BFF1113
Engineering Materials

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Course Guidelines:

1. Introduction to Engineering Materials
2. Bonding and Properties
3. Crystal Structures & Properties
4. Imperfection in Solids
5. Mechanical Properties of Materials
6. Physical Properties of Materials
7. Failure & Fundamental of Fracture
8. Metal Alloys
9. Phase Diagram
10. Phase Transformation – Heat Treatment
11. Processing and Application of Metals
12. Ceramic Materials
13. Polymer Materials
14. Composite Materials
15. Corrosion & Degradation of Materials
16. Environment and Sustainability

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METAL

1. INTRODUCTION TO METALS & ALLOYS : GENERAL PROPERTIES & APPLICATIONS
2. **PHASE DIAGRAM**
3. FABRICATION & THERMAL PROCESSES OF METALS

PHASE DIAGRAM

Introduction

- Phase diagram provides valuable information about melting, crystallization, etc.
- It shows the relationships among temperature, composition, and phases present in a particular alloy system at equilibrium.
- Binary alloy- consist 2 components (e.g. Cu-Ni, Cu-Ag, Pb-Sn)
- Ternary alloy- consist of 3 components (e.g. Fe-Ni-Cr)

- **Why study phase diagram?**

Important to engineers, related to design and control of heat-treating procedures since there is a strong correlation between microstructure and mechanical properties

Phase Equilibria: Solubility Limit

- Solubility Limit:

  Max concentration for which only a single phase solution occurs.

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

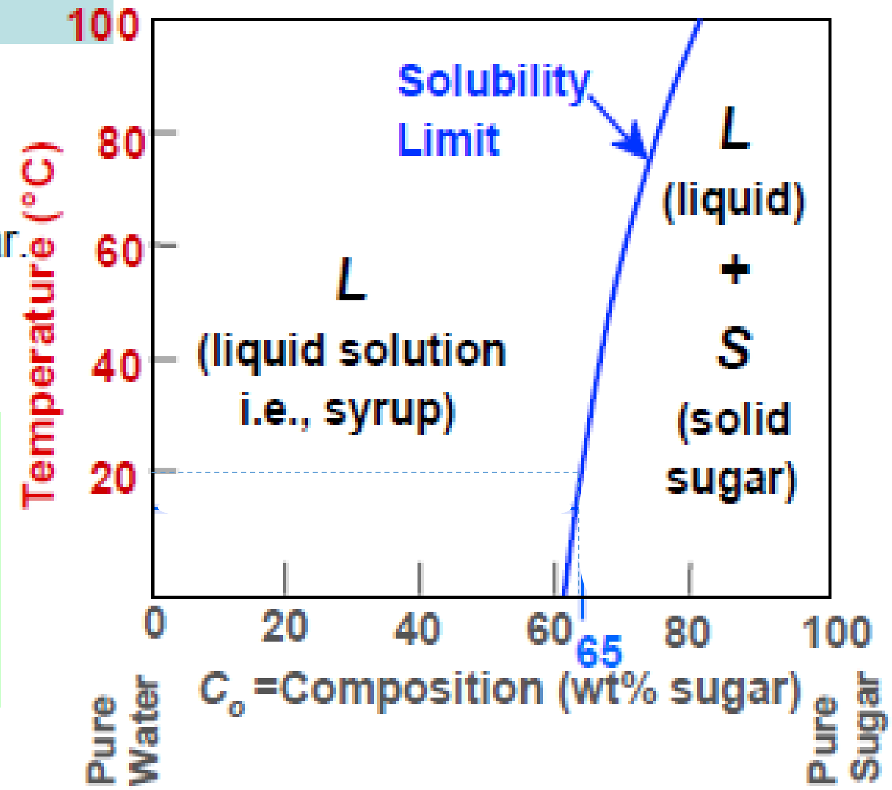
Answer: 65 wt% sugar.

If C_o < 65 wt% sugar: syrup

If C_o > 65 wt% sugar: syrup + sugar.

The solubility limit of sugar in water
Depends on the of water
e.g., if T = 100C, solubility limit = 80wt% sugar.

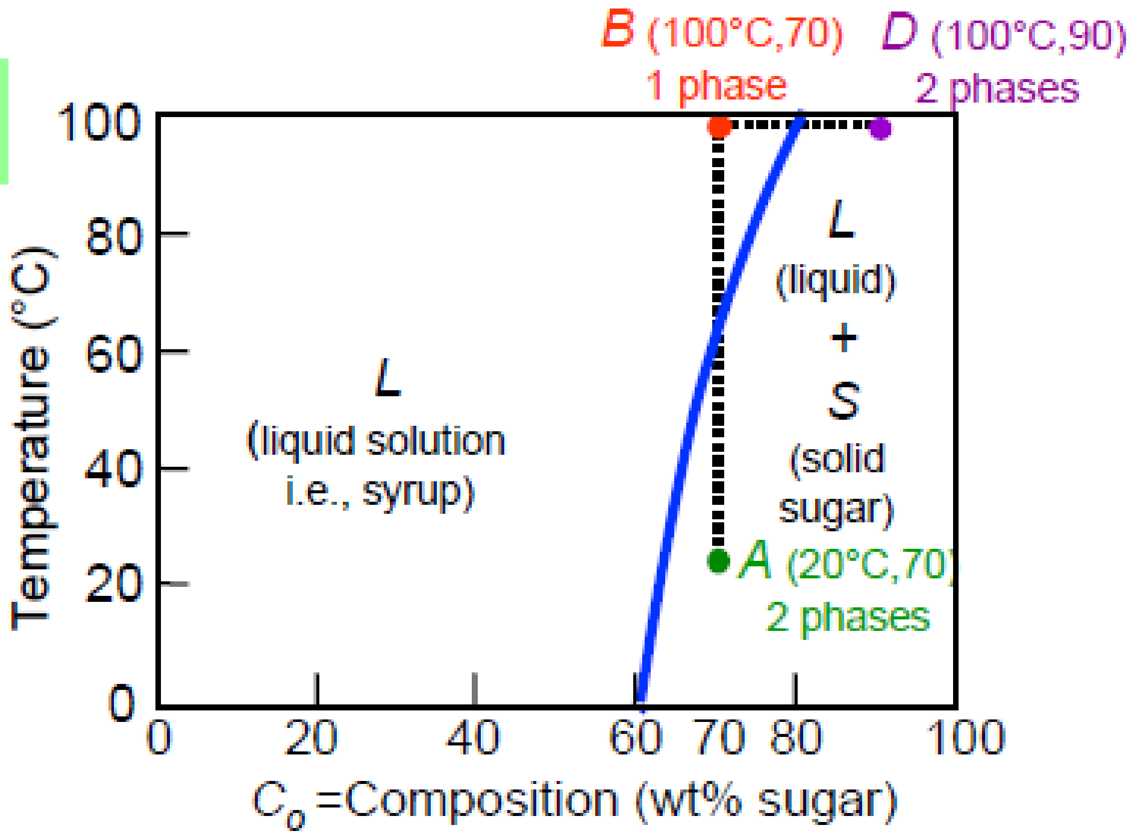
Sucrose/Water Phase Diagram



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.*

Binary System

Alloy that contain 2 components

(1) Isomorphous – complete liquid and solid solubility of the 2 components, e.g. Cu-Ni

$$L \iff \alpha \text{ (Cu-Ni solid solution)}$$

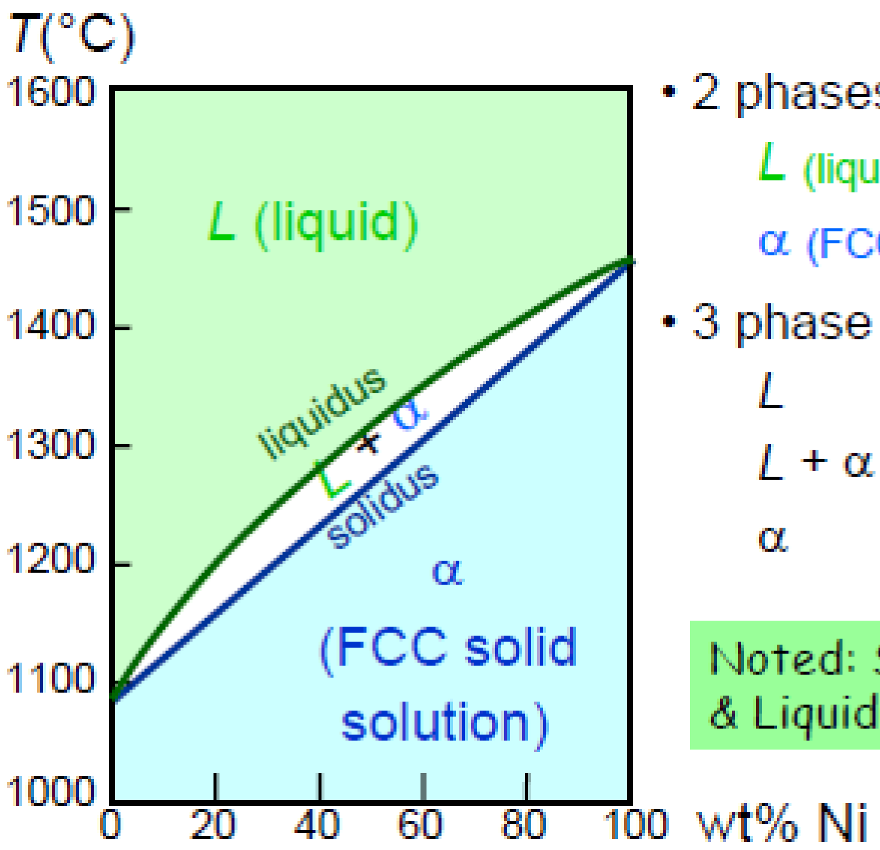
(2) Eutectic – limited solubility, upon cooling liquid phase is transformed into 2 solid phases. e.g. Cu-Ag, Pb-Sn

