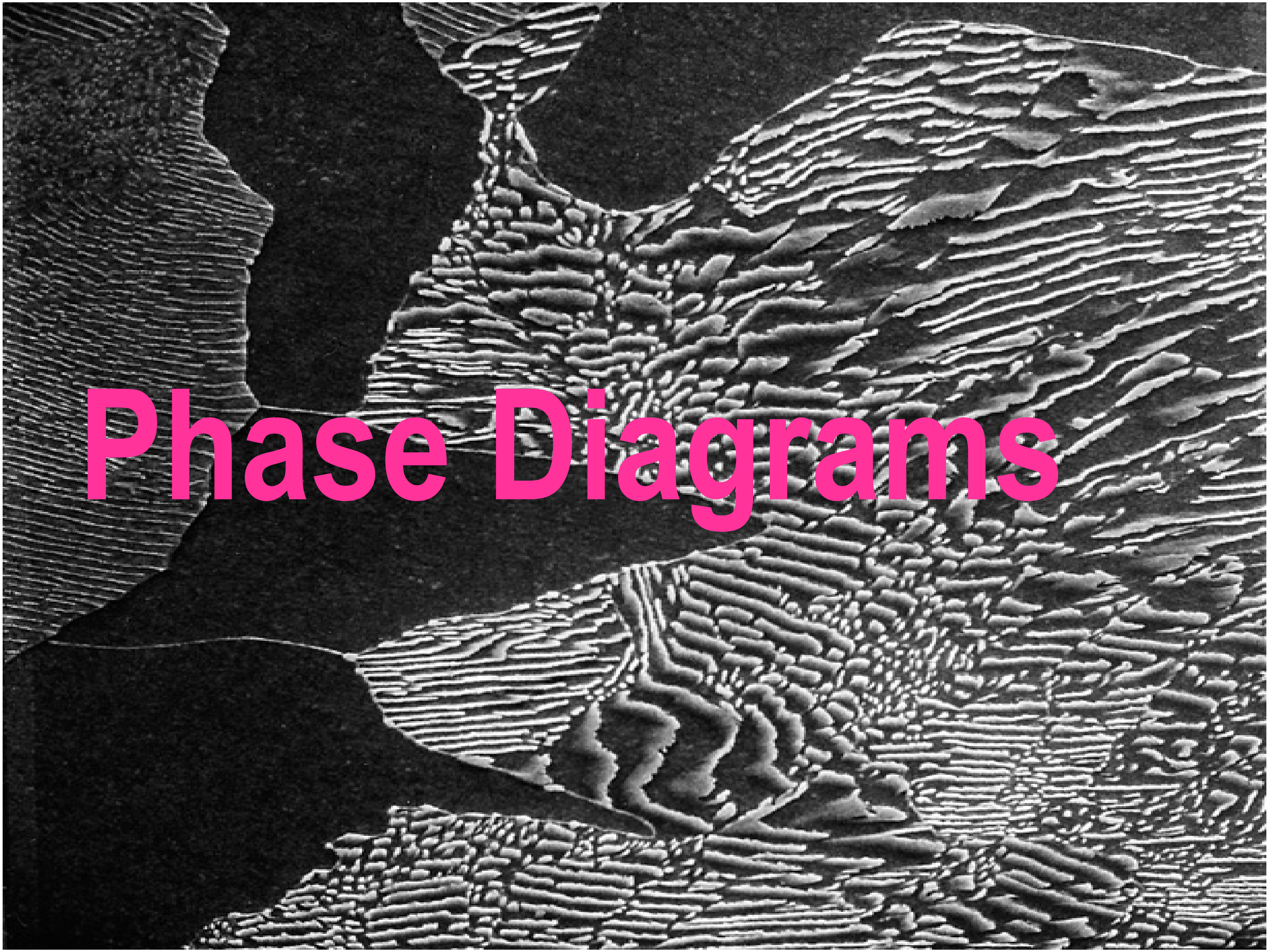
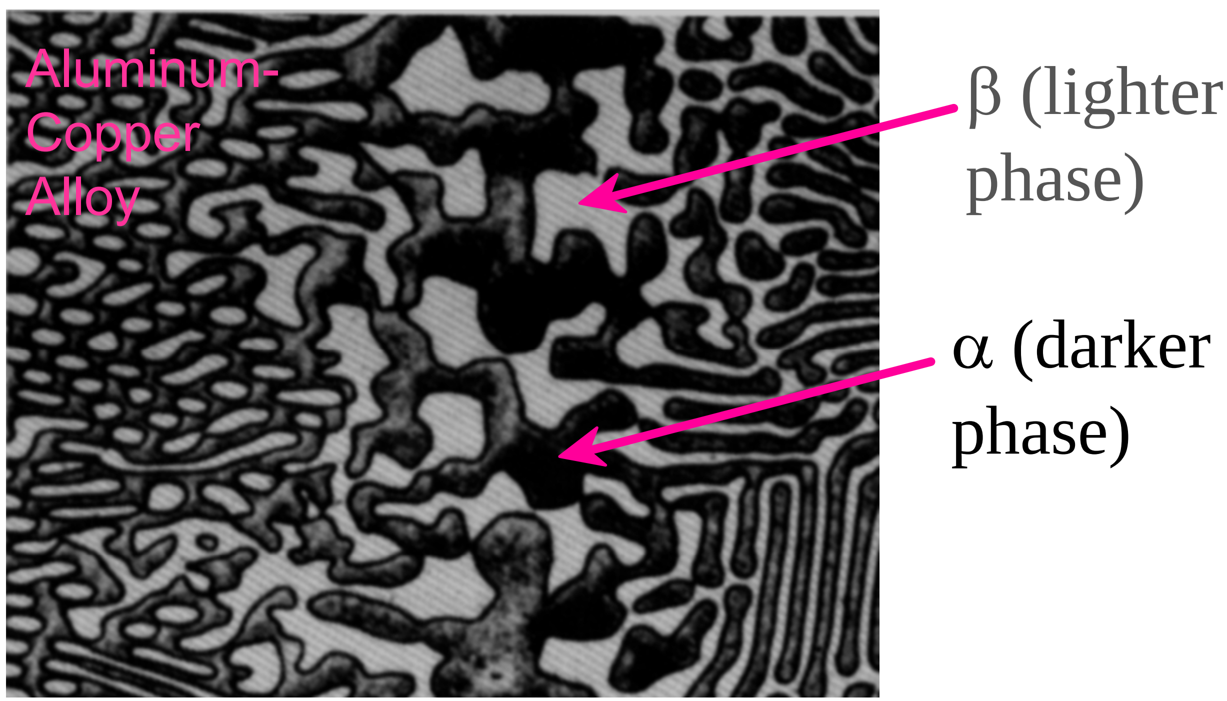
Phase Diagrams



- Introduction
- Solubility Limits
- Phases
- Phase Equilibrium
- Interpretation of Phase Diagrams
- Binary Isomorphous Systems (Cu-Ni)
- Development of Microstructure
- Mechanical Properties
- Binary Eutectic Systems
- Development of Eutectic Alloy Microstructure

Components and Phases

- Components:
  The elements or compounds that are mixed initially (Al and Cu).
- Phases:
  A phase is a homogenous, physically distinct and mechanically separable portion of the material with a given chemical composition and structure (α and β).



Phase Equilibria: Solubility Limit

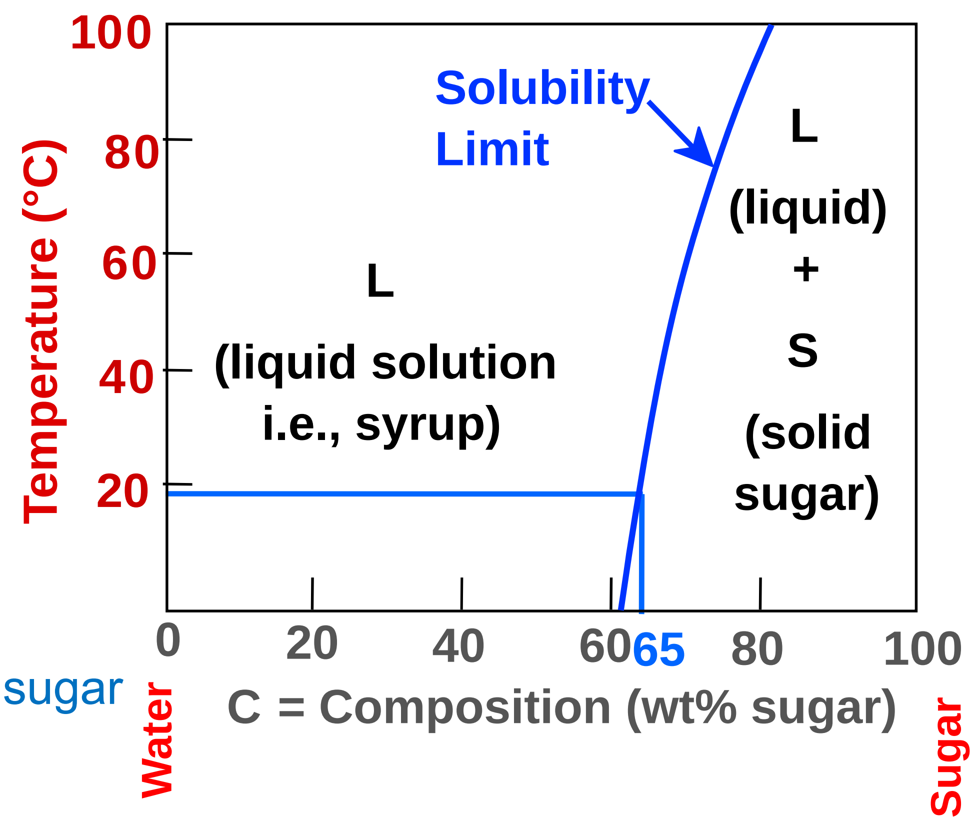
- Solution – solid, liquid, or gas solutions, single phase
- Mixture – more than one phase

- Solubility Limit:
  Maximum concentration for which only a single phase solution exists.

Question: What is the solubility limit for sugar in water at 20°C?

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

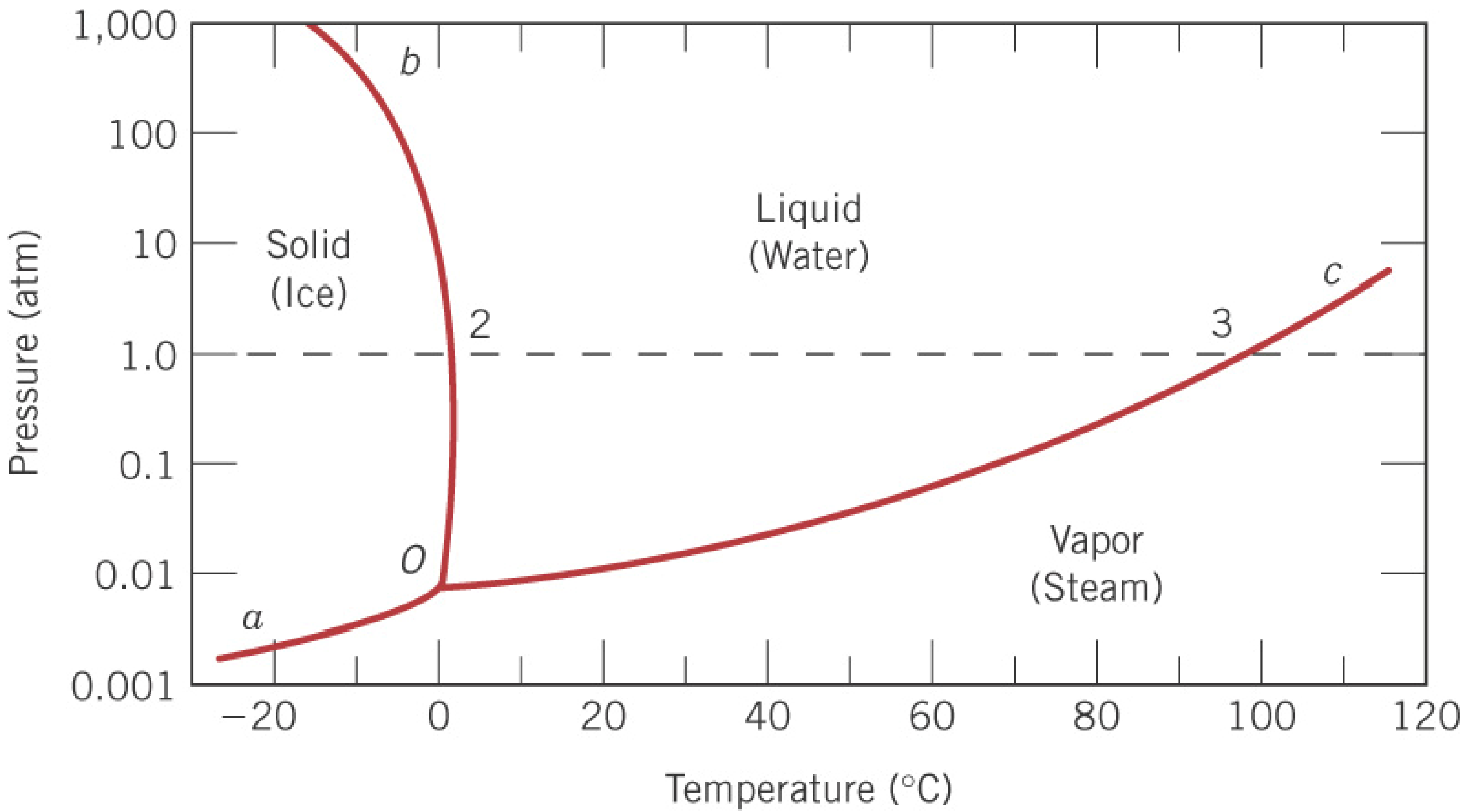
Sugar/Water Phase Diagram



Equilibrium

- A system is at equilibrium if its free energy is at a minimum, given a specified combination of temperature, pressure and composition.
- The (macroscopic) characteristics of the system do not change with time — the system is stable.
- A change in T, P or C for the system will result in an increase in the free energy and possible changes to another state whereby the free energy is lowered.

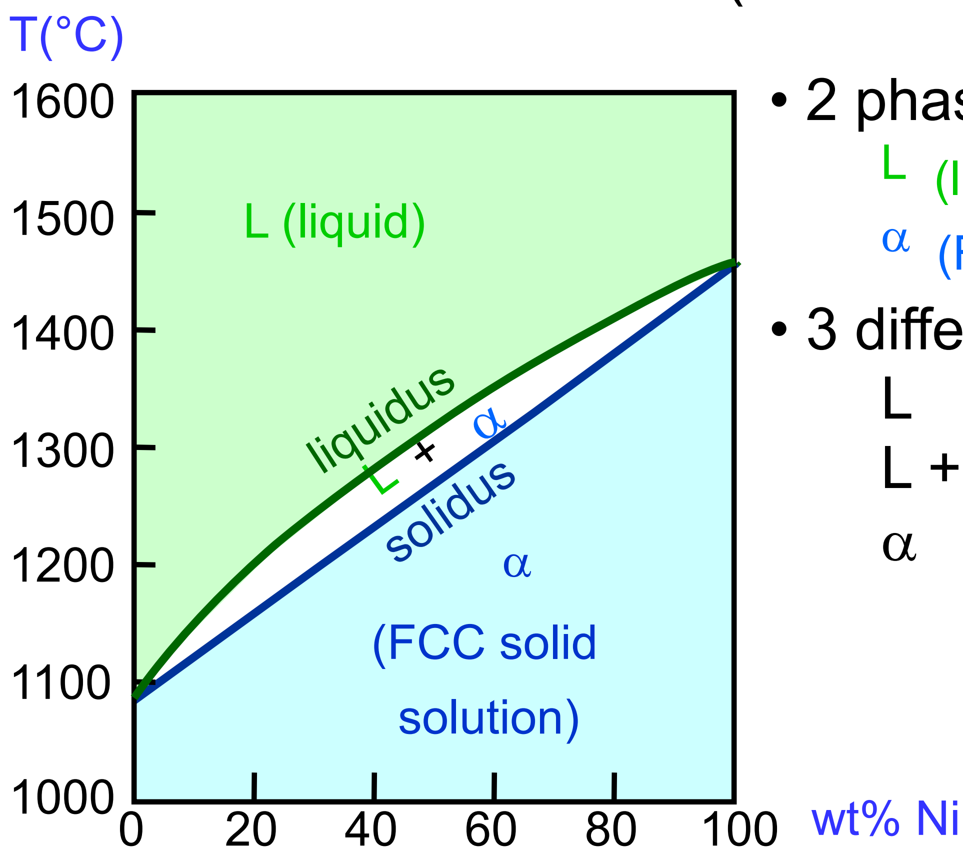
One Component Phase Diagram



Phase Diagrams

- Indicate phases as a function of Temp, Comp and Pressure.
- Focus on:
  - binary systems: 2 components.
  - independent variables: T and C (P = 1 atm is almost always used).

Cu-Ni system

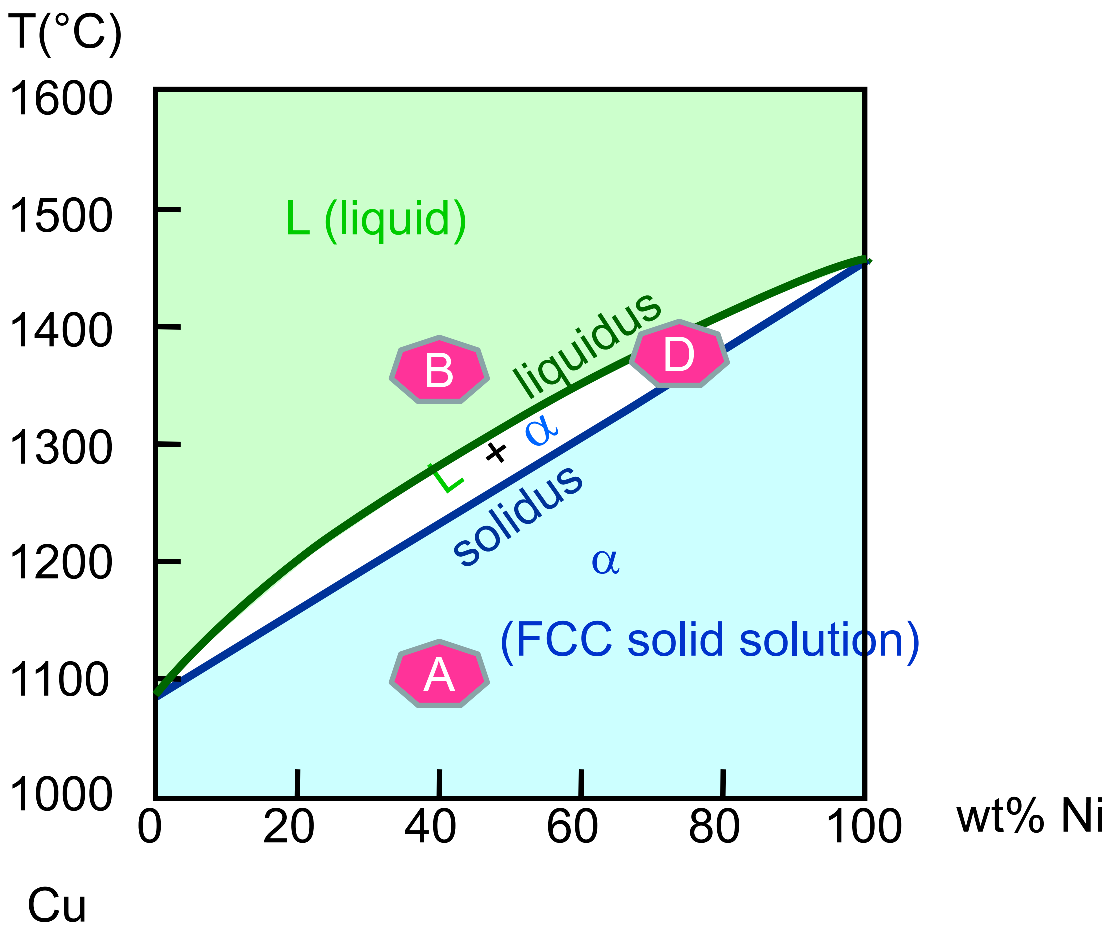


- 2 phases:
  - L (liquid)
  - α (FCC solid solution)
- 3 different phase fields:
  - L
  - L + α
  - α

Effect of Temperature & Composition (C_o)

- Changing T can change # of phases: path A to B.
- Changing C_o can change # of phases: path B to D.

