt% C
$C_{pearlite} = C_\gamma$ = ______ wt% C

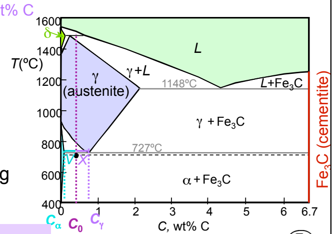
$$W_{pearlite} = \frac{V}{V+X} = \frac{C_0 - C_\alpha}{C_\gamma - C_\alpha}$$

$$= \frac{0.40 - 0.022}{0.76 - 0.022} = 0.512$$

Amount of pearlite in 100 g

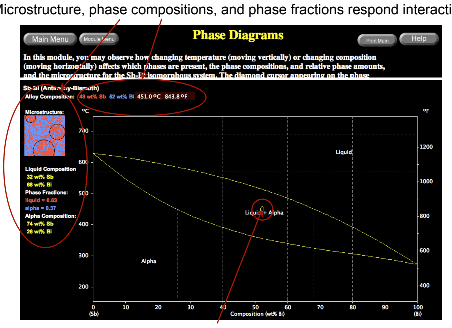
= (100 g)$W_{pearlite}$

= (100 g)(0.512) = ______



VMSE: Interactive Phase Diagrams

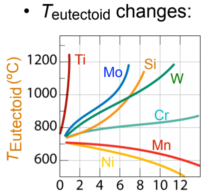
Microstructure, phase compositions, and phase fractions respond interactively



Change alloy composition

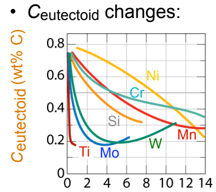
Alloying with Other Elements

- $T_{eutectoid}$ changes:



Adapted from Fig. 9.34,*Callister & Rethwisch 8e.* (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 & Rethwisch 8e.* (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 present,
  -- the composition of each phase,
  -- and the weight fraction of each phase

  given the temperature and composition of the system.
- The microstructure of an alloy depends on
  -- its composition, and
  -- whether or not cooling rate allows for maintenance of equilibrium.
- Important phase diagram phase transformations include eutectic, eutectoid, and peritectic.

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