$$L \iff \alpha + \beta$$

Binary Isomorphous Phase Diagrams

- -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

Noted: Solidus line & Liquidus line

Binary Isomorphous

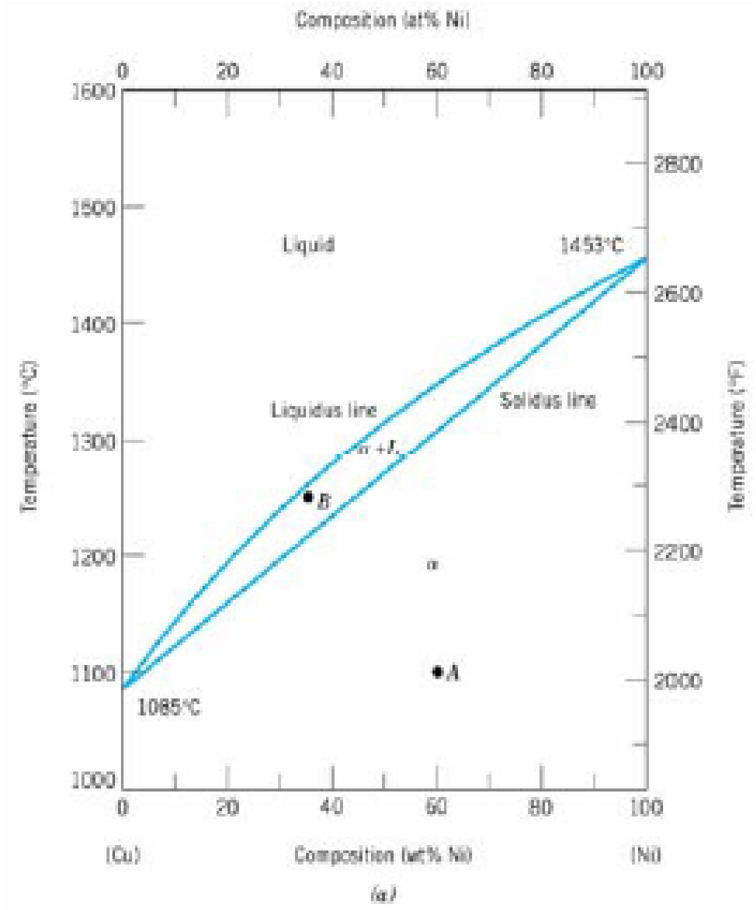
At temperature below 1080°C, Cu & Ni are soluble in each other (complete solubility) due to;

i. Same crystal structure (FCC)

ii. Nearly identical atomic radii

iii. Nearly identical electronegetivity

iv. Similar valences



Interpretation of Phase Diagrams

- 3 kind of information are available:

  i. Type of phase that are present

  (α phase or L phase or α + L phase?)

  ii. The composition of these phases

  % of composition **e.g.: Cu or Ni**

  iii. The percentage or weight fractions of the phases **e.g.: % L or % α**

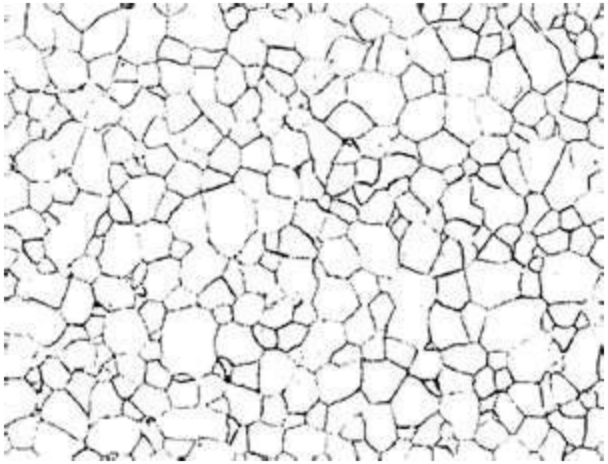
TERMS THAT YOU NEED TO KNOW…

- The *lowest* temperature at which the alloy is still completely liquid is known as the **Eutectic point**
- The lowest temperature at which a single solid phase (austenite) transforms into two other solid phase (ex. ferrite and cementite) is know as the **Eutectoid point**
- **Ferrite**
- **Austenite**
- **Cementite**
- **Pearlite**
- **Spherodite**
- **Bainite**
- **Martensite**
- **Retained Austenite**
- **Tempered Martensite**


Austenite
Pearlite
Martensite
Bainite
Ferrite
Cementite

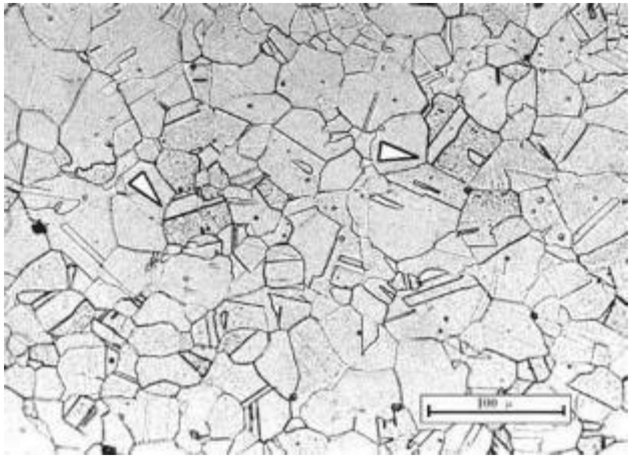
Ferrite

- **Alpha ferrite** denoted α-ferrite or **ferrite**
- Delta ferrite (δ-ferrite) is stable only at very high temperatures
- Ferrite is soft and ductile
- It is magnetic from room temperature to 768°C, *Curie temperature*



Austenite

- Within a certain temperature range, iron undergoes a **polymorphic transformation** from a bcc to a fcc structure,
- Becomes *gamma iron* (γ-iron) or **austenite**
- Austenite is denser than ferrite and important in heat treatment
- Possesses good formability

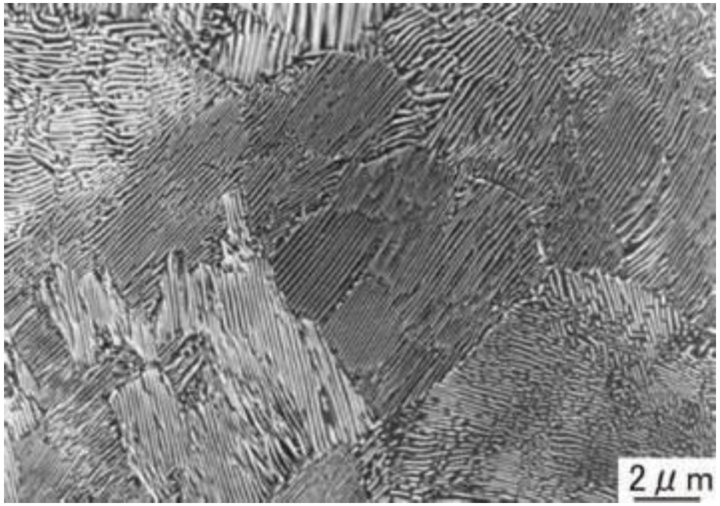


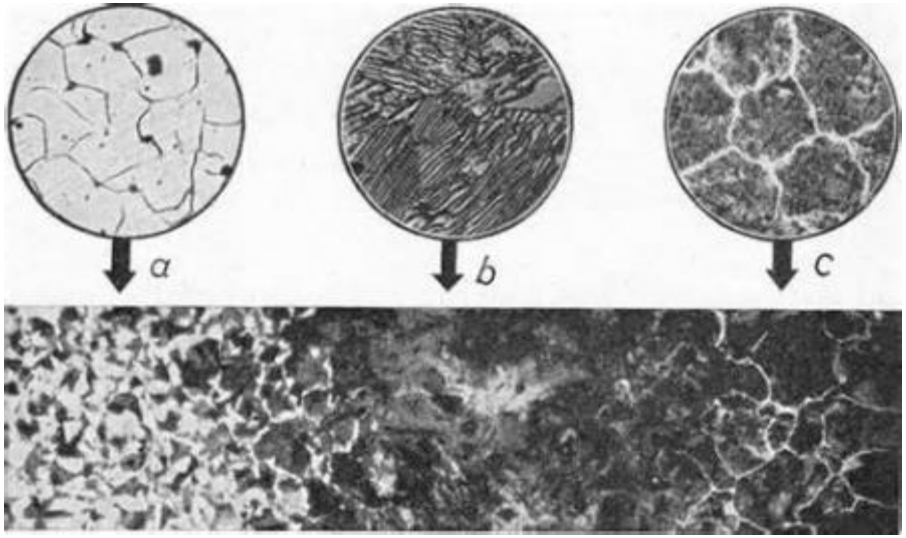
Cementite

- Also called **carbide**
- Cementite is very hard and brittle intermetallic compound
- Has a significant influence on the properties of steels

Pearlite

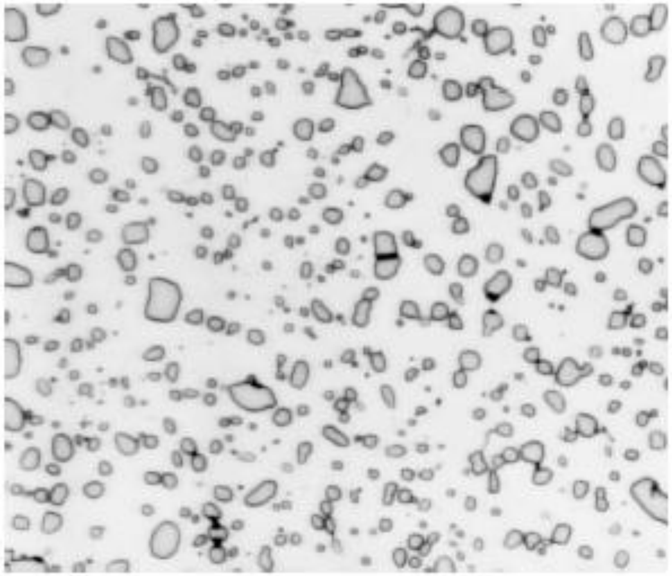
- **Fine pearlite** is where **ferrite and cementite lamellae** in the pearlite structure of the eutectoid steel are thin and closely packed
- **Coarse pearlite** is thick and widely spaced





Spheroidite

- **Subcritical annealing** is when pearlite is heated to just below the eutectoid temperature for a period of time
- **Spheroidites** are less conducive to stress concentration because of their rounded shapes