Cu-Ni system



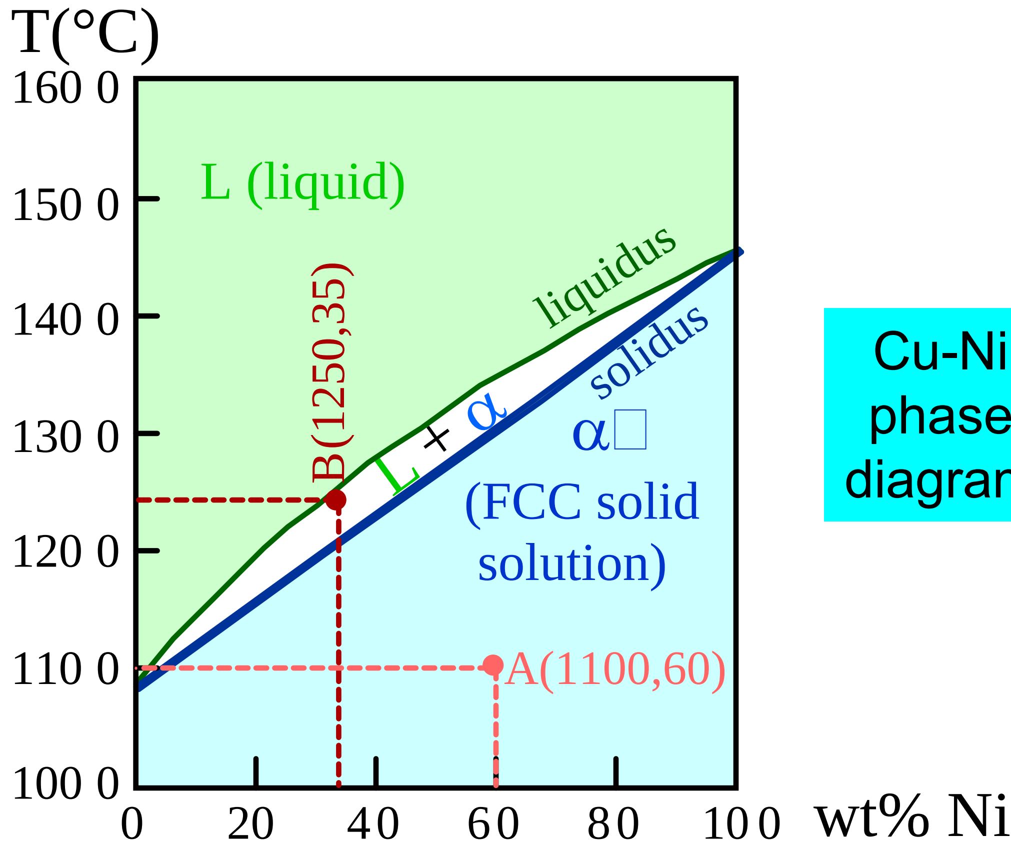
Determination of phase(s) present

- Rule 1: If we know T and C_o, then we know:
  --how many phases and which phases are present.

- Examples:

A(1100, 60):
  1 phase: α

B(1250, 35):
  2 phases: L + α



Cu-Ni phase diagram

Melting points: Cu = 1085°C, Ni = 1453 °C

Solidus - Temperature where alloy is completely solid. Above this line, liquefaction begins.
Liquidus - Temperature where alloy is completely liquid. Below this line, solidification begins.

Phase Diagrams: composition of phases

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

- Examples:

At T_A = 1320°C:

Only Liquid (L) present

$C_L = C_0$ (= 35 wt% Ni)

At T_D = 1190°C:

Only Solid (α) present

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

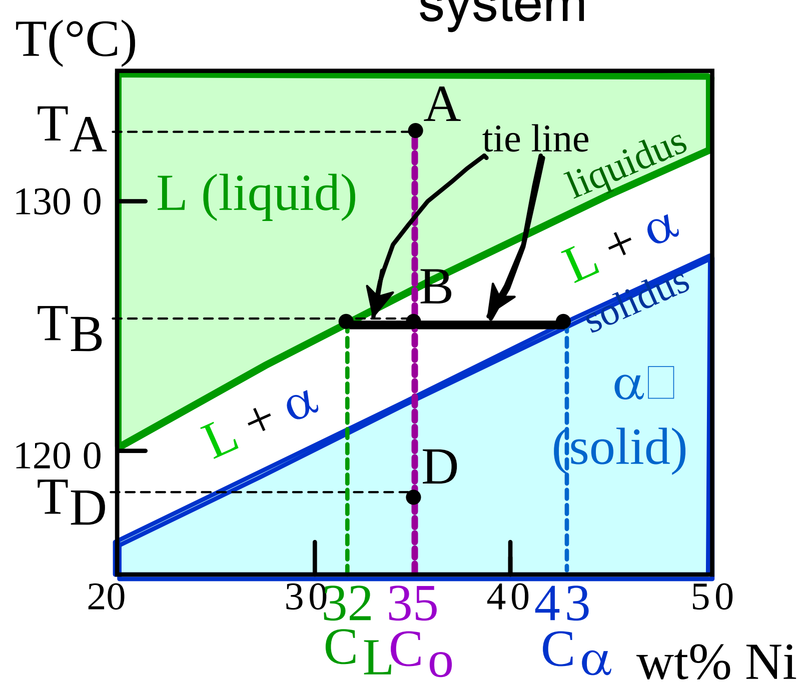
At T_B = 1250°C:

Both α and L present

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

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

Cu-Ni system



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 = 35wt%Ni

At T_A: Only Liquid (L)

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

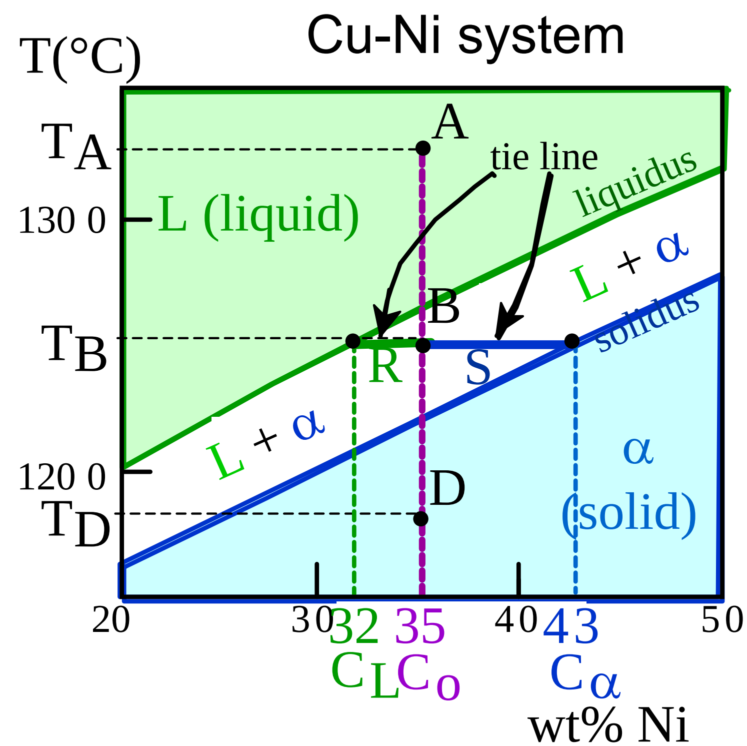
At T_D: Only Solid (α)

$W_L = 0$, W_α = 100wt%

At T_B: Both α and L

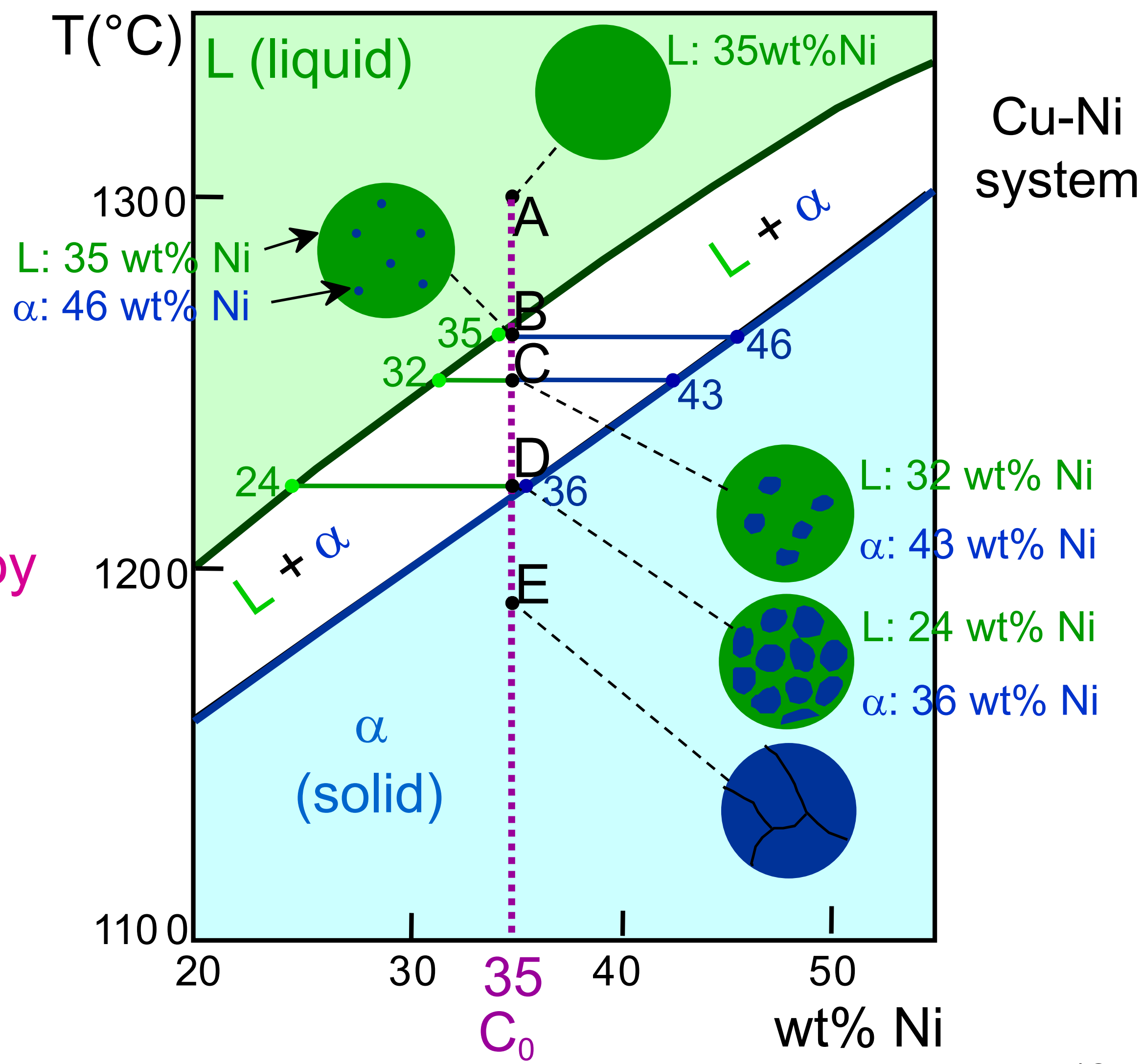
$$W_L = \frac{C_\alpha - C_o}{C_\alpha - C_L} = \frac{43-35}{43-32} = 73\text{wt}\%$$

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

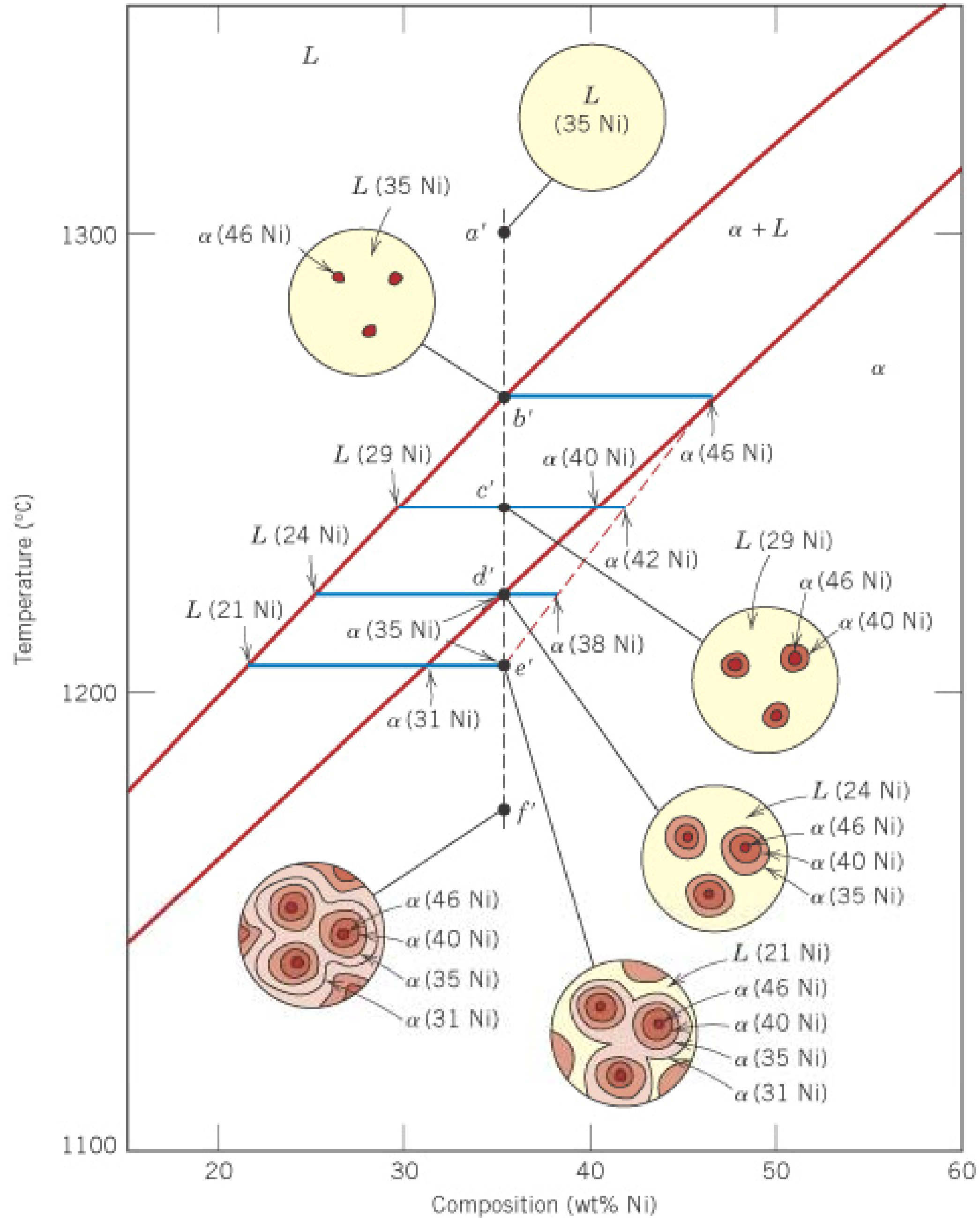


Ex: Equilibrium Cooling of a Cu-Ni Alloy

- Phase diagram: Cu-Ni system.
- Consider microstuctural changes that accompany the cooling of a C_0 = 35 wt% Ni alloy



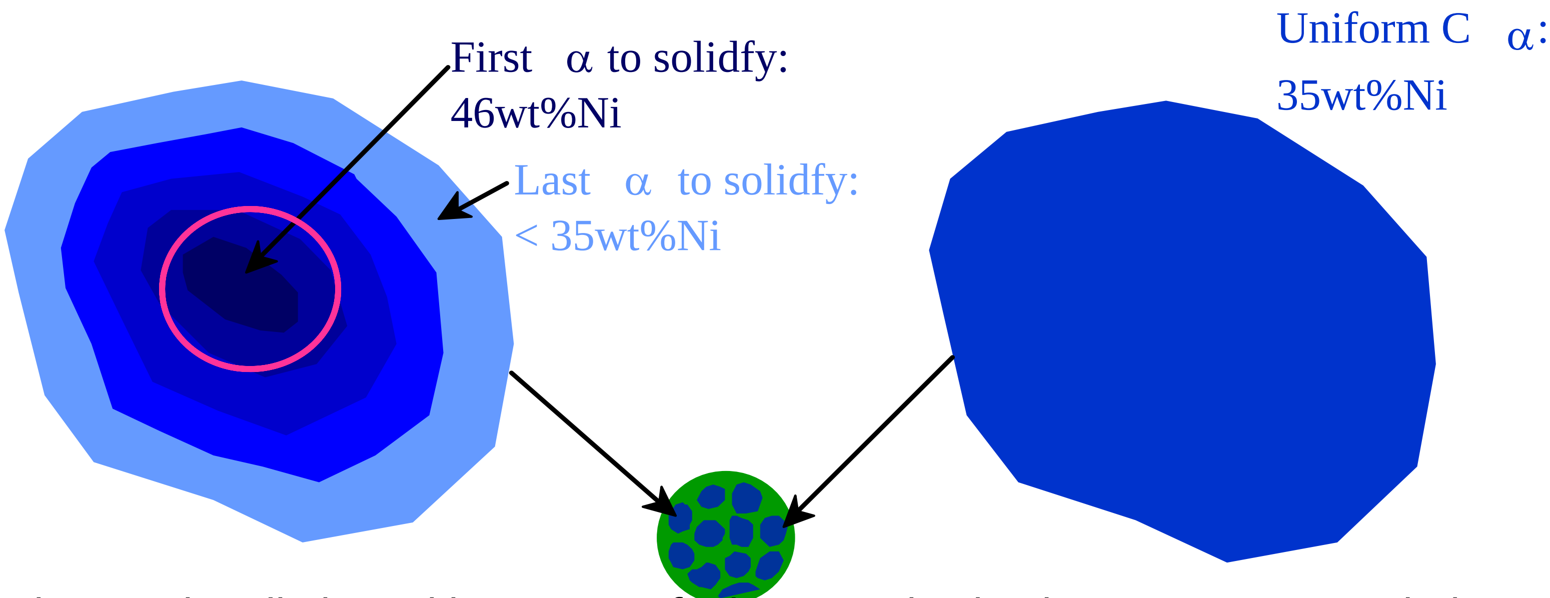
- Development of microstructure during the non-equilibrium solidification of a 35 wt% Ni-65 wt% Cu alloy outcome:
- Segregation- nonuniform distribution of elements within grains.
- Weaker grain boundaries if alloy is reheated.