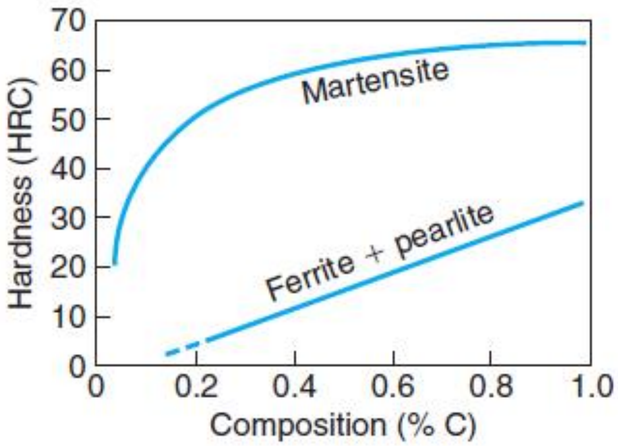


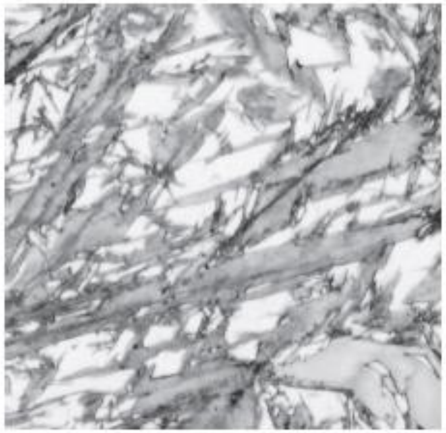
Bainite

- **Bainite** is a acicular microstructure, a very fine microstructure consisting of **ferrite and cementite** having a different morphology
- Produced in steels with alloying elements and at cooling rates that are higher than those required for transformation to pearlite

Martensite

- As austenite is cooled at a high rate, fcc structure is transformed into a **body-centered** structure
- Does not have as many slip systems, thus lacks toughness and limited use



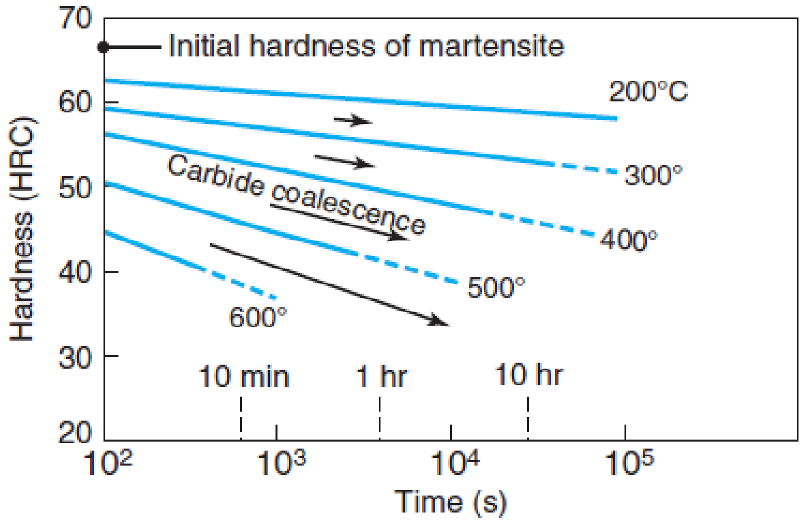


Retained Austenite

- When alloy temperature is not quenched sufficiently low, only a portion of the structure is transformed to martensite.
- The rest is **retained austenite** which can cause dimensional instability and cracking.
- Lower the hardness and strength of the alloy.

Tempered Martensite

- **Tempering** is a heating process to reduce hardness and improve toughness, thus improve the mechanical properties of the metal.
- With increasing tempering time and temperature, the hardness of tempered martensite decreases.



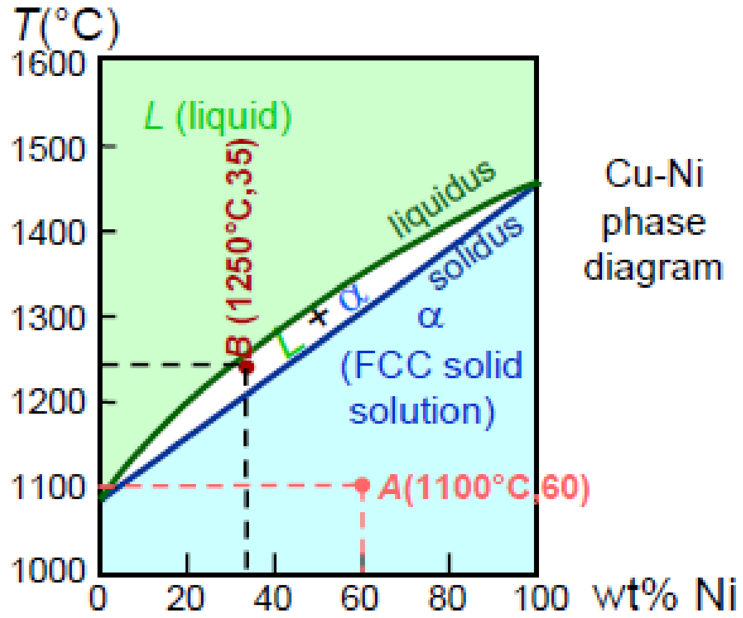
1

i. Type of Phase that are present

- 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

Phases: The physically and chemically distinct material regions, e.g., α and β in Aluminum-Copper alloy

Composition of phases

2

- Rule 2: If we know *T* and C_o, then we know: the composition of each phase.

There are 2 cases:

a. Single phase region

b. Two phase region

Components: The elements or compounds which are present in the mixture (e.g. Al and Cu)

a. Single phase region

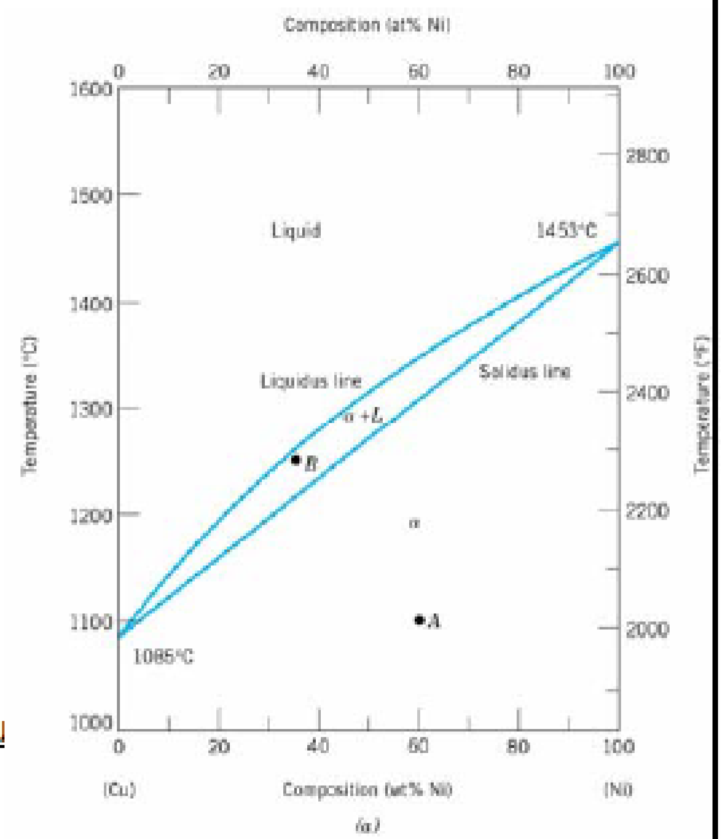
- The phase compositions are easy to be determined

- e.g.: Point A

(60 wt% Ni-40 wt% Cu at 1100°C)

At this C_o and T

- Only α phase is present
- Composition = 60 wt% Ni-40 wt% Cu



b. Two phase region

- The phase composition can be determined by tie line.

- 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)

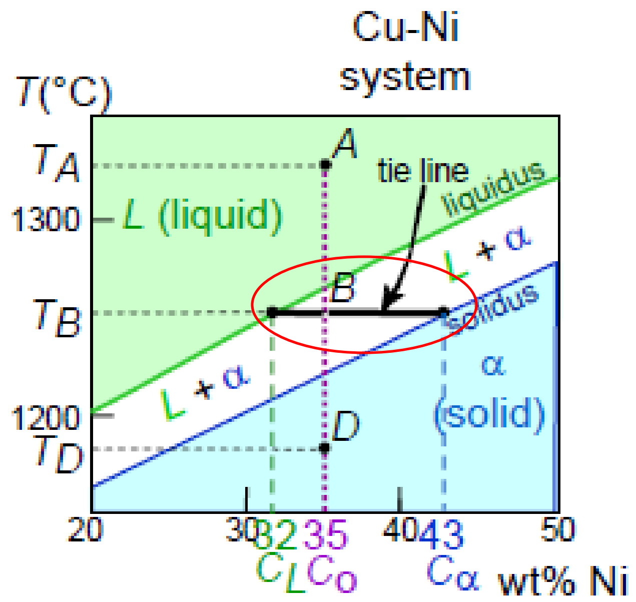
  $C_\alpha = C_o$ (= 35 wt% Ni)

  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)



3 iii. Weight fraction of phase

- Rule 3: If we know T and C_O, then we know:
  --the amount of each phase (given in wt%).

- There are 2 cases:

a) Single phase region

b) Two phase region

a) Single phase region

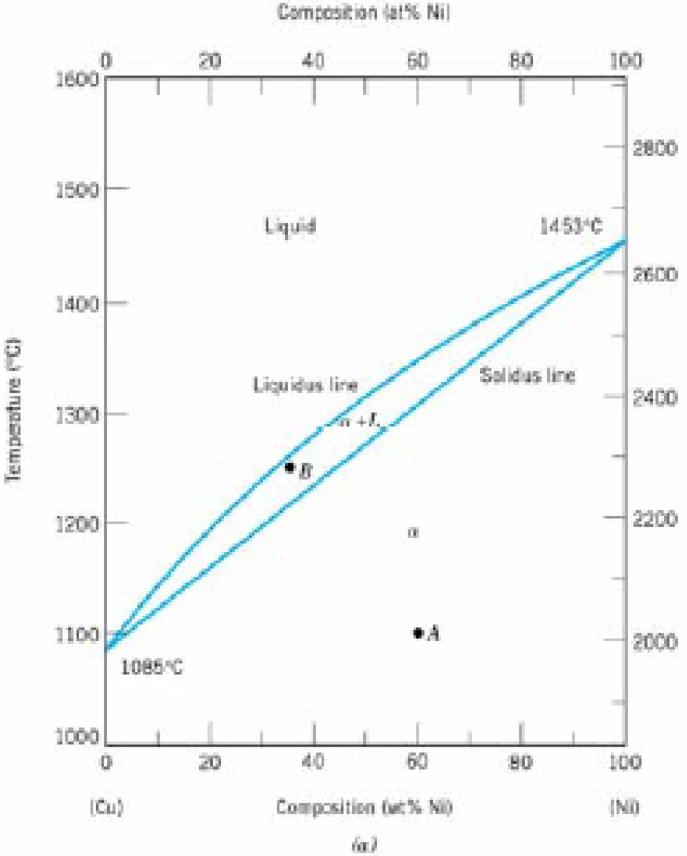
- Example: Point A

(60 wt% Ni-40 wt% Cu at 1100°C)