Cored vs Equilibrium Phases

- C_α changes as it solidifies.
- Cu-Ni case: First α to solidify has C_α = 46wt%Ni.
  Last α to solidify has C_α = 35wt%Ni.

- Fast rate of cooling:
  Cored structure
- Slow rate of cooling:
  Equilibrium structure

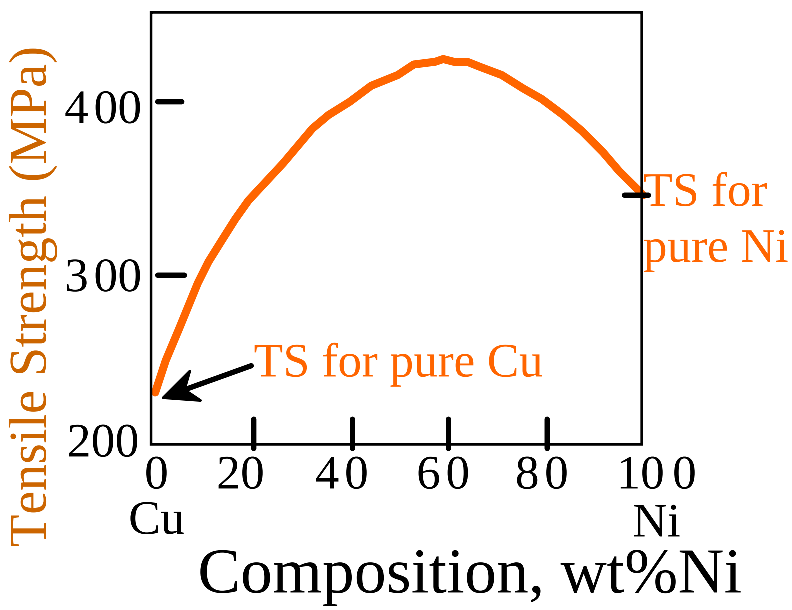


- Coring can be eliminated by means of a homogenization heat treatment carried out at temperatures below the alloy's solidus. During the process, atomic diffusion produces grains that are compositionally homogeneous.

Mechanical Properties: Cu-Ni System

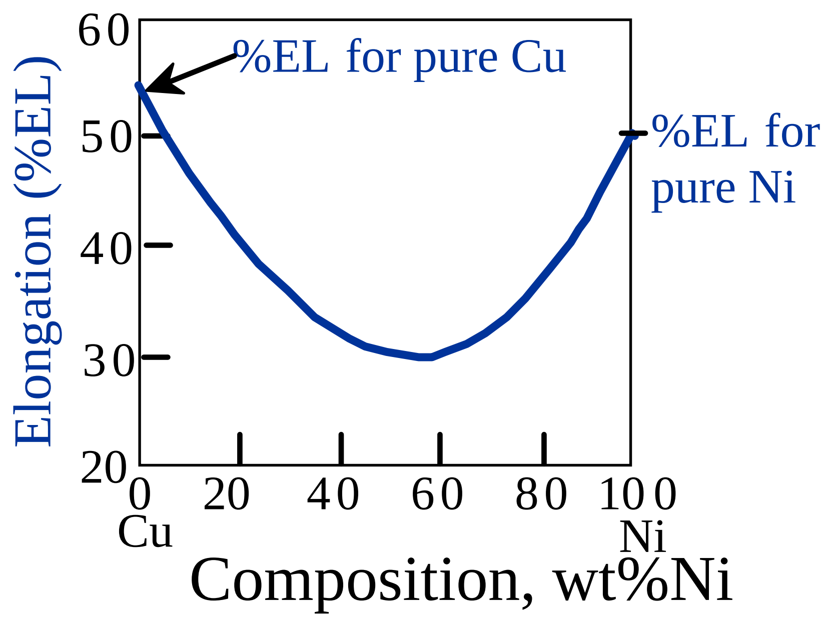
- Effect of solid solution strengthening on:

--Tensile strength (TS)



--Peak as a function of C_o

--Ductility (%EL,%AR)

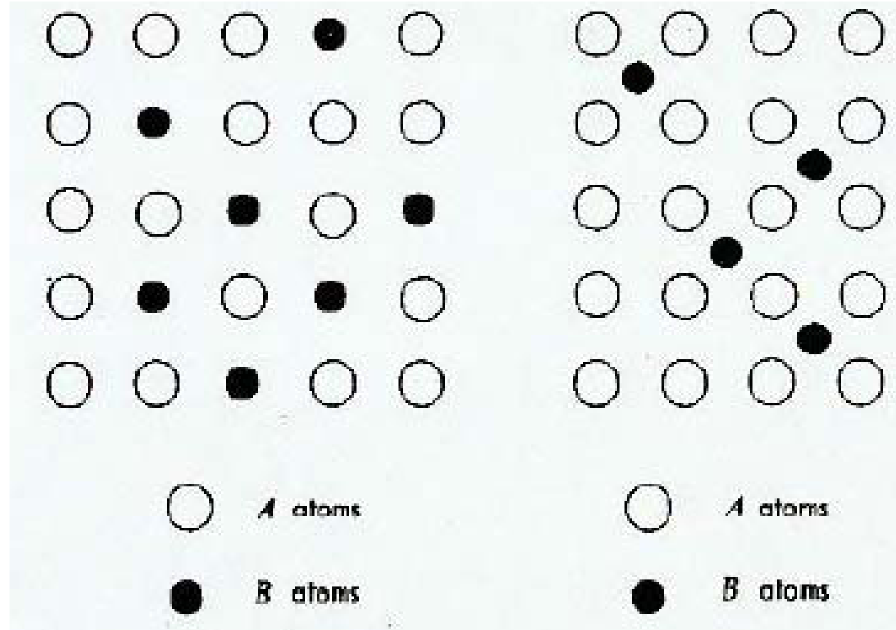


--Min. as a function of C_o

Binary Isomorphous Systems

Cu-Ni system:

- The liquid L is a homogeneous liquid solution composed of Cu and Ni.
- The α phase is a substitutional solid solution consisting of Cu and Ni atoms with an FCC crystal structure.
- At temperatures below 1080 C, Cu and Ni are mutually soluble in each other in the solid state for all compositions.
- The complete solubility is explained by their FCC structure, nearly identical atomic radii and electro-negativities, and similar valences.
- The Cu-Ni system is termed isomorphous because of this <u>complete liquid and solid solubility of the 2 components</u>.



What is a solid solution?

When foreign atoms are incorporated into a crystal structure, whether in substitutional or interstitial sites, the resulting phase is a solid solution of the matrix material (solvent) and the foreign atoms (solute)

Substitutional Solid Solution: Foreign (solute) atoms occupy "normal" lattice sites occupied by matrix (solvent) atoms, e.g. Cu-Ni;Ge-Si

Interstitial Solid Solutions: Foreign (solute) atoms occupy interstitial sites, e.g., Fe-C

Criteria for Solid Solubility

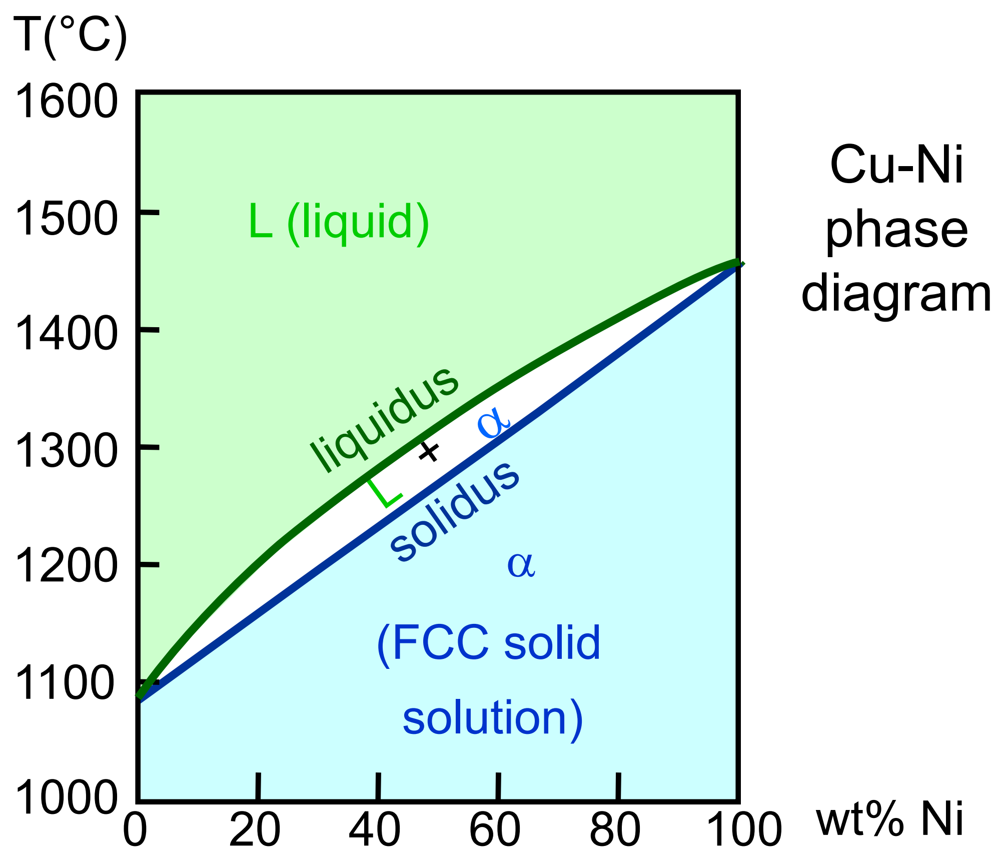
Simple system (e.g., Ni-Cu solution)

	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 soluble in one another for all proportions.

Isomorphous Binary Phase Diagram

- Phase diagram:
  Cu-Ni system.
- System is:
  -- binary
  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.



Importance of Phase Diagrams

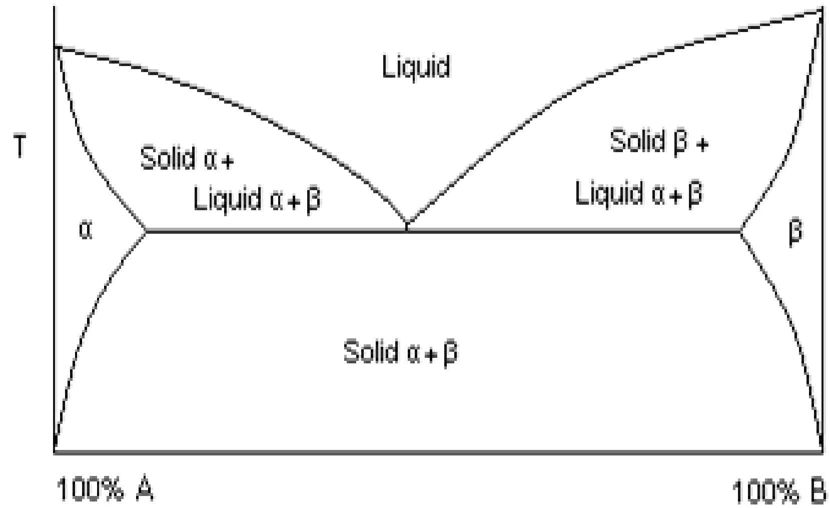
- There is a strong correlation between microstructure and mechanical properties, and the development of alloy microstructure is related to the characteristics of its phase diagram.
- Phase diagrams provide valuable information about melting, casting, crystallization and other phenomena.

Microstructure

- In metal alloys, microstructure is characterized by the number of phases, their proportions, and the way they are arranged.
- The microstructure depends on:
  - Alloying elements
  - Concentration
  - Heat treatment (temperature, time, rate of cooling)

Eutectic

- A **eutectic** or **eutectic mixture** is a mixture of two or more phases at a composition that has the lowest melting point.
- It is where the phases simultaneously crystallize from molten solution.
- The proper ratios of phases to obtain a eutectic is identified by the eutectic point on a binary phase diagram.
- The term comes from the Greek 'eutektos', meaning 'easily melted.'



- The phase diagram displays a simple binary system composed of two components, **A** and **B**, which has a eutectic point.
- The phase diagram plots relative concentrations of A and B along the X-axis, and temperature along the Y-axis. **The eutectic point is the point where the liquid phase borders directly on the solid α + β phase; it** represents the minimum melting temperature of any possible A B alloy.
- The temperature that corresponds to this point is known as the **eutectic temperature**.
- Not all binary system alloys have a eutectic point: those that form a solid solution at all concentrations, such as the gold-silver system, have no eutectic. An alloy system that has a eutectic is often referred to as a eutectic system, or eutectic alloy.
- Solid products of a eutectic transformation can often be identified by their lamellar structure, as opposed to the dendritic structures commonly seen in non-eutectic solidification. The same conditions that force the material to form lamellae can instead form an amorphous solid if pushed to an extreme.

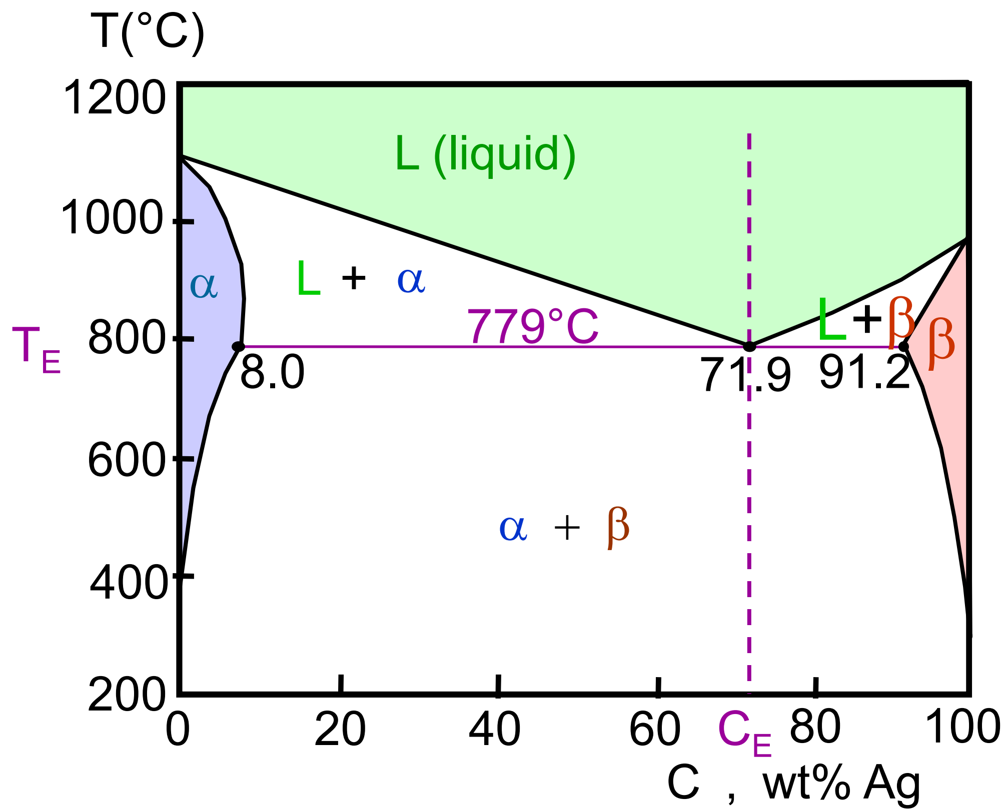
Binary-Eutectic Systems

2 components

has a special composition with a min. melting T.

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 : Composition at temperature T_E

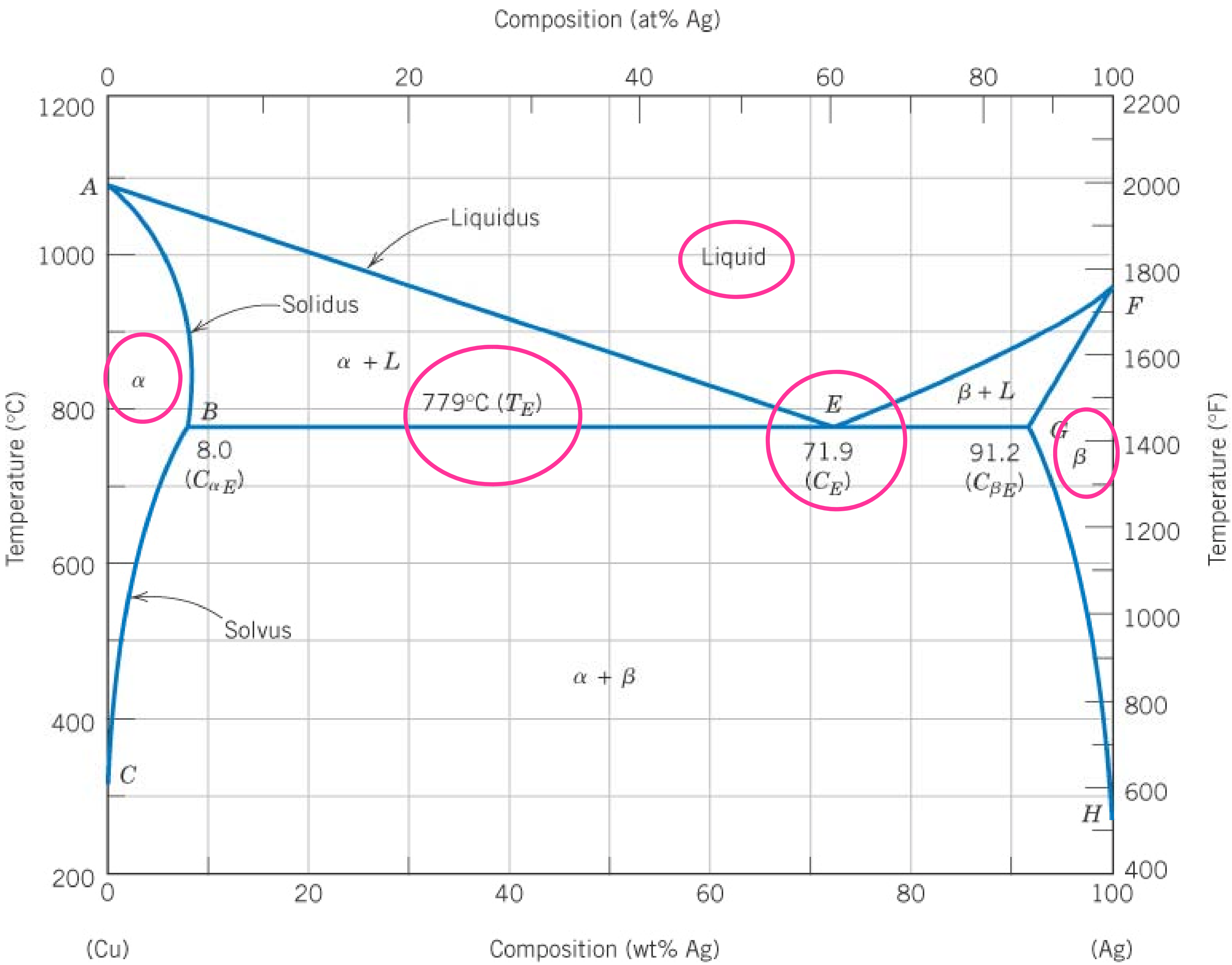


- **Eutectic reaction**

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

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

Copper-Silver Phase Diagram



Eutectic Reaction

- Solvus – (solid solubility line) BC, GH
- Solidus – AB, FG, BEG (eutectic isotherm)
- Liquidus – AEF
- Maximum solubility: α = 8.0 wt% Ag, β = 8.8 wt %Cu
- Invariant point (where 3 phases are in equilibrium) is at E; C_E = 71.9 wt% Ag, T_E = 779C (1434F).