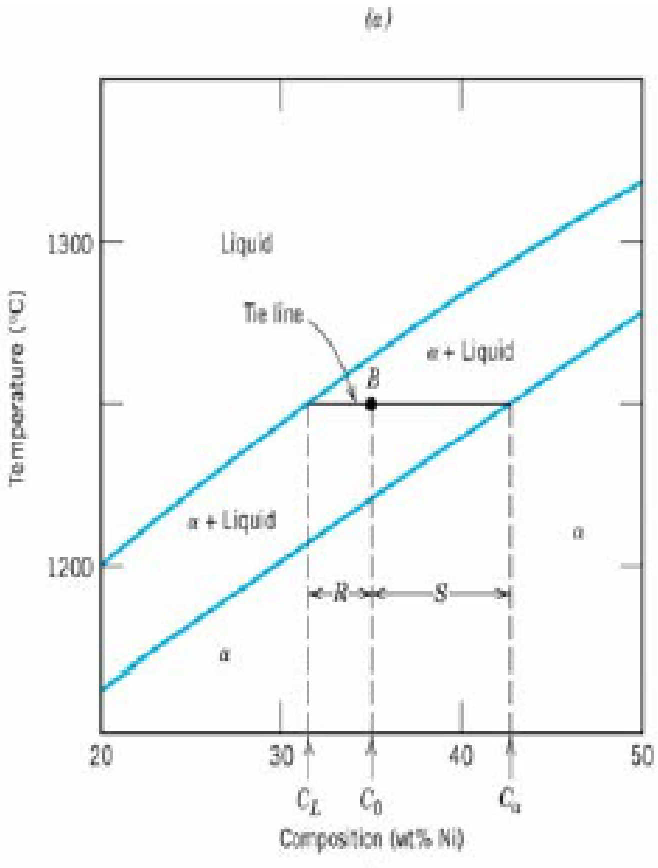
At this C_o and T;

- Only α phase is present
- The alloy is composed entirely of this phase, so the phase fraction;

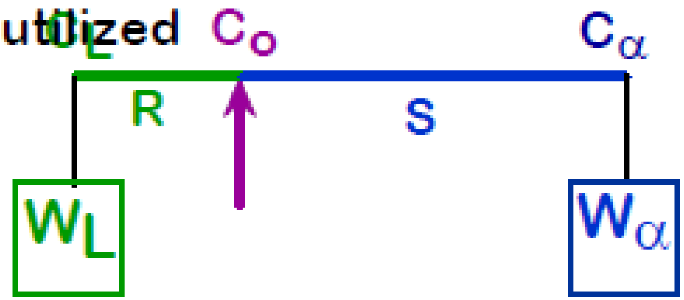
W_{α} = 1.0 (or 100%)



b) Two phase region



Tie line and *Lever Rule* *(inverse lever Rule)* must be utilized



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

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

- total weight fraction: $W_L + W_\alpha = 1$

b) Two phase region (continue...)

- Examples:

C_o = 35 wt% Ni

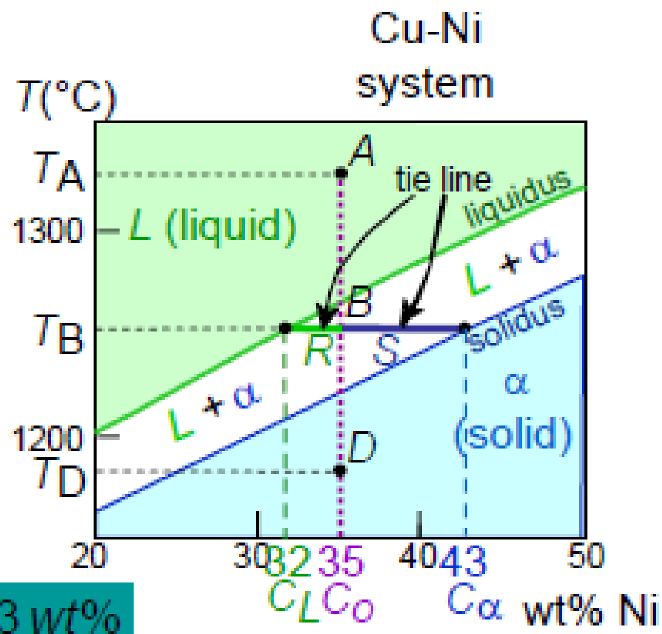
At T_A: Only Liquid (L)

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

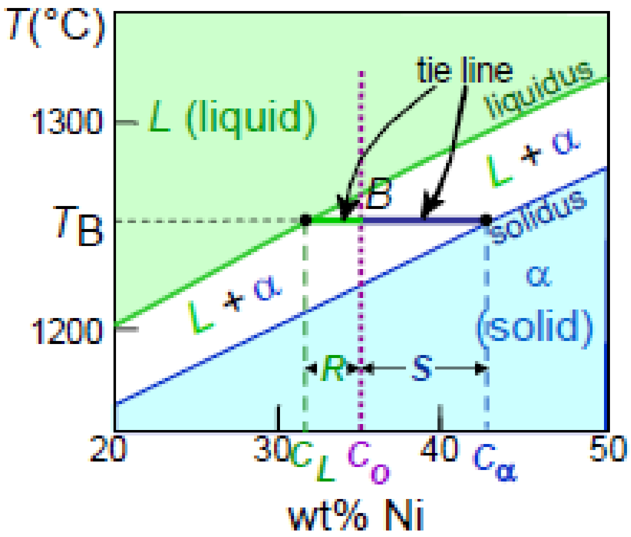


$$W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L} = \frac{43-35}{43-32} = 73\ wt\%$$

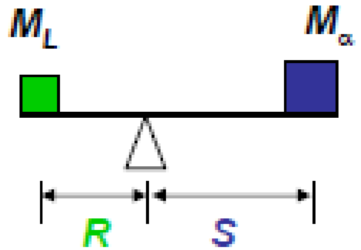
$$W_\alpha = \frac{C_o - C_L}{C_\alpha - C_L} = 27\ wt\%$$

The Lever Rule

- **Tie line – connects the phases in equilibrium with each other**



How much of each phase?
Think of it as a lever (teeter-totter)



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

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

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

Development of Microstructure

a. Equilibrium cooling

extremely slow cooling. Readjustment in the L and α phases composition in accordance with the phase diagram

b. Nonequilibrium cooling

cooling rate too rapid to allow these compositional readjustment, thus nonequilibrium microstructure develop

a. Equilibrium cooling

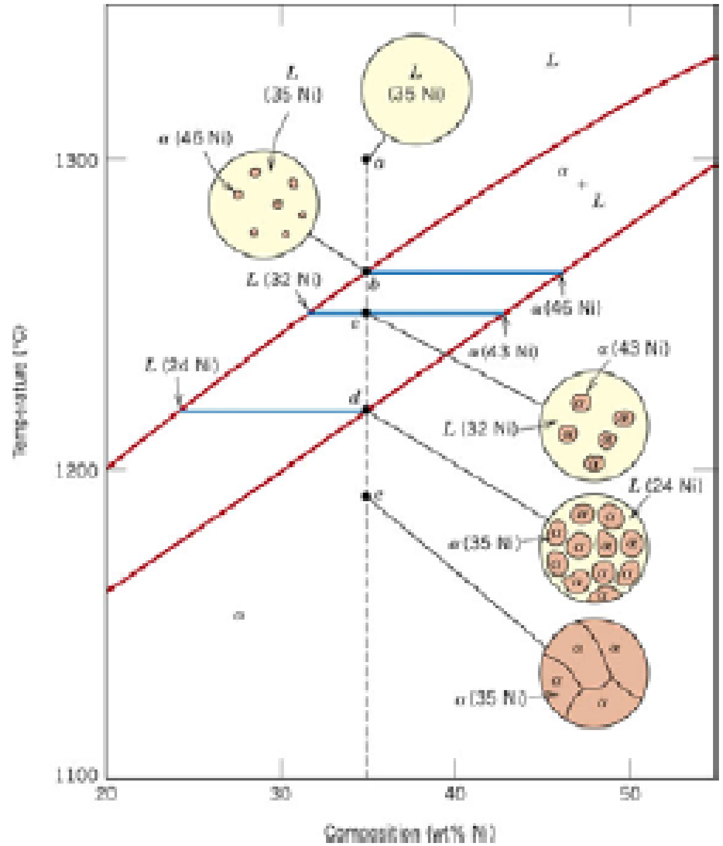
i. Point a (1300°C)
   Alloy is in liquid form

ii. Point b (1260°C)
   α phase begin to form at liquidus line, based on tie line, the composition is;
   L = 35wt% Ni-65wt% Cu
   α = 46wt% Ni-54wt% Cu

iii. Point c (1250°C)
   solid α & liquid composition
   L = 32wt% Ni-68wt% Cu
   α = 43wt% Ni-57wt% Cu

iv. Point d (1220°C)
   Solidification is virtually completed

v. Point e (1180°C)
   Solidification complete, Final product- polycrystalline α phase solid solution
   α = 35 wt % Ni- 65 wt% Cu



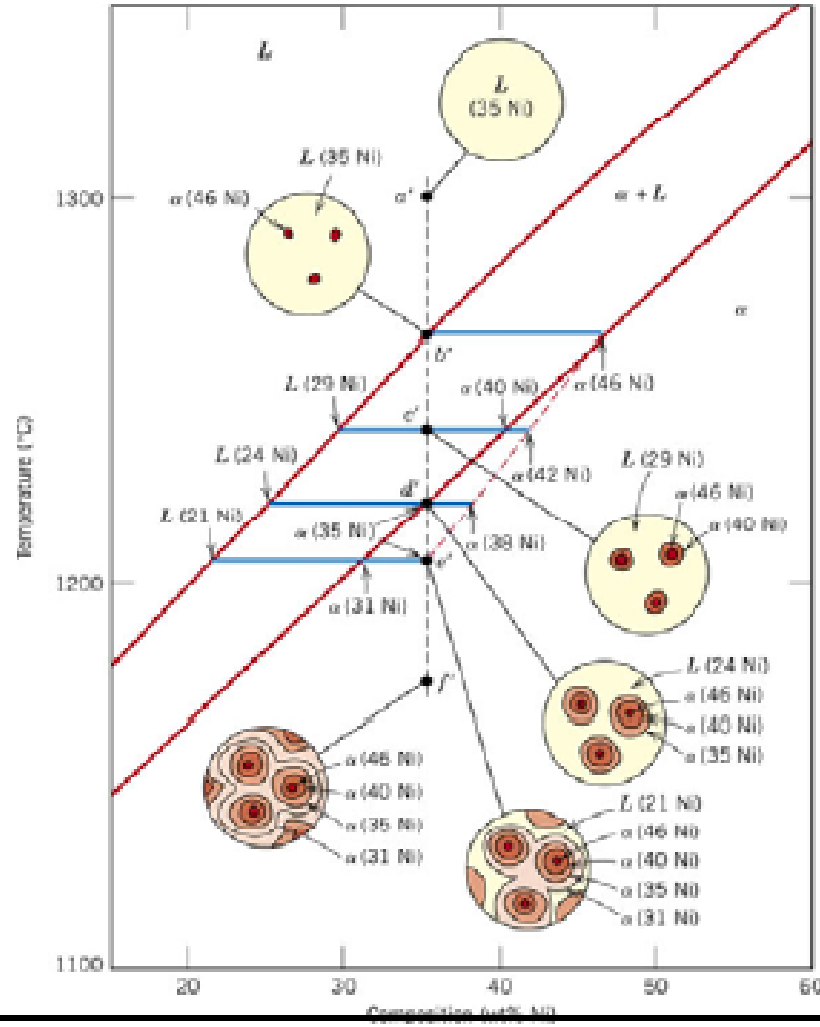
b. Nonequilibrium cooling

Nonequilibrium cooling :