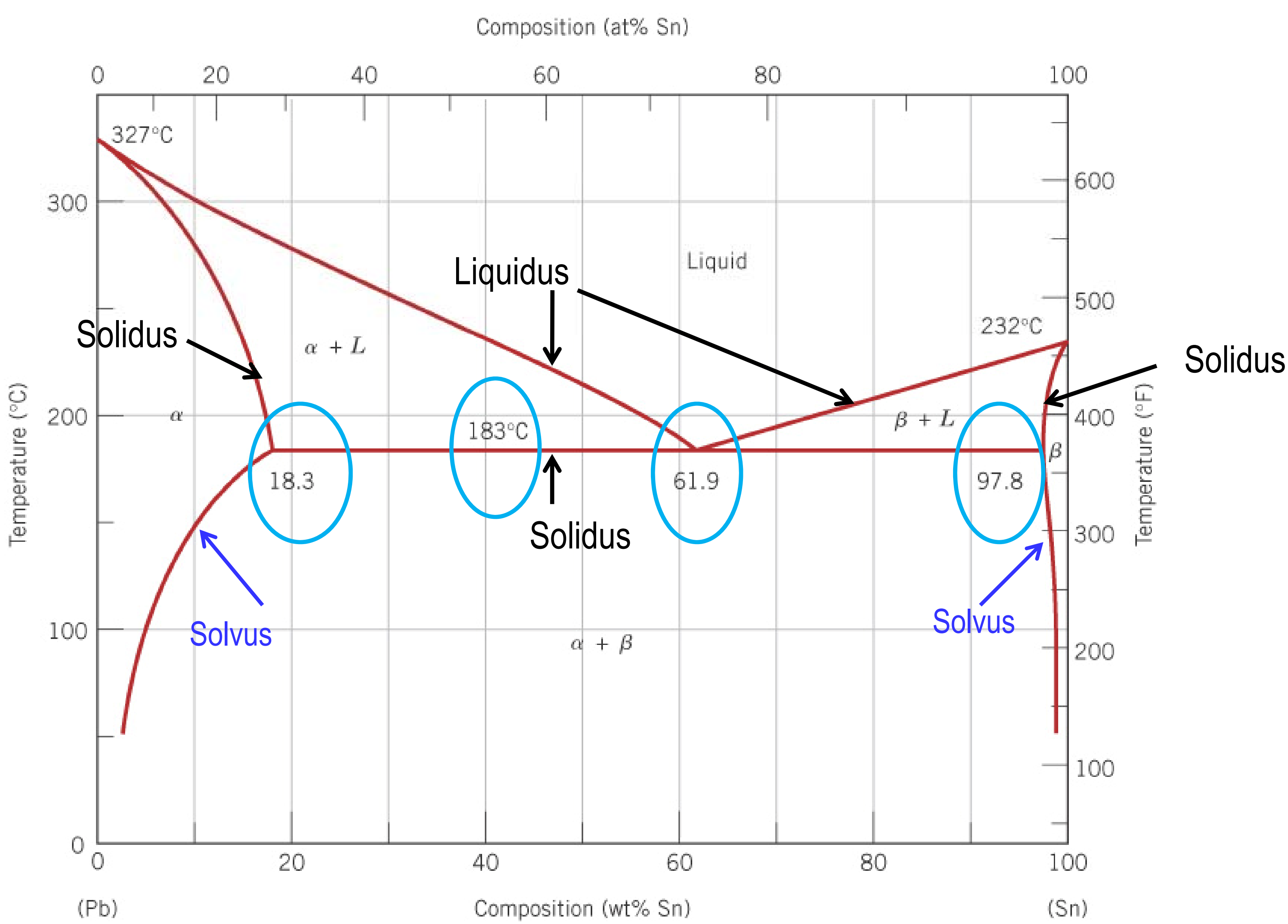
- An isothermal, reversible reaction between two (or more) solid phases during the heating of a system where a single liquid phase is produced.

Eutectic reaction

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

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

Pb-Sn Phase Diagram



Solidification of Eutectic Mixtures

- Mixtures of some metals, such as copper & nickel, are completely soluble in both liquid and solid states for all concentrations of both metals. Copper & nickel have the same crystal structure (FCC) and have nearly the same atomic radii. The solid formed by cooling can have any proportion of copper & nickel. Such completely miscible mixtures of metals are called **isomorphous**.
- By contrast, a mixture of lead & tin that is **eutectic** is only partially soluble when in the solid state. Lead & tin have different crystal structures (FCC versus BCT) and lead atoms are much larger. No more than 18.3 weight % solid tin can dissolve in solid lead and no more than 2.2% of solid lead can dissolve in solid tin (according to previous phase diagram).
- The solid lead-tin alloy consists of a mixture of two solid phases, one consisting of a maximum of 18.3 wt% tin (the **alpha** phase) and one consisting of a maximum of 2.2 wt% lead (the **beta** phase).

(Ex 1) Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, determine:
  - -- the phases present

Answer: $\alpha + \beta$

  -- the phase compositions

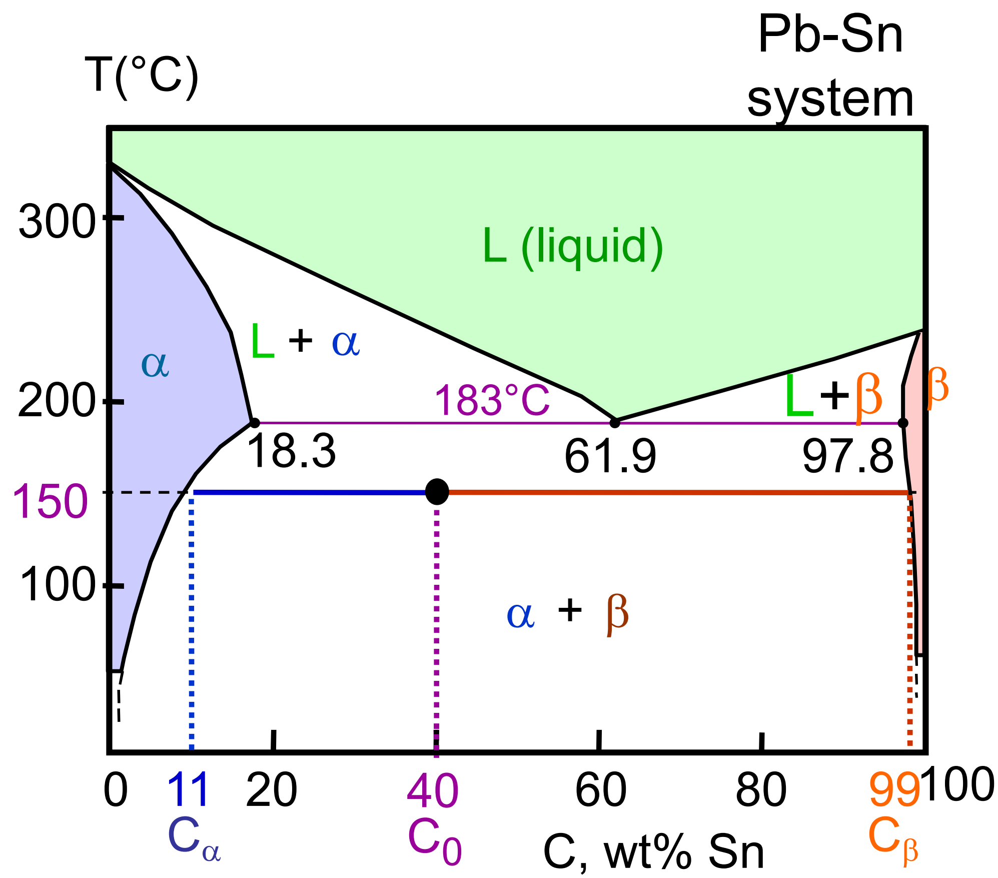
Answer: C_α = 11 wt% Sn
C_β = 99 wt% Sn

  -- the relative amount of each phase

Answer:

$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = \frac{99 - 40}{99 - 11} = \frac{59}{88} = 0.67$$

$$W_\beta = \frac{C_0 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 11}{99 - 11} = \frac{29}{88} = 0.33$$



(Ex 2) Pb-Sn Eutectic System

- For a 40 wt% Sn-60 wt% Pb alloy at 220°C, determine:
  - -- the phases present:

Answer: α + L

-- the phase compositions

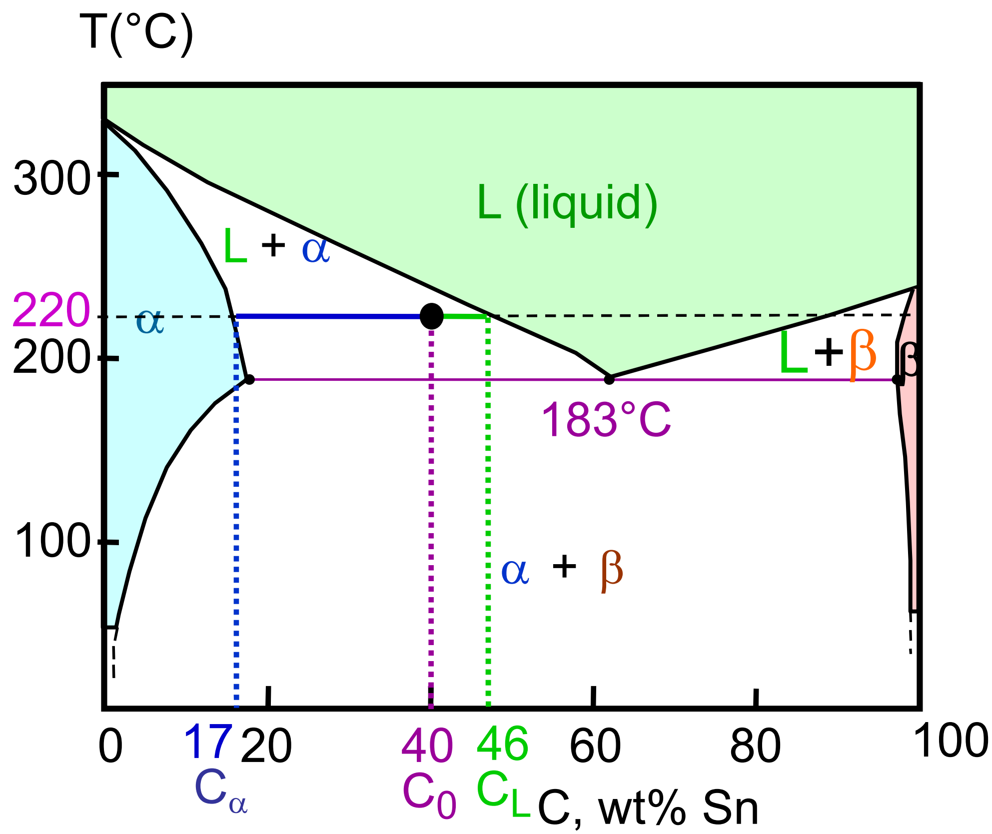
Answer: C_α = 17 wt% Sn
C_L = 46 wt% Sn

-- the relative amount of each phase

Answer:

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 0.21$$

$$W_L = \frac{C_0 - C_\alpha}{C_L - C_\alpha} = \frac{23}{29} = 0.79$$



Pb-Sn

- For lead & tin the eutectic composition is 61.9 wt% tin and the eutectic temperature is 183ºC -- which makes this mixture useful as **solder**.
- At 183ºC, compositions of greater than 61.9 wt% tin result in precipitation of a tin-rich solid in the liquid mixture, whereas compositions of less than 61.9 wt% tin result in precipitation of lead-rich solid.

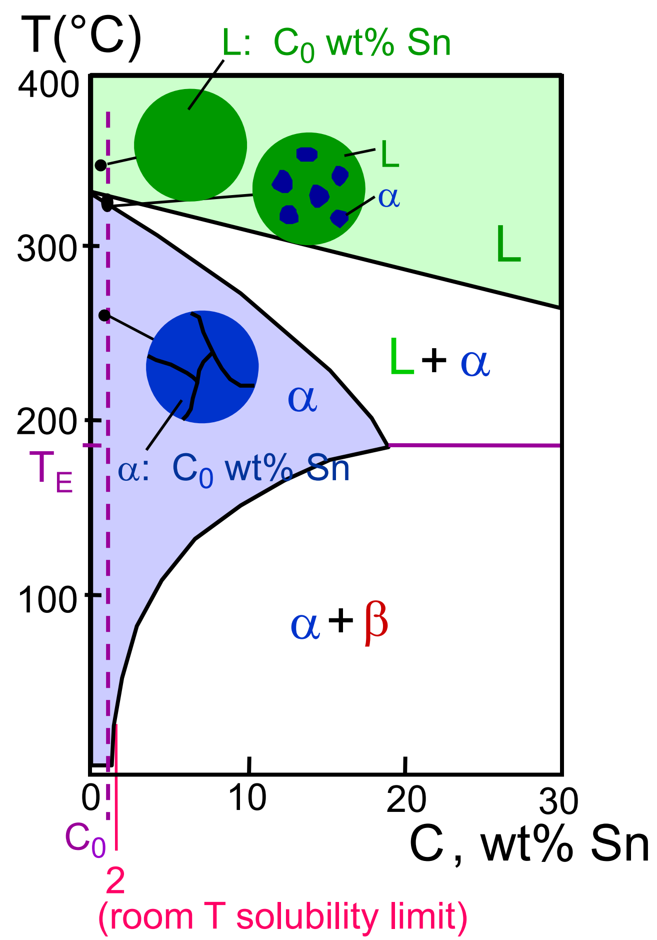
Microstructural Developments in Eutectic Systems - I

- For alloys where

  $C_0 < 2$ wt% Sn

- Result at room temperature is a polycrystalline with grains of α phase having composition C_0

Pb-Sn system

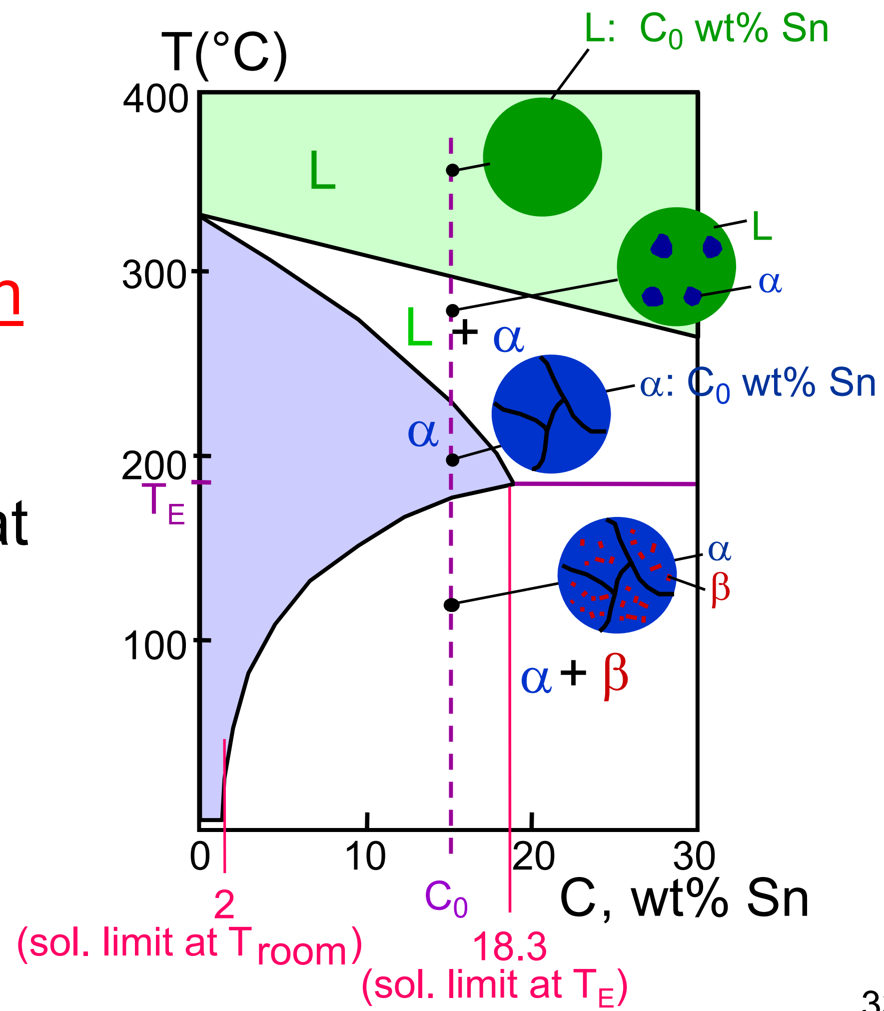


Microstructural Developments in Eutectic Systems - II

Pb-Sn system

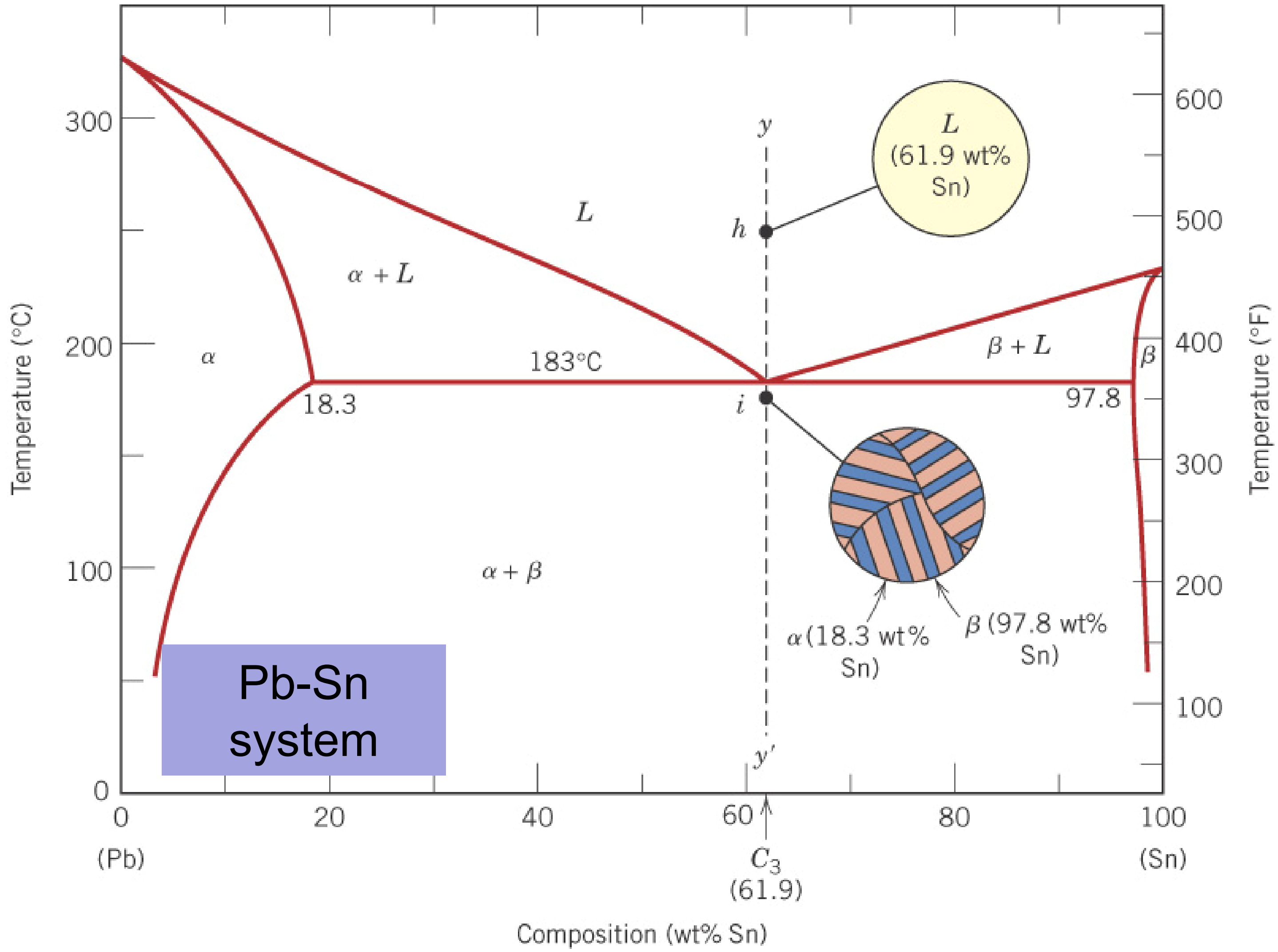
2 wt% Sn < C_0 < 18.3 wt% Sn

- Results in polycrystalline microstructure with α grains and small β-phase particles at lower temperatures.



Microstructures in Eutectic Systems - III

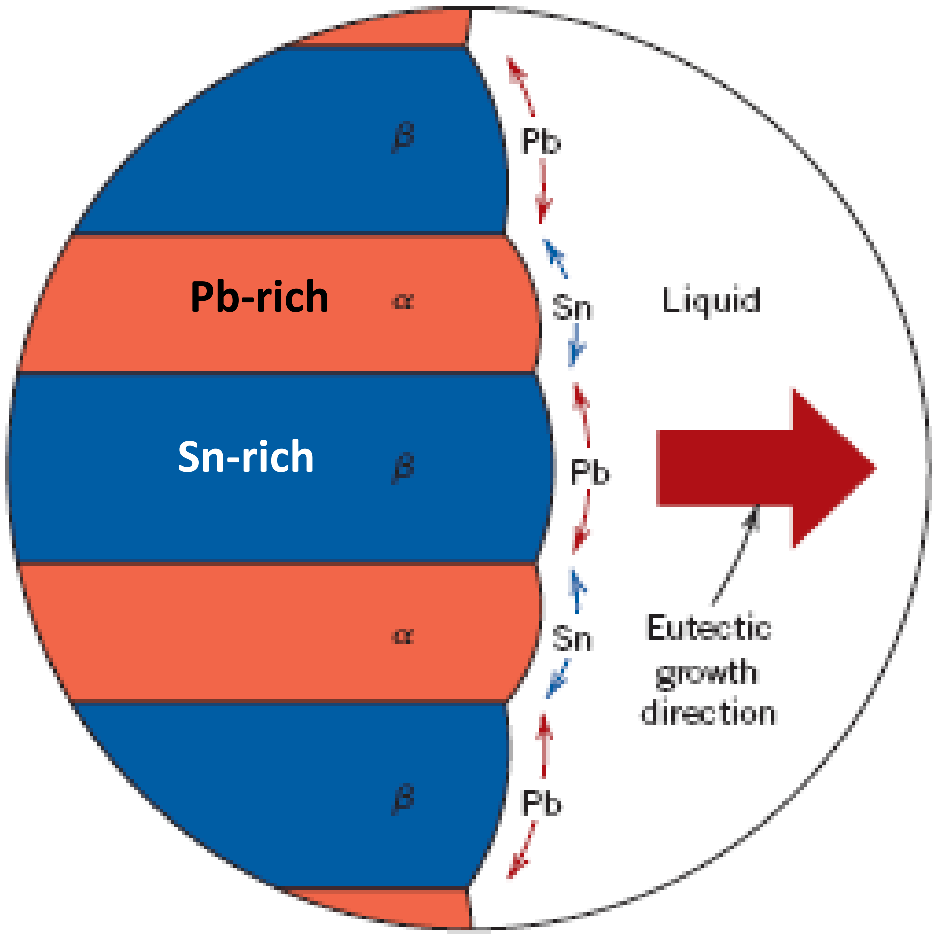
- $C_O = C_E$
- Results in a eutectic microstructure with alternating layers of α and β crystals.



$$L(61.9\text{ wt\% Sn}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(18.3\text{ wt\% Sn}) + \beta(97.8\text{ wt\% Sn})$$

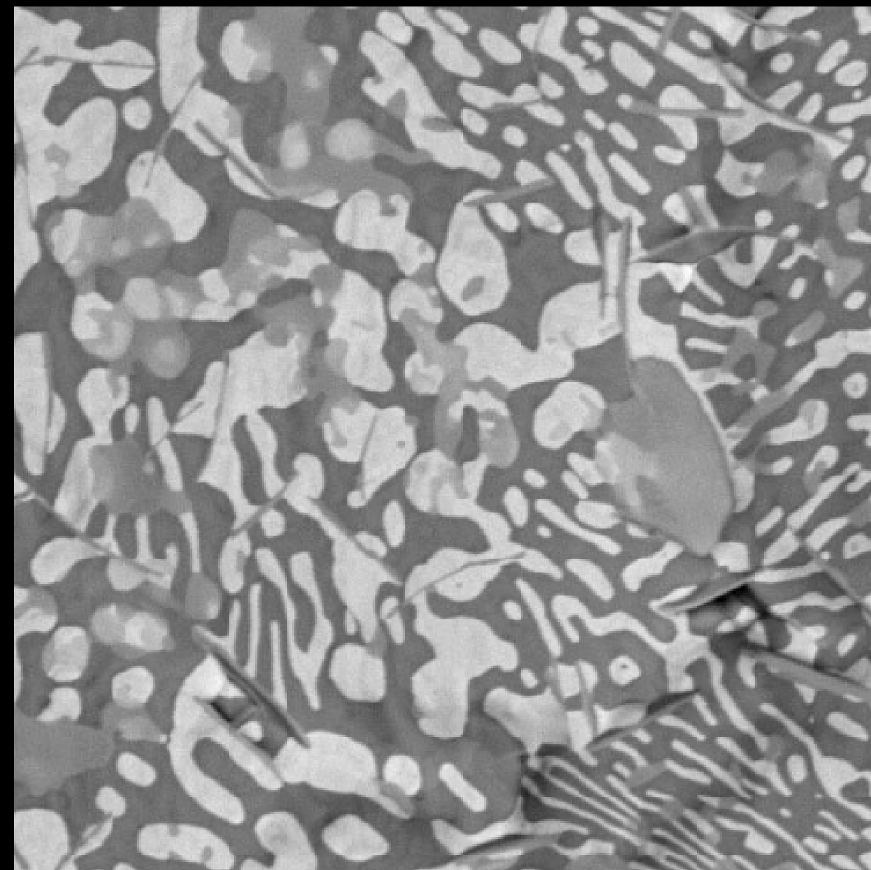
Lamellar Eutectic Structure

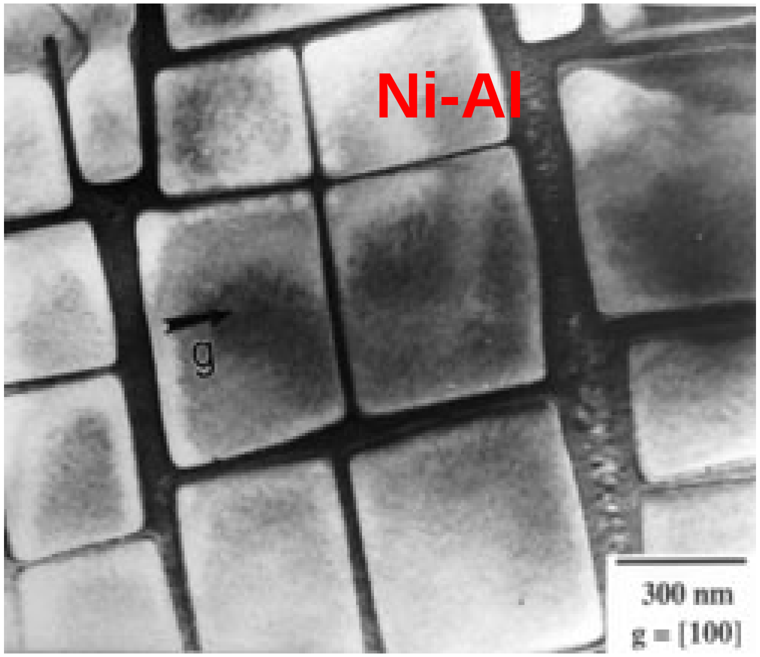
- A 2-phase microstructure resulting from the solidification of a liquid having the eutectic composition where the phases exist as a lamellae that alternate with one another.
- Formation of eutectic layered microstructure in the Pb-Sn system during solidification at the eutectic composition. Compositions of α and β phases are very different. Solidification involves redistribution of Pb and Sn atoms by **atomic diffusion**.

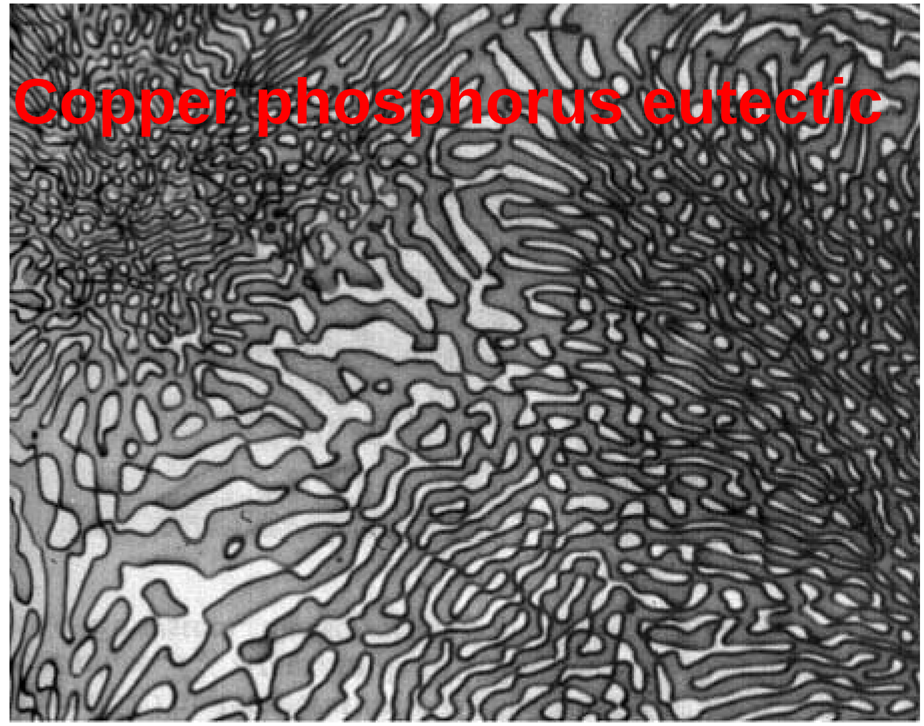


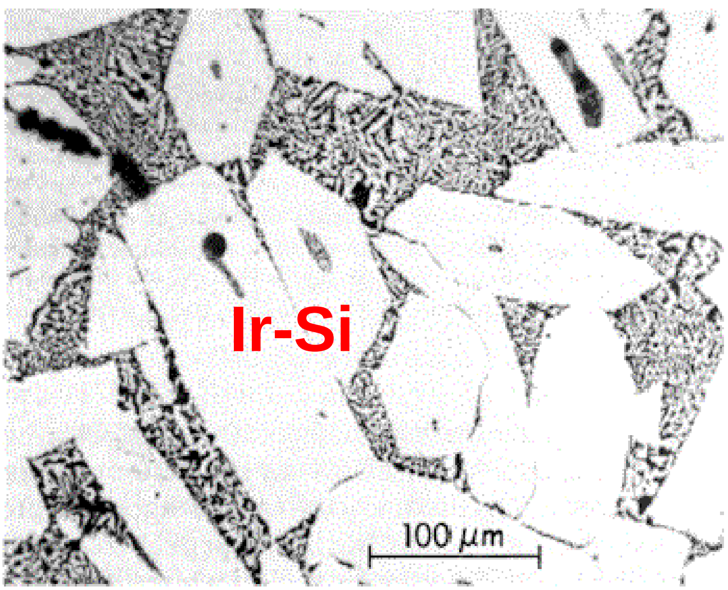
Pb-Sn Microstructures

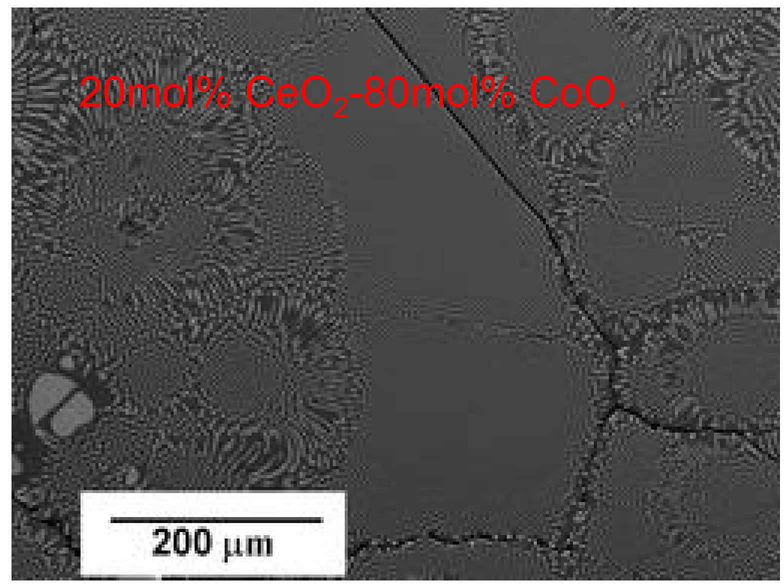
The dark layers are Pb-rich α phase, the light layers are the Sn-rich β phase.




Ni-Al
g
300 nm
g = [100]


Copper phosphorus eutectic

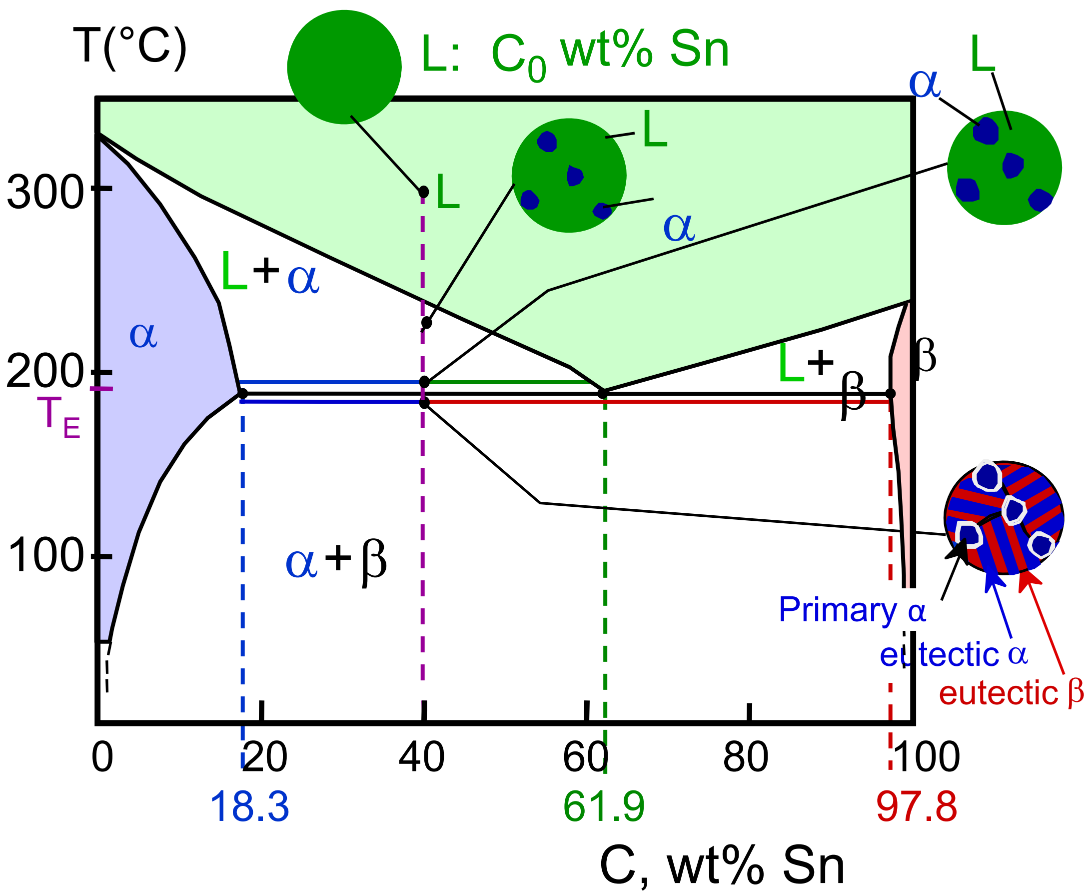

Ir-Si
100 μm


20mol% CeO_2-80mol% CoO.
200 μm

Microstructures in Eutectic Systems - IV

Pb-Sn system

- For alloys with18.3 wt% Sn < C_0 < 61.9 wt% Sn
- Result: α phase particles and a eutectic microconstituent



- Just above T_E :

C_α = 18.3 wt% Sn

C_L = 61.9 wt% Sn

$$W_\alpha = \frac{C_L - C_0}{C_L - C_\alpha} = 0.50$$

W_L = (1- W_α) = 0.50

- Just below T_E :