Point c (1250°C)
grain boundary

Point d (1220°C)
Solidification should be completed, however there is still liquid remaining

Point e (1180°C)
Solidification reaches completion



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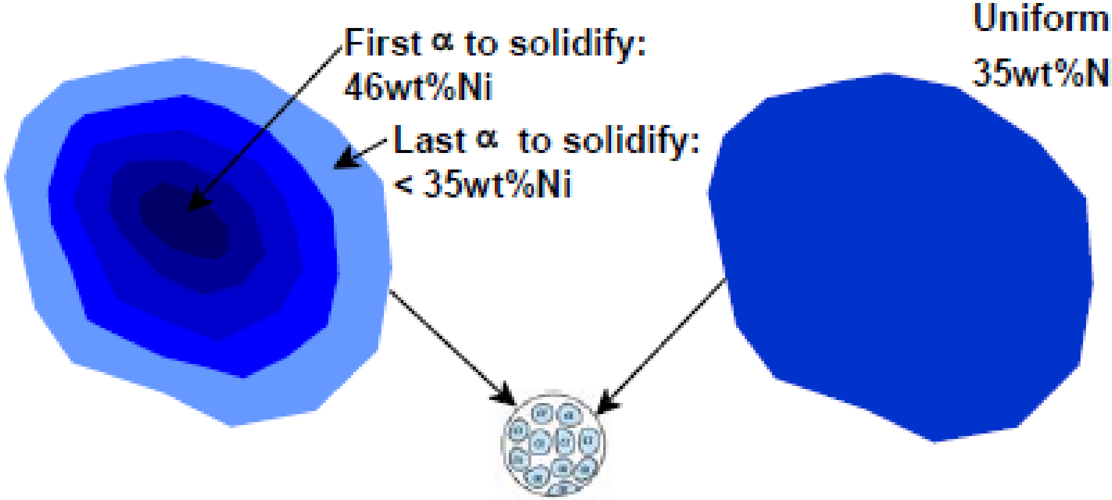
Nonequilibrium vs. Equilibrium Cooling

In nonequilibrium system

- Cu-Ni system: First α to solidify has C_α = 46wt%Ni.

  Last α to solidify has C_α = 35wt%Ni.



Nonequilibrium cooling

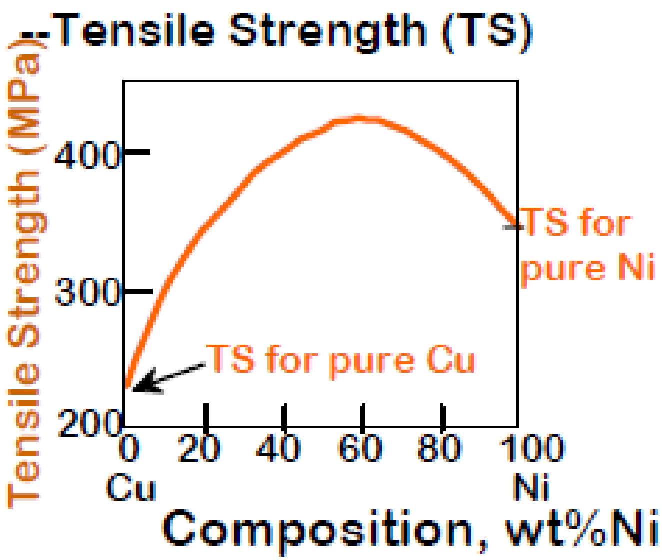
Rapid cooling rate. Segregation or concentration gradients are established

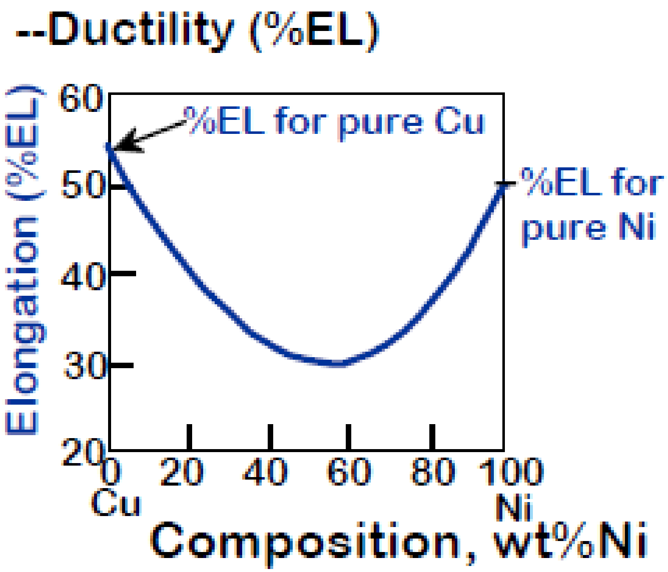
Equilibrium cooling

Slow rate, composition in accordance with the phase diagram

Mechanical Properties

- Effect of composition on mechanical properties (Tensile strength and elongation) of Copper-nickel system:

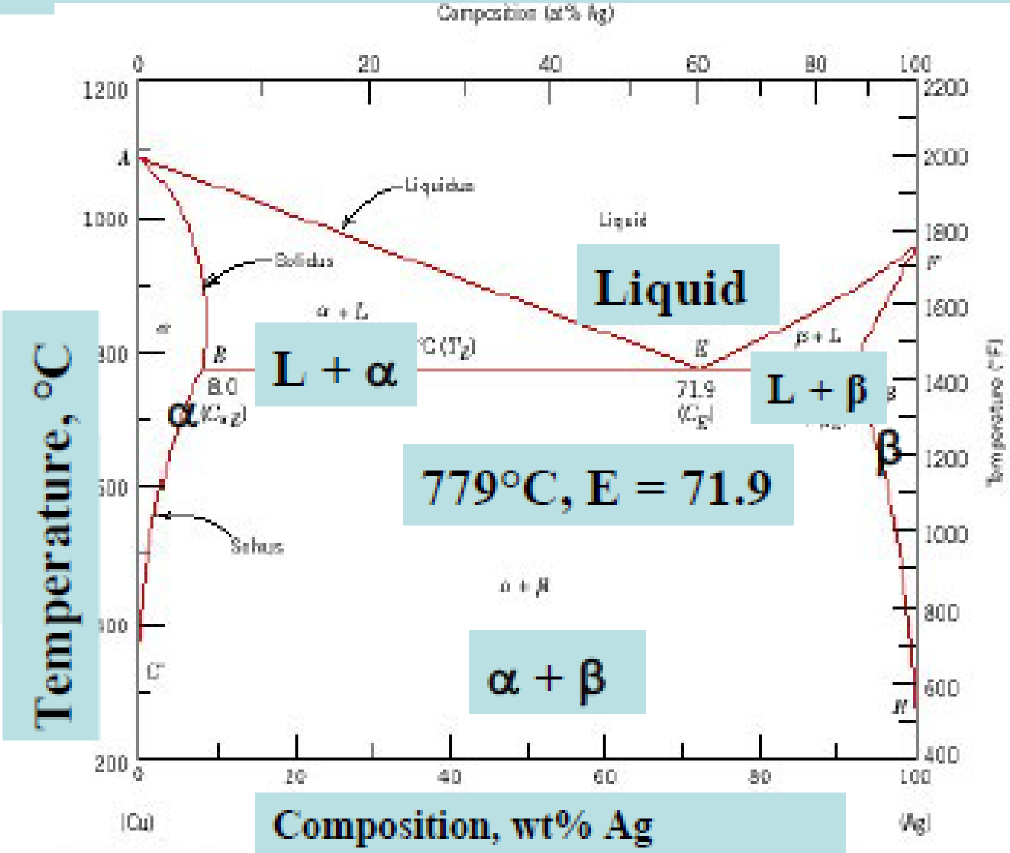




--At some intermediate composition, the curve passes through the maximum

--The ductility decreases with the addition of second component, where the curve exhibit the minimum

Binary Eutectic System



- **Eutectic transition**

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

-The solubility of solid phases (α and β) is limited, e.g. solubility limit α phase is at **CBA** boundary line.