C_α = 18.3 wt% Sn

C_β = 97.8 wt% Sn

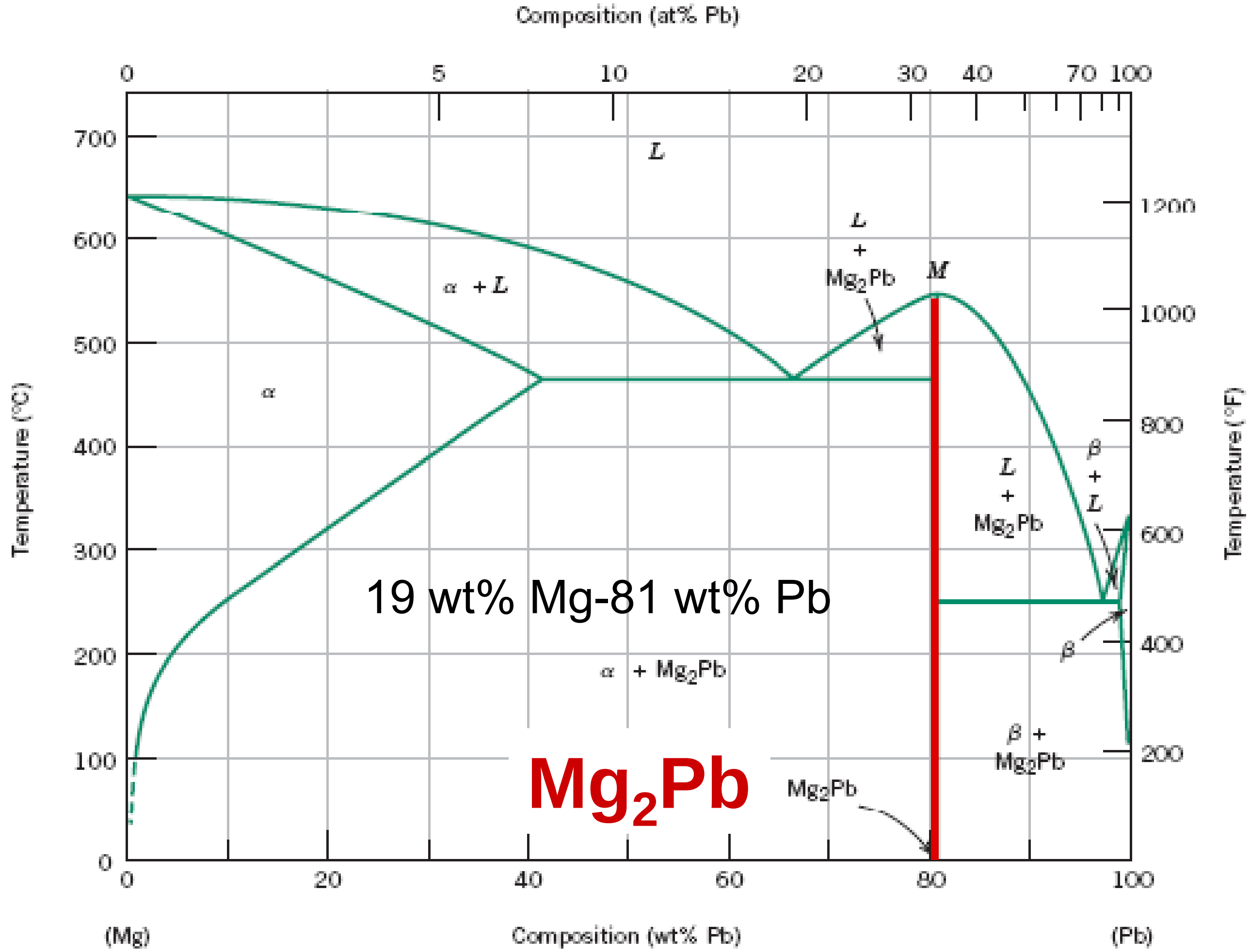
$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = 0.727$$

W_β = 0.273 wt% Sn

(part 2)

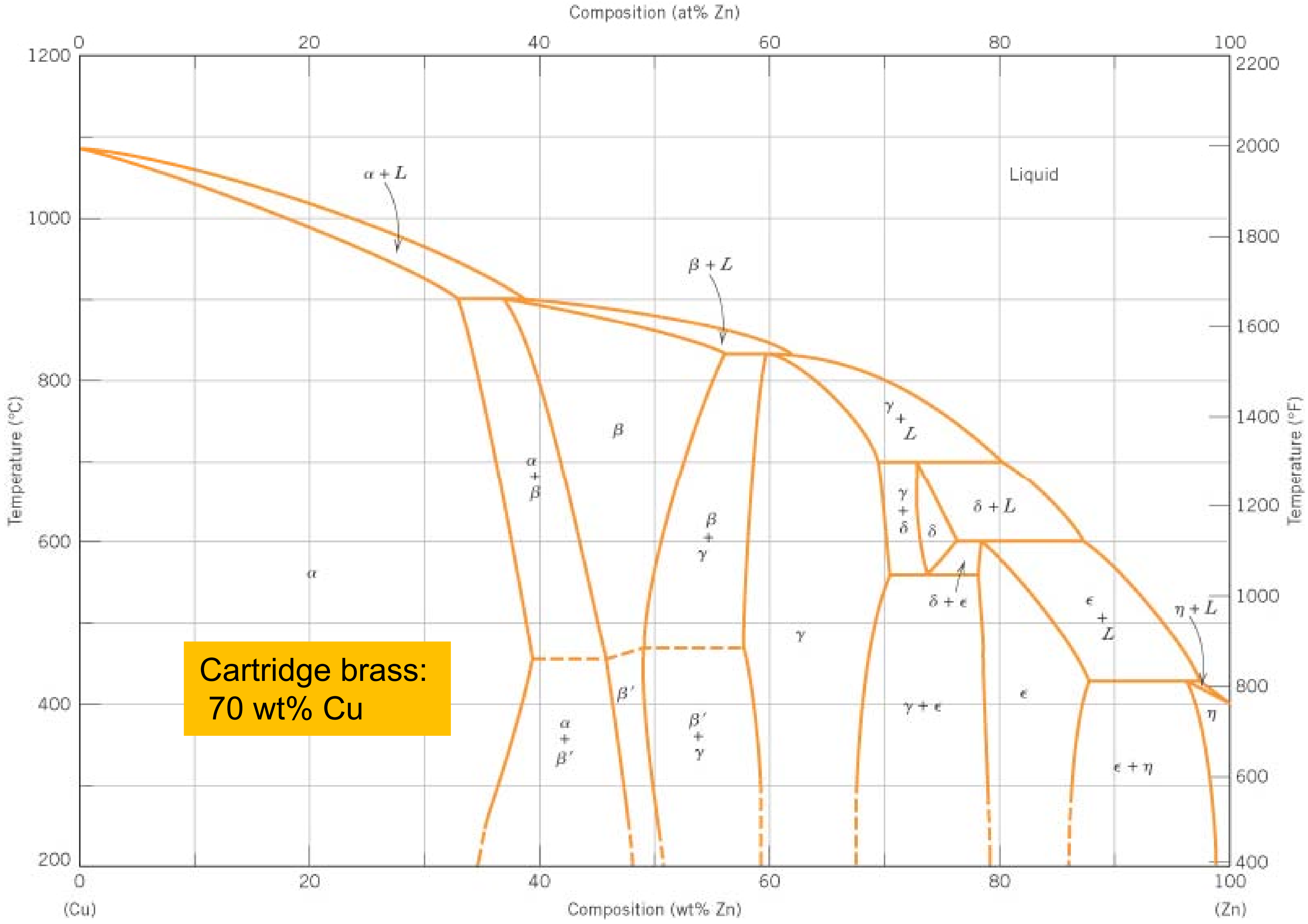
- Equilibrium Diagrams with Intermediate Phases or Compounds
- Eutectoid and Peritectic Reactions
- Ceramic Phase Diagrams
- The Gibbs Phase Rule
- The Iron-Iron Carbide Phase Diagram
- Development of Microstructures in Iron-Carbon Alloys
- Hypoeutectoid Alloys
- Hypereutectoid Alloys
- Influence of Other Alloying Elements

Intermetallic Compounds



Note: intermetallic compounds exist as a line on the diagram - not a phase region. The composition of a compound has a distinct chemical formula.

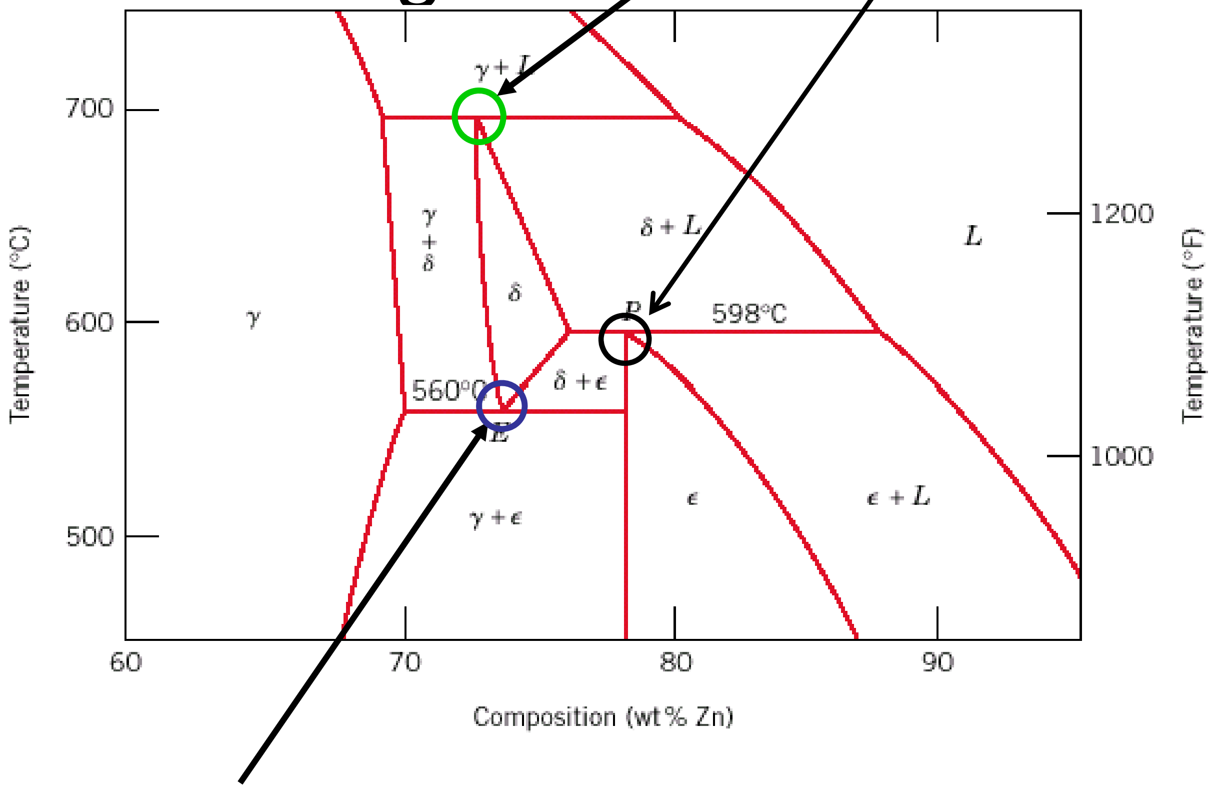
Cu-Zn System (Brass)



Eutectoid & Peritectic

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

Cu-Zn Phase diagram



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

Eutectic, Eutectoid, & Peritectic

- Eutectic - liquid transforms to two solid phases

  $$L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$$ (For Pb-Sn, 183°C, 61.9 wt% Sn)

- Eutectoid – one solid phase transforms to two other solid phases

  $Solid_1 \leftrightarrow Solid_2 + Solid_3$

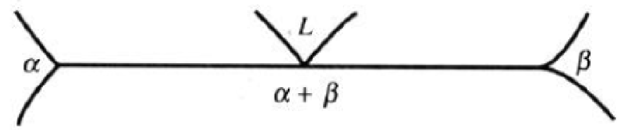
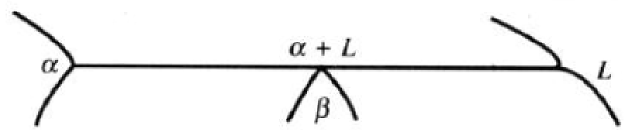
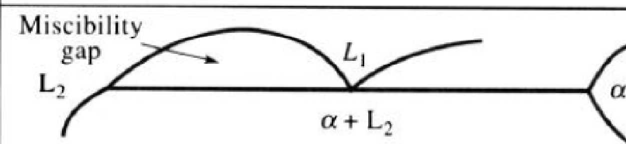
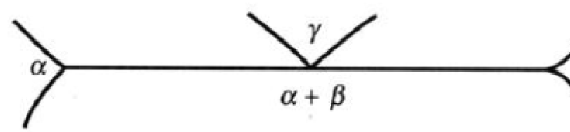
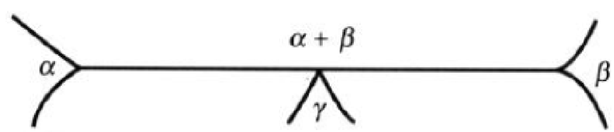
  $$\gamma \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + Fe_3C$$ (For Fe-C, 727°C, 0.76 wt% C)

- Peritectic - liquid and one solid phase transform to a 2nd solid phase

  $Solid_1 + Liquid \leftrightarrow Solid_2$

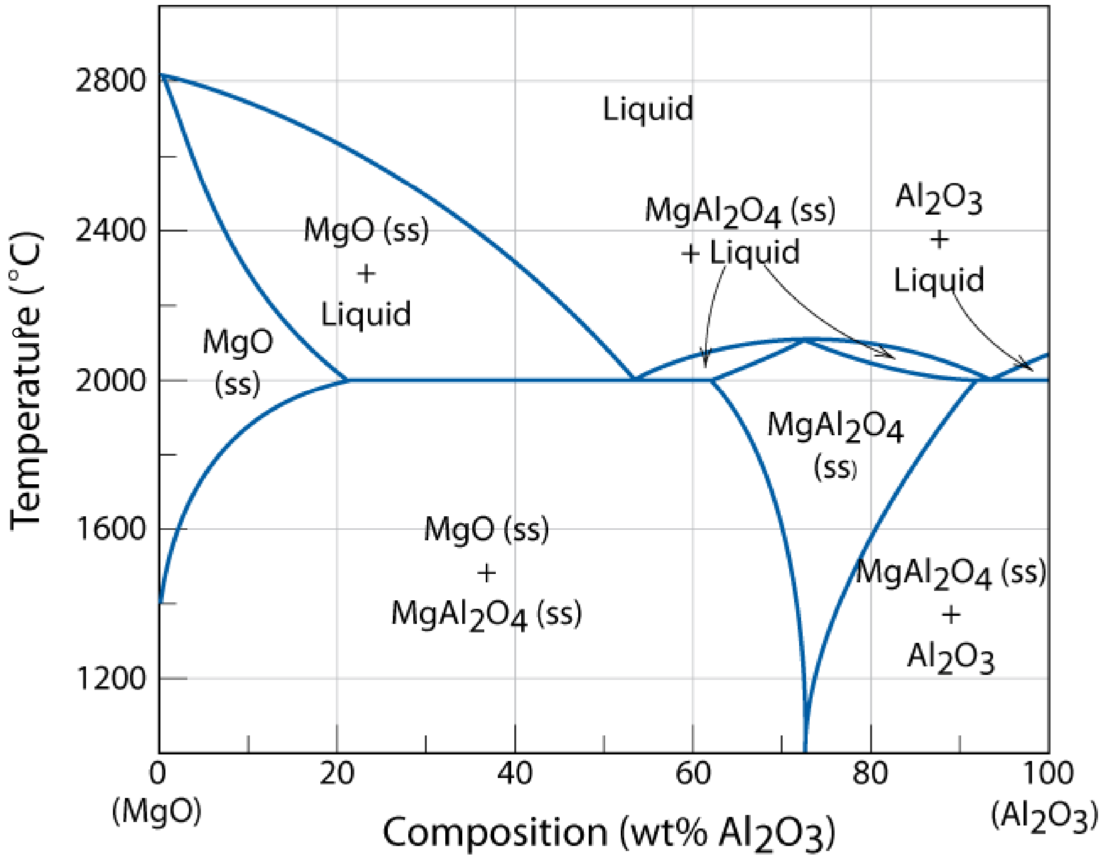
  $$\delta + L \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \varepsilon$$ (For Cu-Zn, 598°C, 78.6 wt% Zn)

Three-Phase Reactions

Eutectic	$L \rightarrow \alpha + \beta$	
Peritectic	$\alpha + L \rightarrow \beta$	
Monotectic	$L_1 \rightarrow L_2 + \alpha$	
Eutectoid	$\gamma \rightarrow \alpha + \beta$	
Peritectoid	$\alpha + \beta \rightarrow \gamma$	

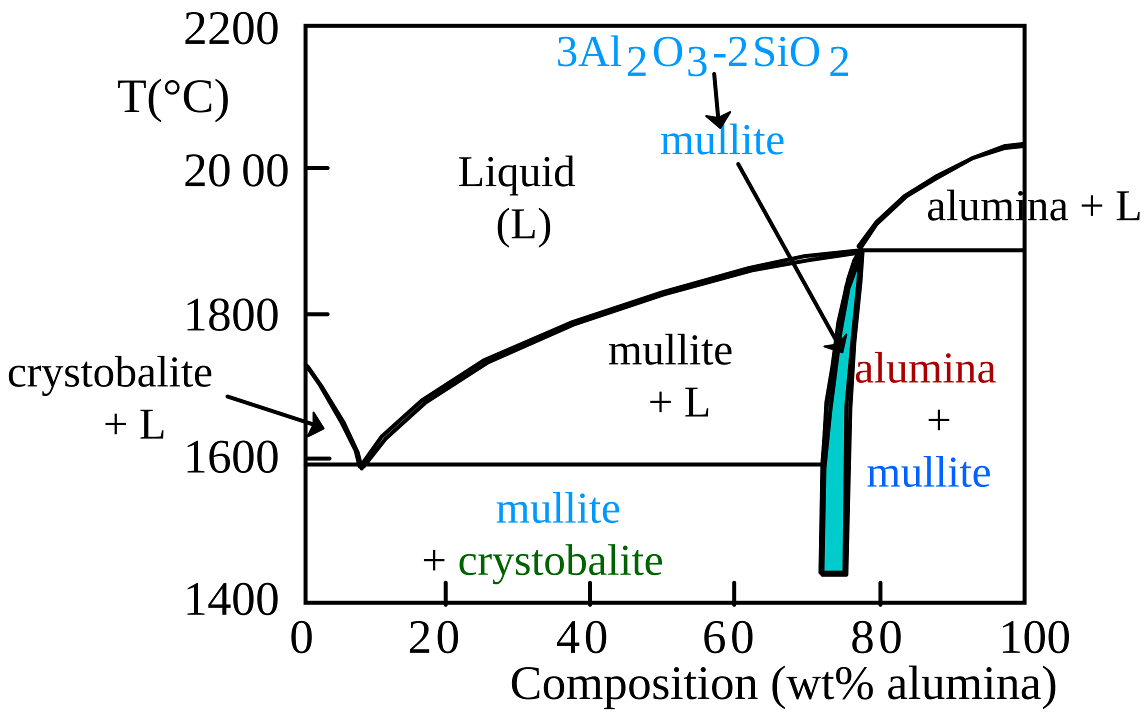
Ceramic Phase Diagrams

$MgO-Al_2O_3$ diagram:

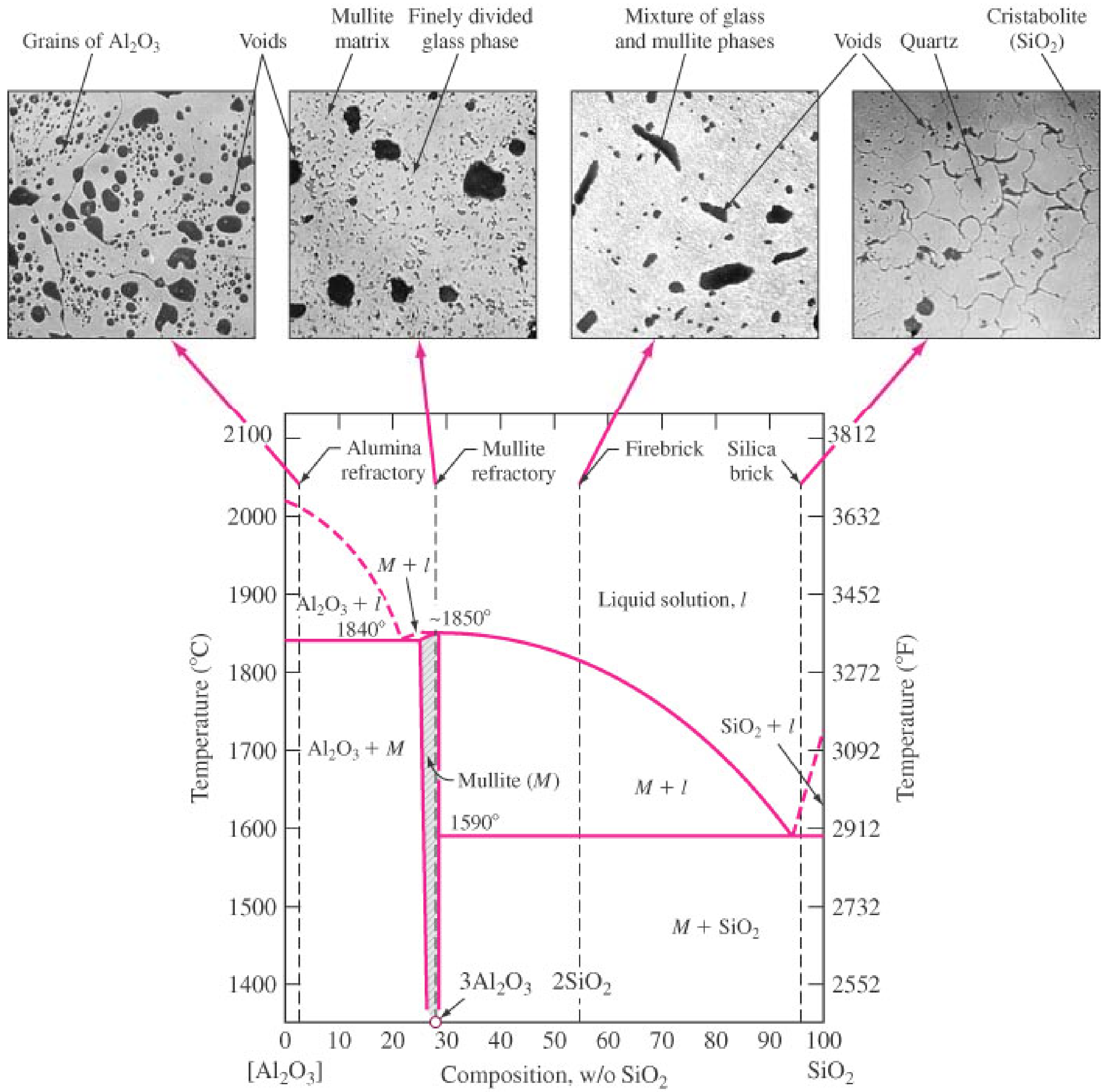


APPLICATION: REFRACTORIES

- Need a material to use in high temperature furnaces.
- Consider Silica (SiO_2) - Alumina (Al_2O_3) system.
- Phase diagram shows: mullite, alumina and crystobalite (made up of SiO_2) are candidate refractories.



Ceramic Phases and Cements



Gibbs Phase Rule

- Phase diagrams and phase equilibria are subject to the laws of thermodynamics.
- Gibbs phase rule is a criterion that determines how many phases can coexist within a system at equilibrium.

$$P + F = C + N$$

P: # of phases present

F: degrees of freedom (temperature, pressure, composition)

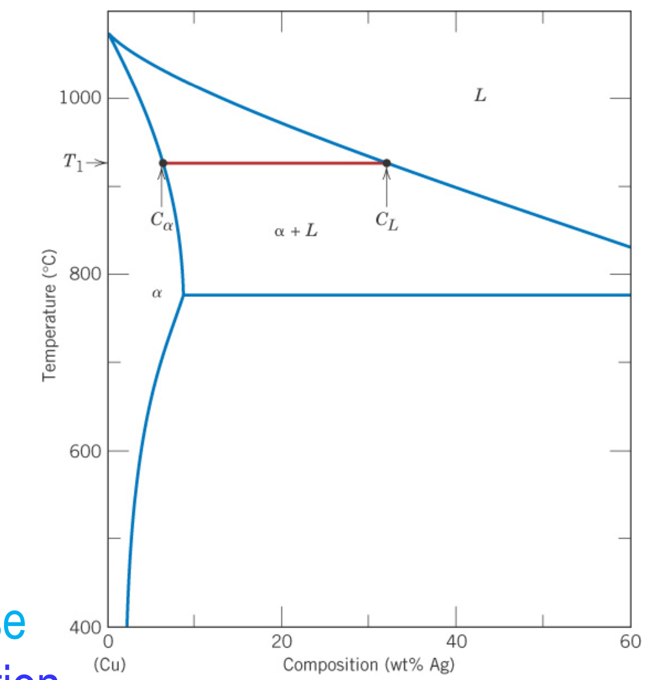
C: components or compounds

N: noncompositional variables

For the Cu-Ag system @ 1 atm for a single phase P:

N=1 (temperature), C = 2 (Cu-Ag), P= 1 (α, β, L)

F = 2 + 1 – 1= 2



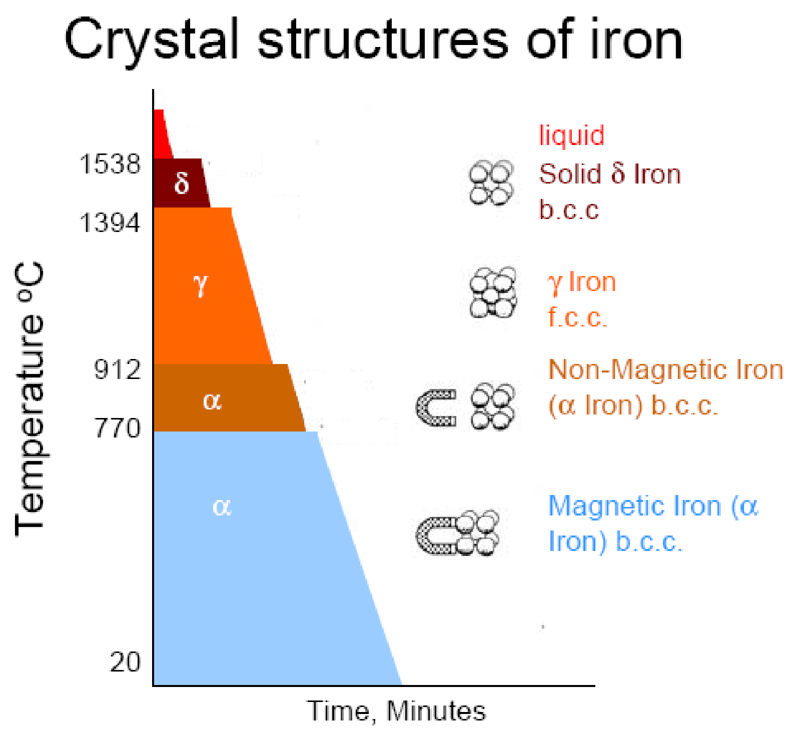
This means that to characterize the alloy within a single phase field, 2 parameters must be given: temperature and composition.

If 2 phases coexist, for example, α+L , β+L, $\alpha+\beta$, then according to GPR, we have 1 degree of freedom: F = 2 + 1 – 2= 1. So, if we have Temp or composition, then we can completely define the system.

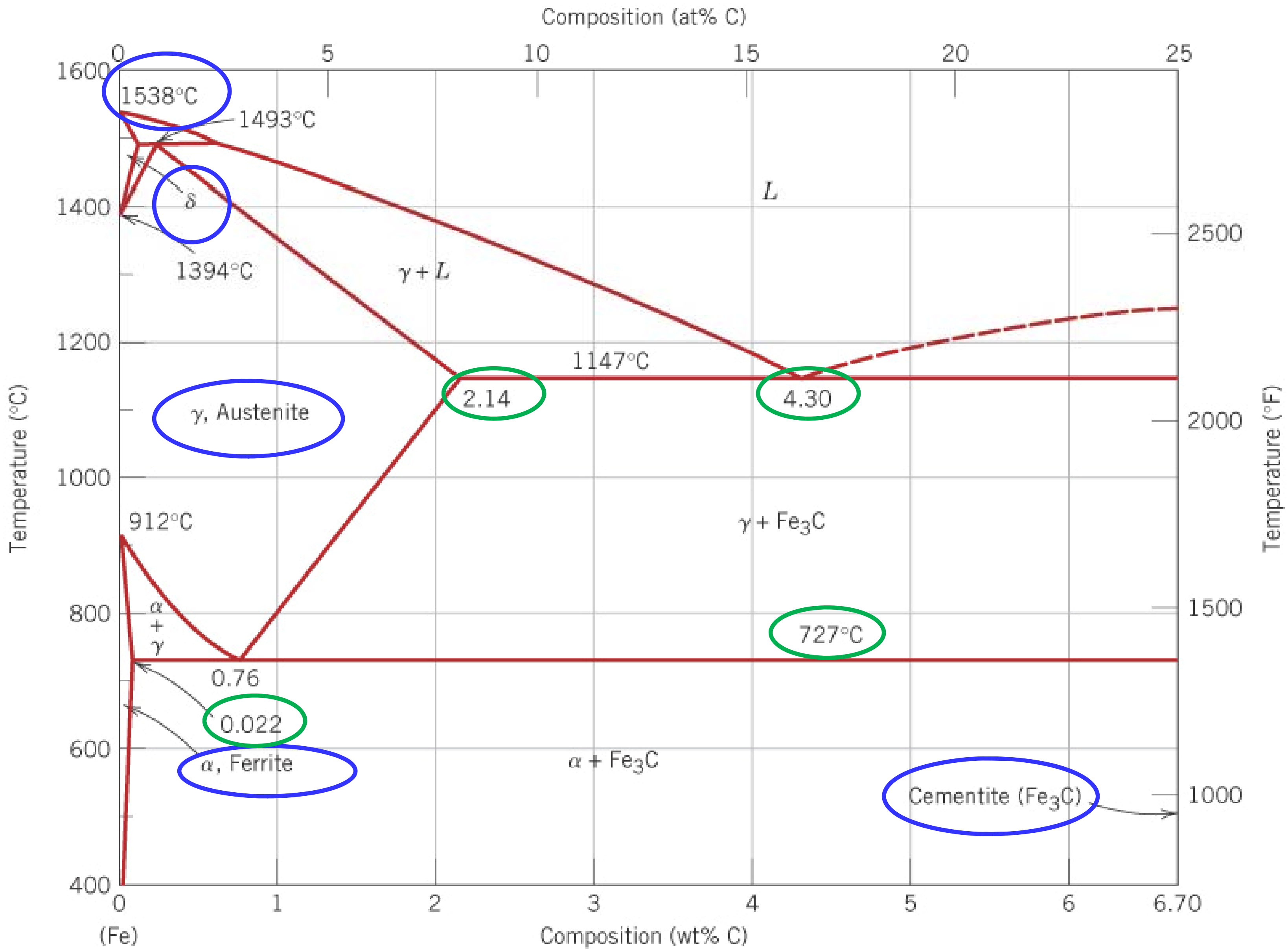
If 3 phases exist (for a binary system), there are 0 degrees of freedom. This means the composition and Temp are fixed. This condition is met for a eutectic system by the eutectic isotherm.

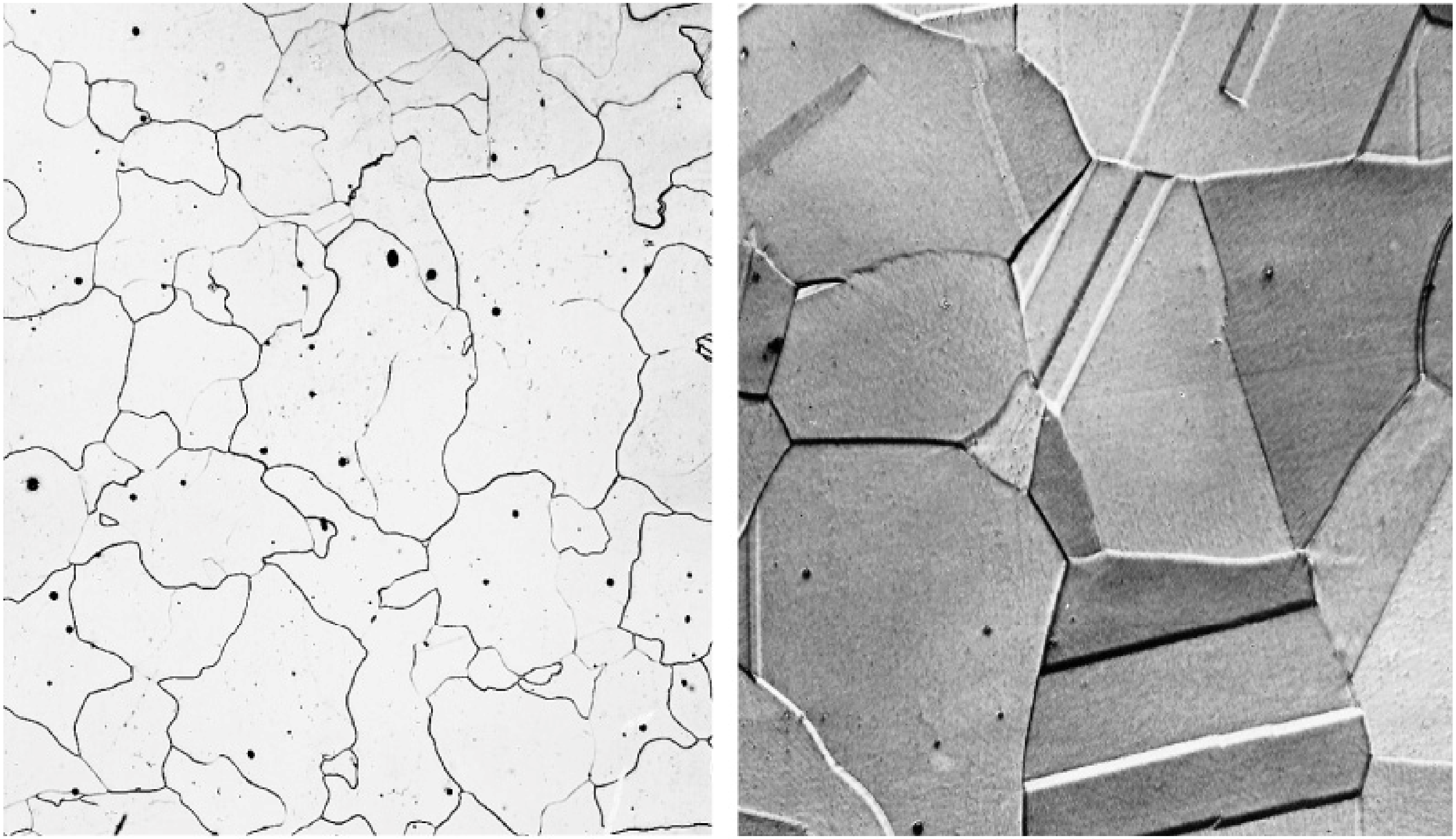
Iron-Carbon System

- Pure iron when heated experiences 2 changes in crystal structure before it melts.
- At room temperature the stable form, ferrite (α iron) has a BCC crystal structure.
- Ferrite experiences a polymorphic transformation to FCC austenite (γ iron) at 912 ˚C (1674 ˚F).
- At 1394˚C (2541˚F) austenite reverts back to BCC phase δ ferrite and melts at 1538 ˚C (2800 ˚F).
- Iron carbide (cementite or Fe_3C) an intermediate compound is formed at 6.7 wt% C.
- Typically, all steels and cast irons have carbon contents less than 6.7 wt% C.
- Carbon is an interstitial impurity in iron and forms a solid solution with the α, γ, δ phases.



Iron-Carbon System





(a) (b)

Though carbon is present in relatively low concentrations, it significantly influences the mechanical properties of ferrite: (a) α ferrite, (b) austenite.

4 Solid Phases

- **α-ferrite**
  - solid solution of carbon in a iron,
  - BCC structure
  - carbon only slightly soluble in the matrix
    - maximum solubility of 0.02%C at 723°C to about 0.008%C at room temperature.
- **Austenite (γ)**
  - solid solution of carbon in γ–iron
  - FCC structure: can accommodate more carbon than ferrite
    - maximum of 2.08%C at 1148°C, decreases to 0.8%C at 723°C
    - difference in C solid solubility between γ and α is the basis for **hardening** of most steels.