-Example copper-silver phase diagram

- 3 single-phase region exist

i) α phase (rich in copper)

ii) β phase- (rich in silver)

iii) liquid

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

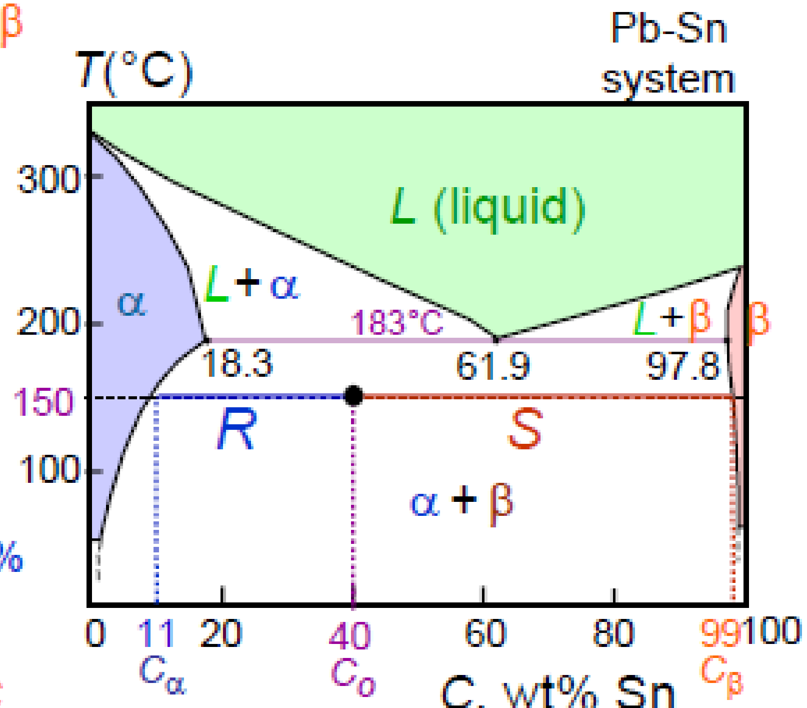
    C_β = 99 wt% Sn
  - --the relative amount of each phase:

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

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

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

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



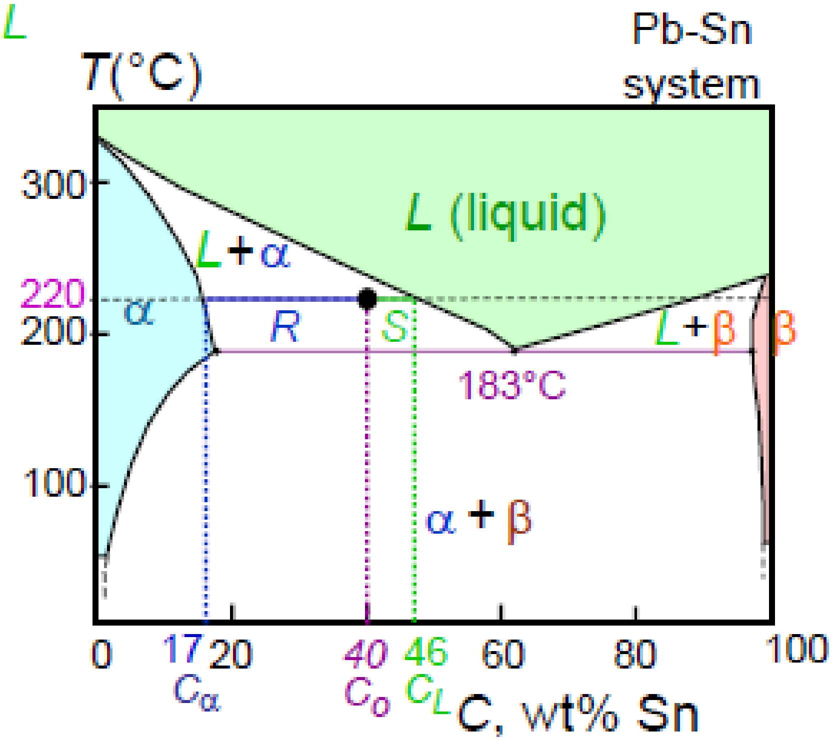
Adapted from Fig. 9.8, *Callister 7e.*

EX: Pb-Sn Eutectic System (2)

- 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_α = 17 wt% Sn
    - C_L = 46 wt% Sn
  - --the relative amount of each phase:

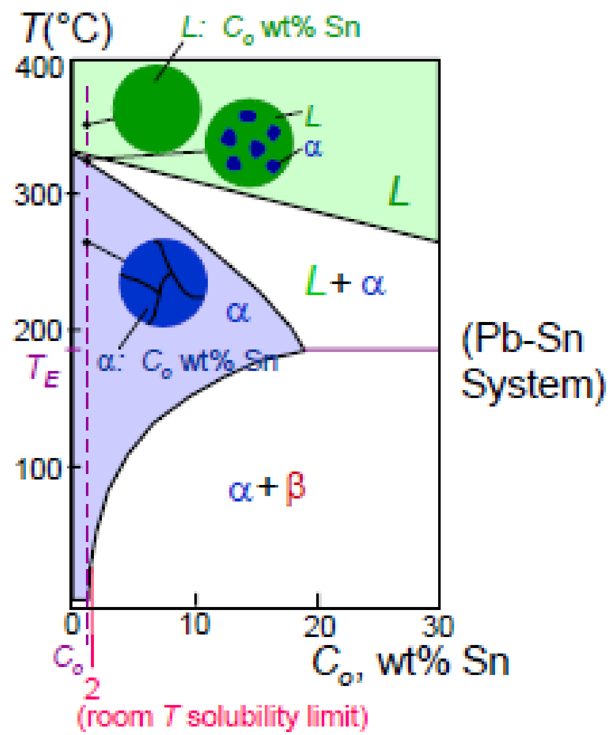
$$W_\alpha = \frac{C_L - C_O}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 21 \text{ wt\%}$$

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



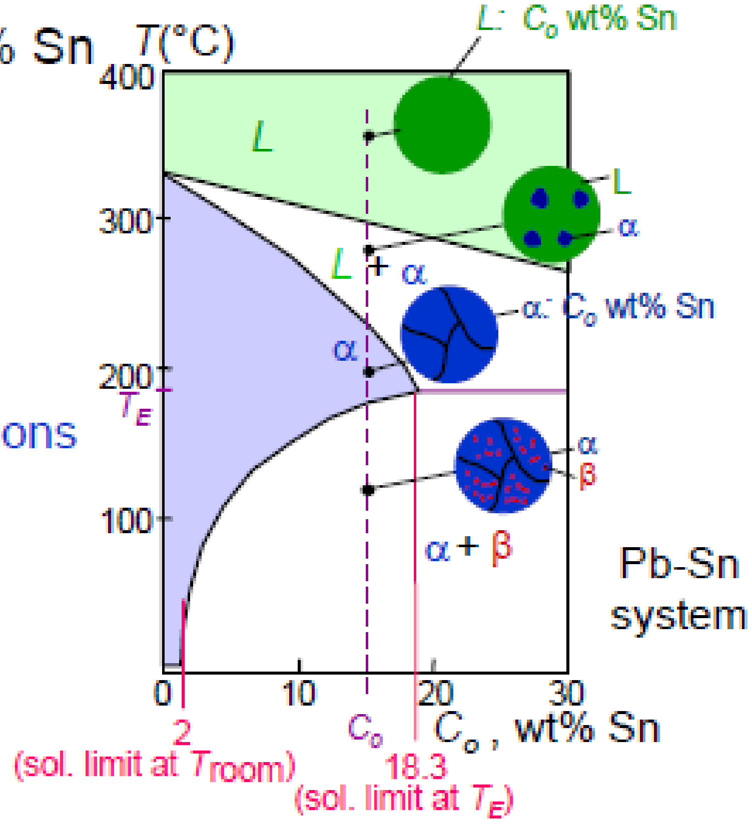
Microstructures in Eutectic Systems: I

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



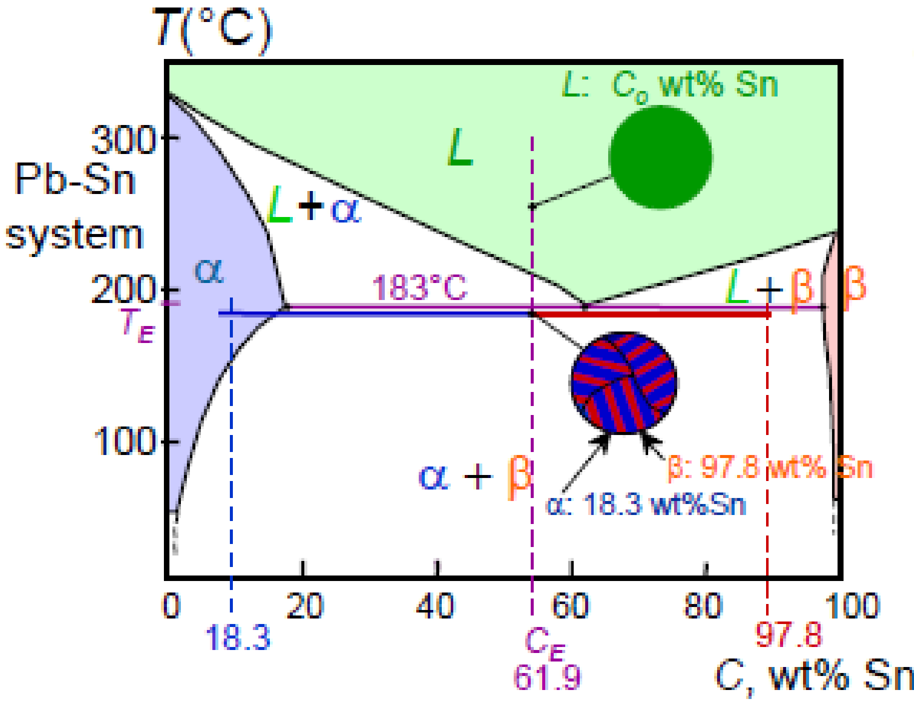
Microstructures in Eutectic Systems: II

- 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

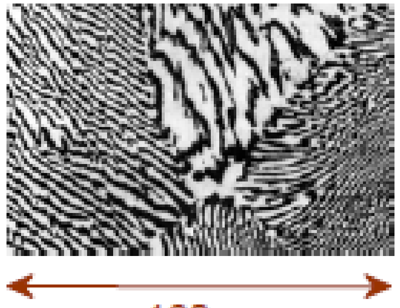


Microstructures in Eutectic Systems: III

- $C_o = C_E$
- **Result:** Eutectic microstructure (lamellar structure)
  --alternating layers (lamellae) of α and β crystals.



Micrograph of Pb-Sn eutectic microstructure



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

- Eutectic reaction; L <=> $\alpha + \beta$ **(Refer to copper-silver phase diagram at 71.9 wt% Ag)**

- Eutectoid reaction– 1 solid phase → 2 other solid phases (upon cooling)

$$\delta <=> \gamma + \varepsilon$$

- Peritectic reaction – 1 solid phase + 1 liquid phase → 1 **another solid** phase (upon cooling)

$$\delta + L <=> \varepsilon$$

THE IRON – IRON CARBON (Fe – Fe_3C)

- In practice, all steel and cast iron have carbon content less than 6.7 wt % C, thus we consider only this phase diagram- iron-iron carbide system
- Carbon is an interstitial impurity in iron.

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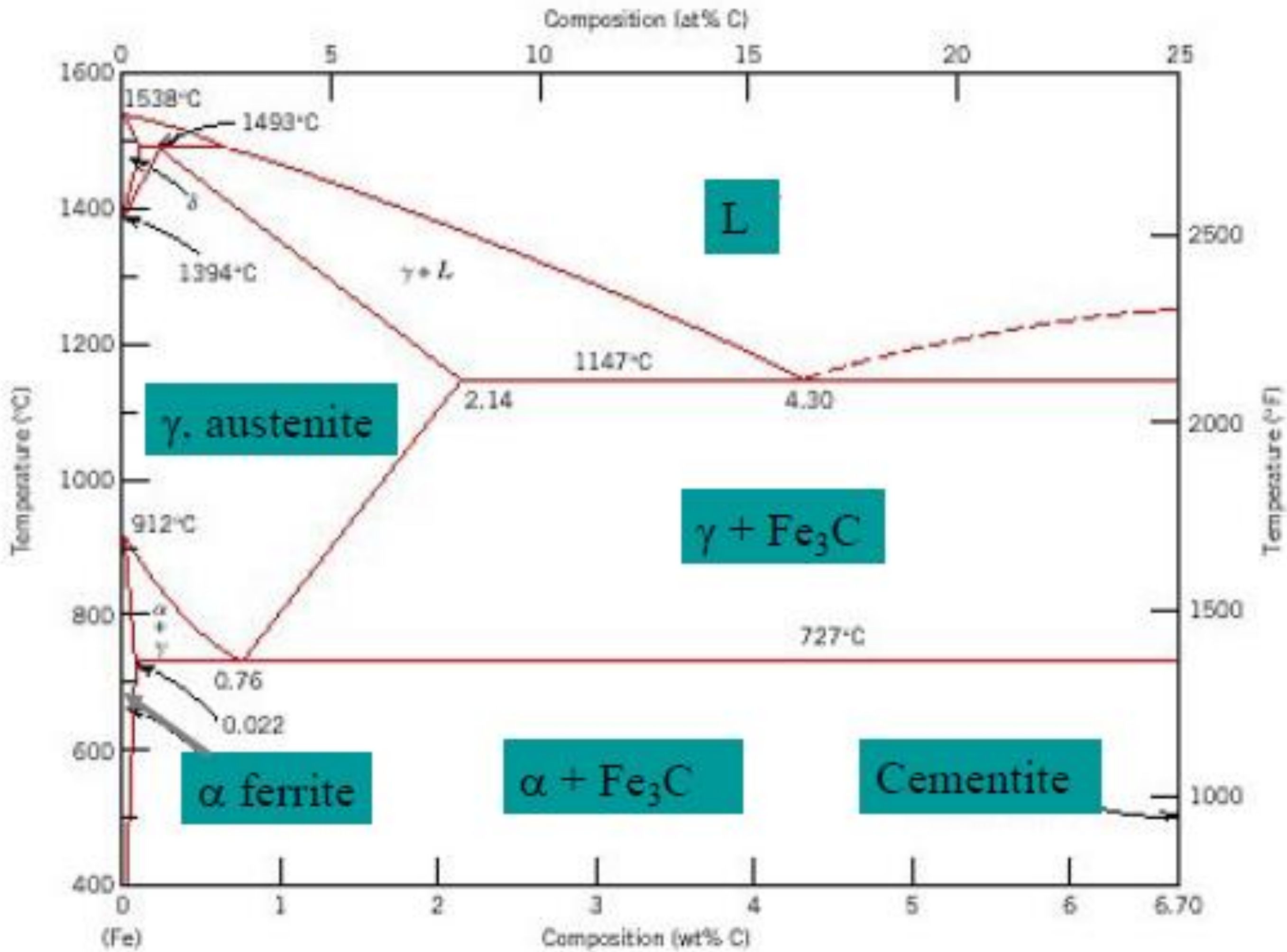


Composition (at% C)
0
5
10
15
20
25
1600
1400
1200
1000
800
600
400
Temperature (°C)
2500
2000
1500
1000
Temperature (°F)
1538°C
1493°C
δ
1394°C
γ + L
L
1147°C
2.14
4.30
γ, austenite
γ + Fe3C
912°C
α + γ
727°C
0.76
0.022
α ferrite
α + Fe3C
Cementite
0
(Fe)
1
2
3
4
5
6
6.70
Composition (wt% C)

Iron-Carbon (Fe-C) Phase Diagram

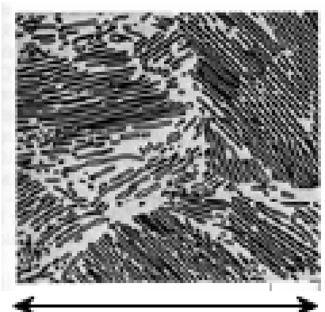
- 2 important points

-Eutectic (*A*):

$L \Rightarrow \gamma + Fe_3C$

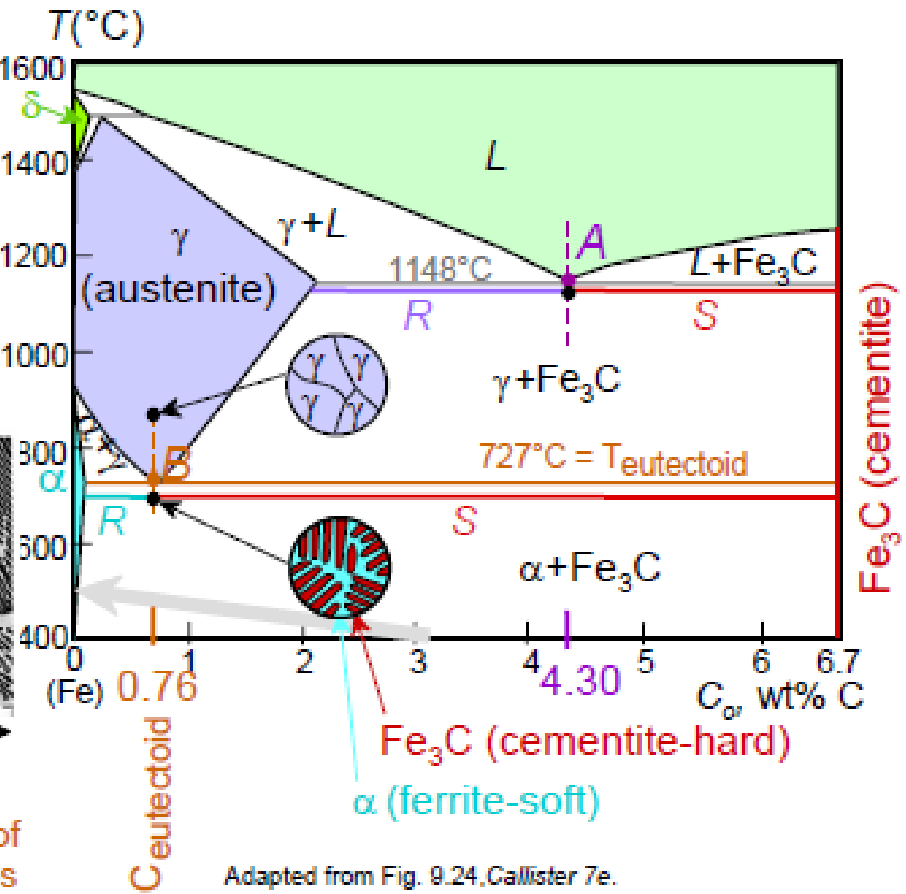
-Eutectoid (*B*):

$\gamma \Rightarrow \alpha + Fe_3C$



Result: Pearlite = alternating layers of α and Fe_3C phases

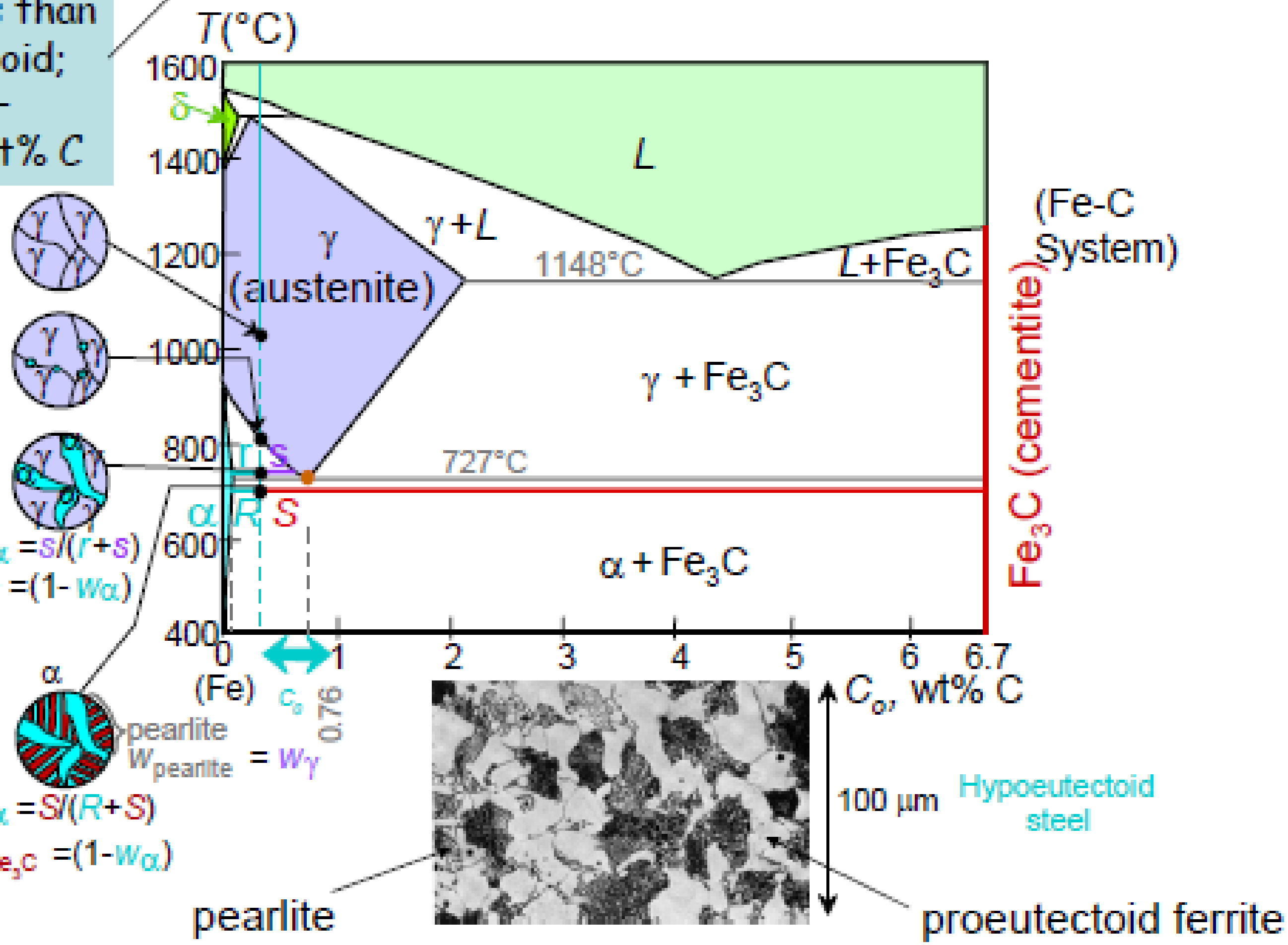
(Adapted from Fig. 9.27, *Callister 7e*.)



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

Hypoeutectoid Steel

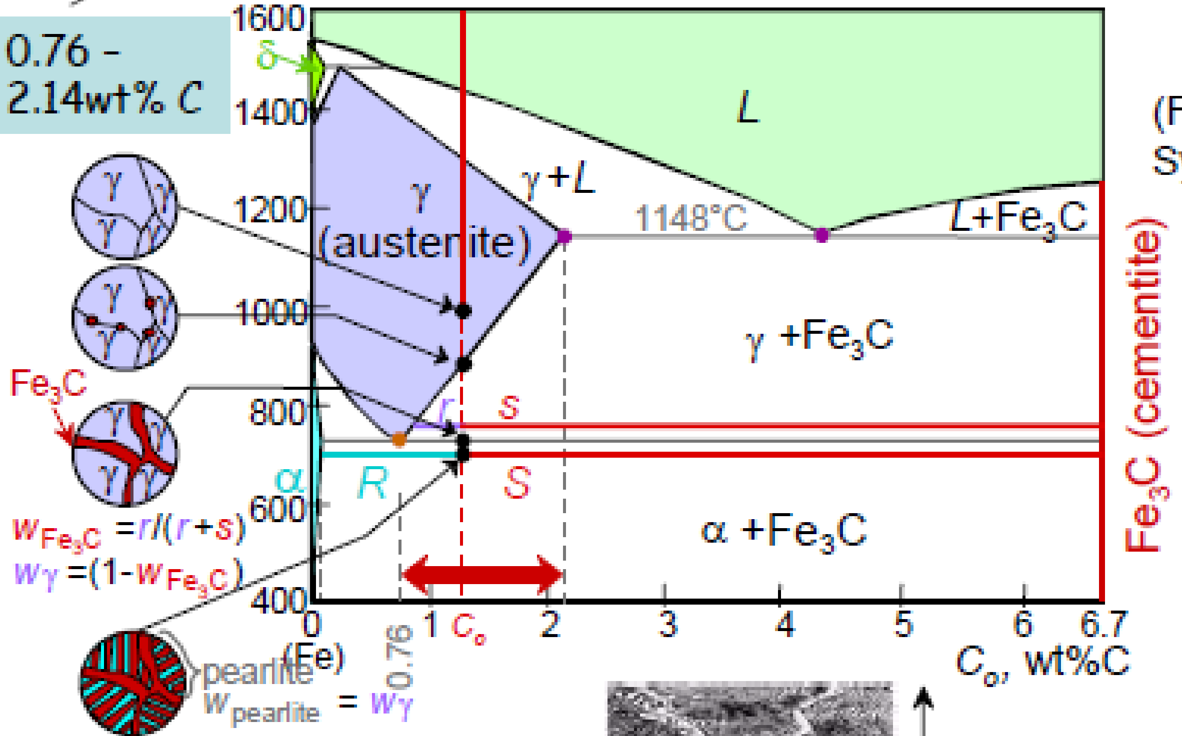
Co less than Eutectoid; 0.002 - 0.76 wt% C



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

Hypereutectoid Steel

0.76 - 2.14wt% C



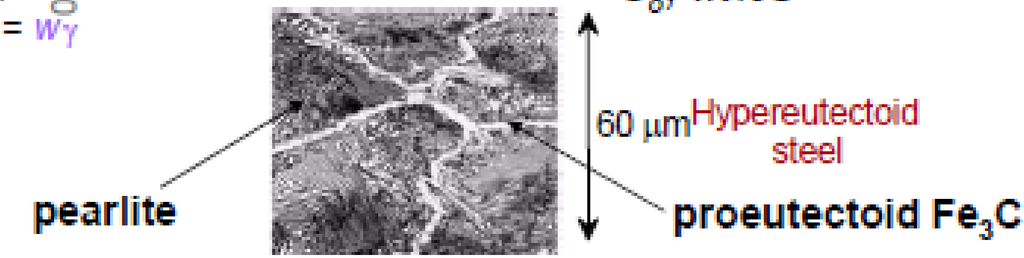
$W_{Fe_3C} = r/(r+s)$

$W_\gamma = (1 - W_{Fe_3C})$

$W_{pearlite} = W_\gamma$

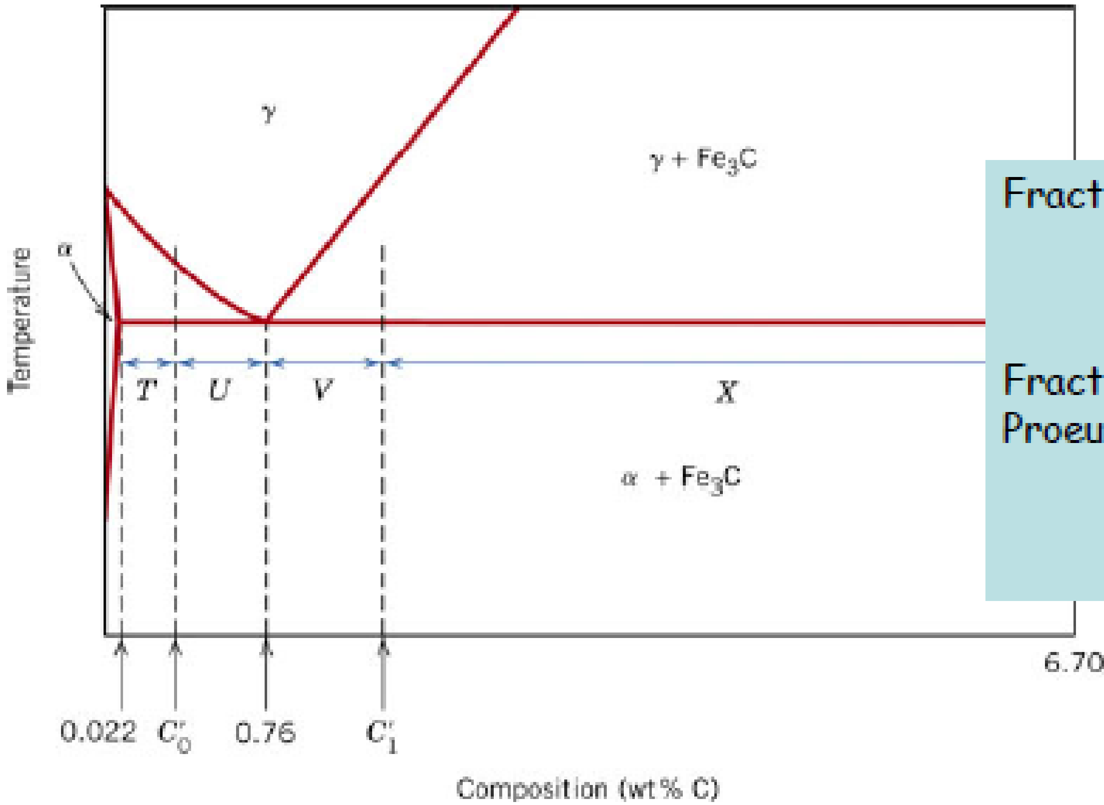
$W_\alpha = S/(R+S)$

$W_{Fe_3C} = (1 - W_\alpha)$



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

Fraction of Pearlite & Proeutectoid α



Fraction of Pearlite, $W_p = \frac{T}{T + U}$

Fraction of Proeutectoid α, $W_\alpha = \frac{U}{T + U}$

- Ferrite that is present in the pearlite is called eutectoid ferrite
- In terms of % C, terms like hypo and hyper-eutectoid alloys are used
- In term of T, Ferrite that formed before eutectoid T is called as proeutectoid ferrite

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)

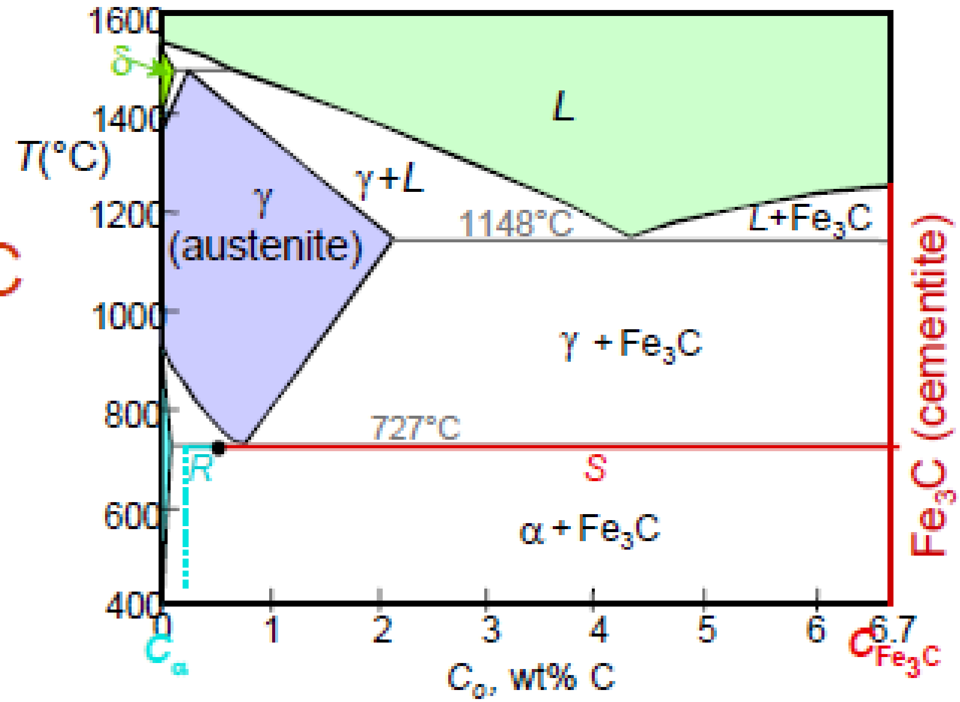
Solution:

a) composition of Fe3C and ferrite (α)

C_O = 0.40 wt% C

C_α = 0.022 wt% C

C_{Fe_3C} = 6.70 wt% C



Solution:

b) the amount of carbide (cementite) in grams that forms per 100 g of steel

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

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

$Fe_3C = 5.7$ g

$\alpha = 94.3$ g

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Solution:

c) the amount of pearlite and proeutectoid ferrite (α)
note: amount of pearlite = amount of g 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