δ-ferrite

- solid solution of carbon in δ–iron
- BCC crystal structure
  - maximum solubility of ferrite being 0.09%C at 1495°C

- **Cementite (Fe_3C)**
  - intermetallic Fe-C compound
    - Fe_3C : 6.67%C and 93.3%Fe.
  - orthorhombic crystal structure: hard and brittle

Iron carbide (Cementite or Fe_3C)

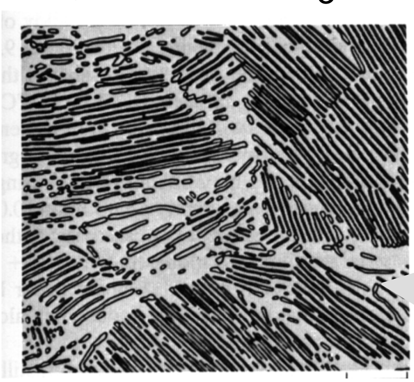
- Forms when the solubility limit of carbon in α ferrite is exceeded at temperatures below 727 ˚C.
- Mechanically, cementite is very hard and brittle.
- For ferrous alloys there are 3 basic types, based on carbon content:
  - Iron (ferrite phase): <0.008 wt% C room temp
  - Steel (α + Fe_3C phase): 0.008 to 2.14 wt% C
  - Cast iron: 2.14 to 6.70 wt% C

Iron-Carbon (Fe-C) Phase Diagram

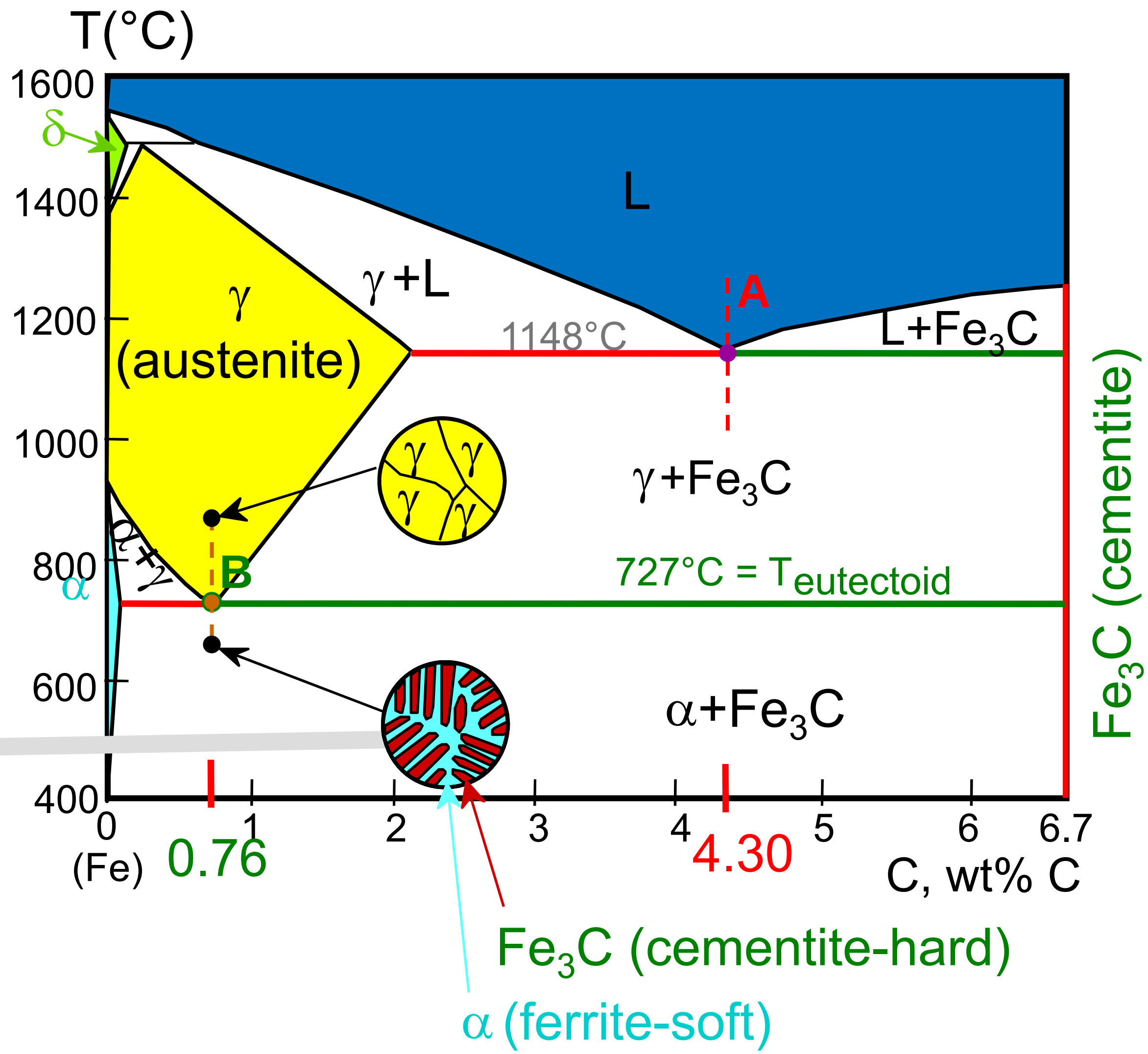
- 2 important points
  - Eutectic (A):

    $L \leftrightarrow \gamma + Fe_3C$
  - Eutectoid (B):

    $\gamma \leftrightarrow \alpha + Fe_3C$



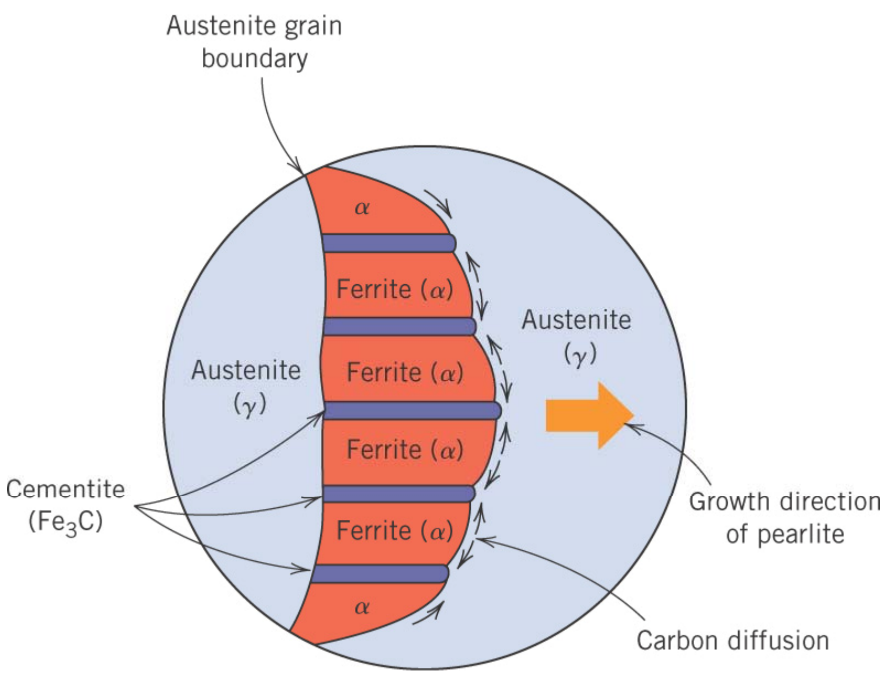
Result: Pearlite = alternating layers of α and Fe_3C phases, not a separate phase.



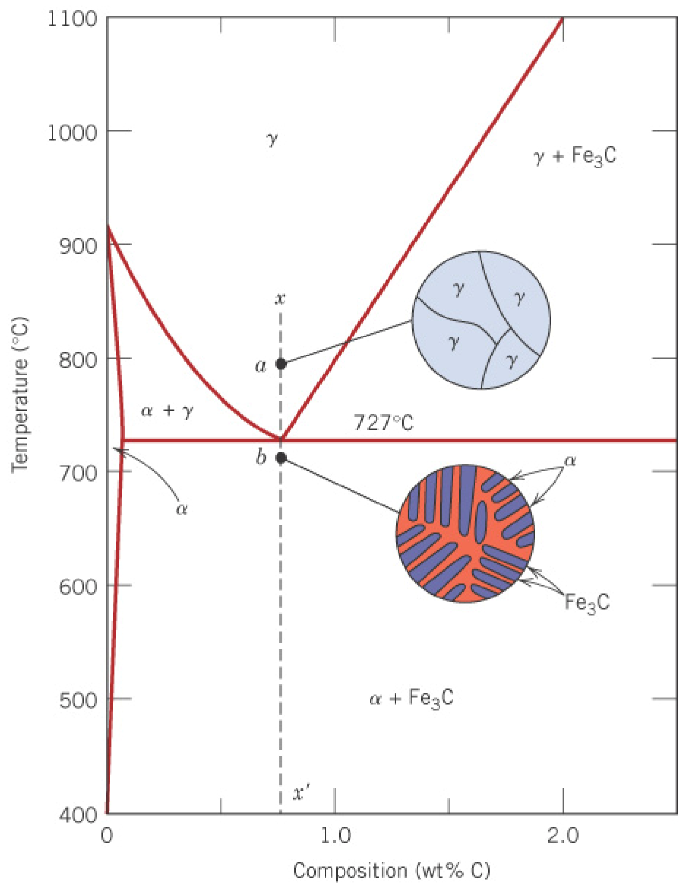
Eutect<u>oid</u> reaction:

$\gamma \leftrightarrow \alpha + Fe_3C$

- formation of the pearlite structure
  - nucleating at γ grain boundaries
  - growth by diffusion of C to achieve the compositions of α and Fe_3C (with structural changes)
  - α lamellae much thicker



Pearlite



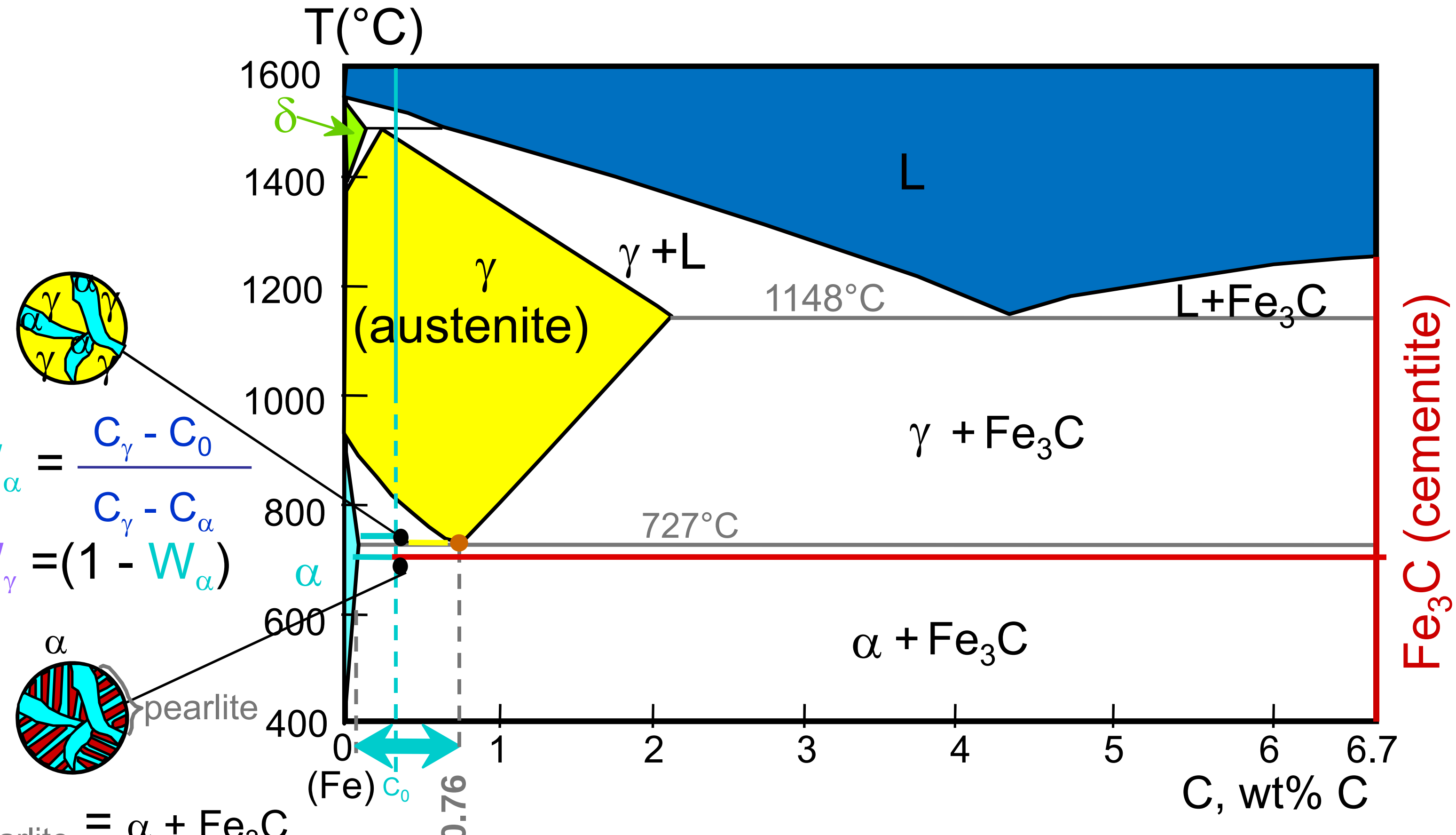
Redistribution of carbon by diffusion

Austenite – 0.76 wt% C

Ferrite - 0.022 wt% C

Cementite - 6.70 wt% C

Hyp**o**eutectoid Steel



$$W_{\alpha} = \frac{C_{\gamma} - C_0}{C_{\gamma} - C_{\alpha}}$$

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

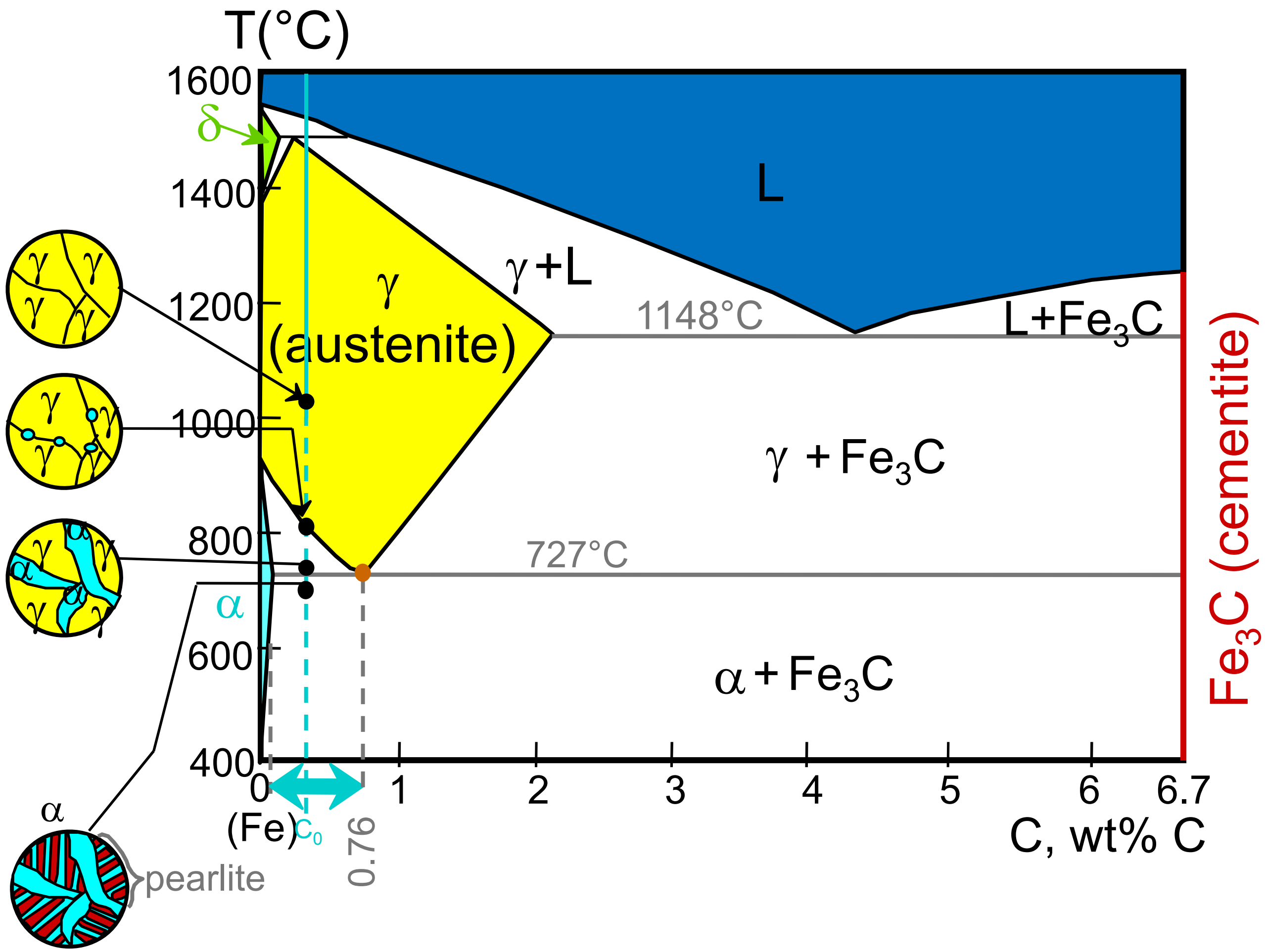
pearlite $= \alpha + Fe_3C$

$$W_{\alpha'} = \frac{C_{Fe3C} - C_0}{C_{Fe3C} - C_{\alpha}}$$

$$W_{pearlite} = (1 - W_{\alpha'})$$

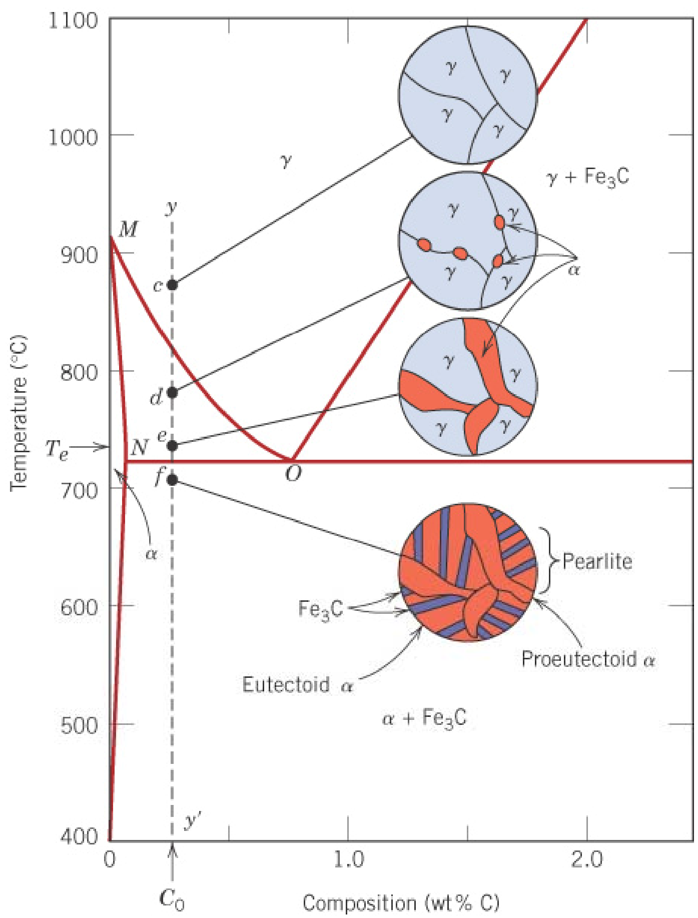
Microstructures for iron-iron carbide alloys that are below the eutectoid with compositions between 0.022 and 0.76 wt% Carbon are hypoeutectoid.

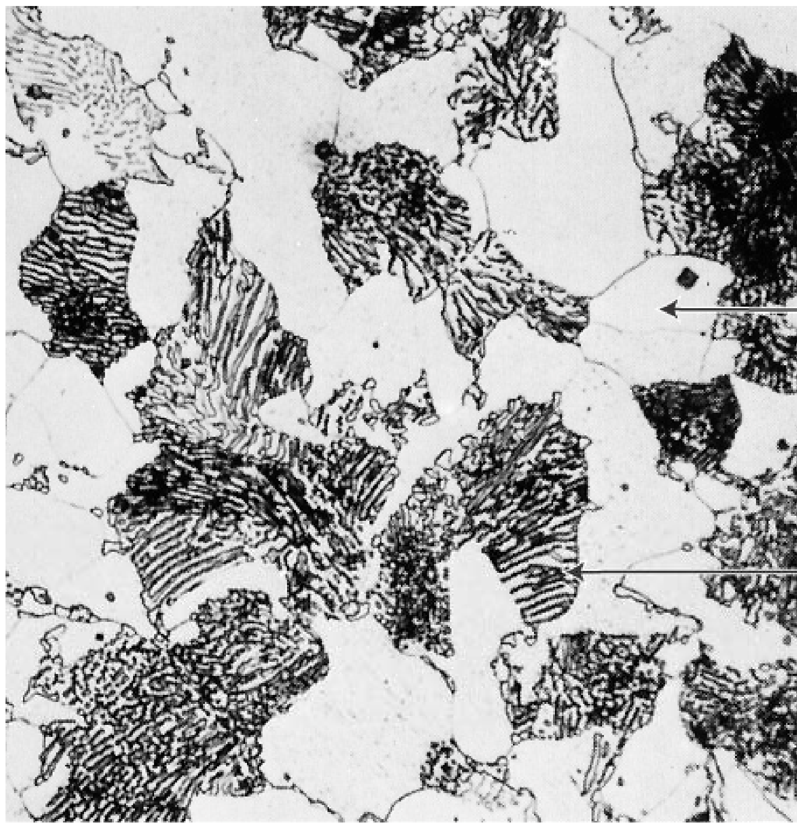
Hypoeutectoid Steel



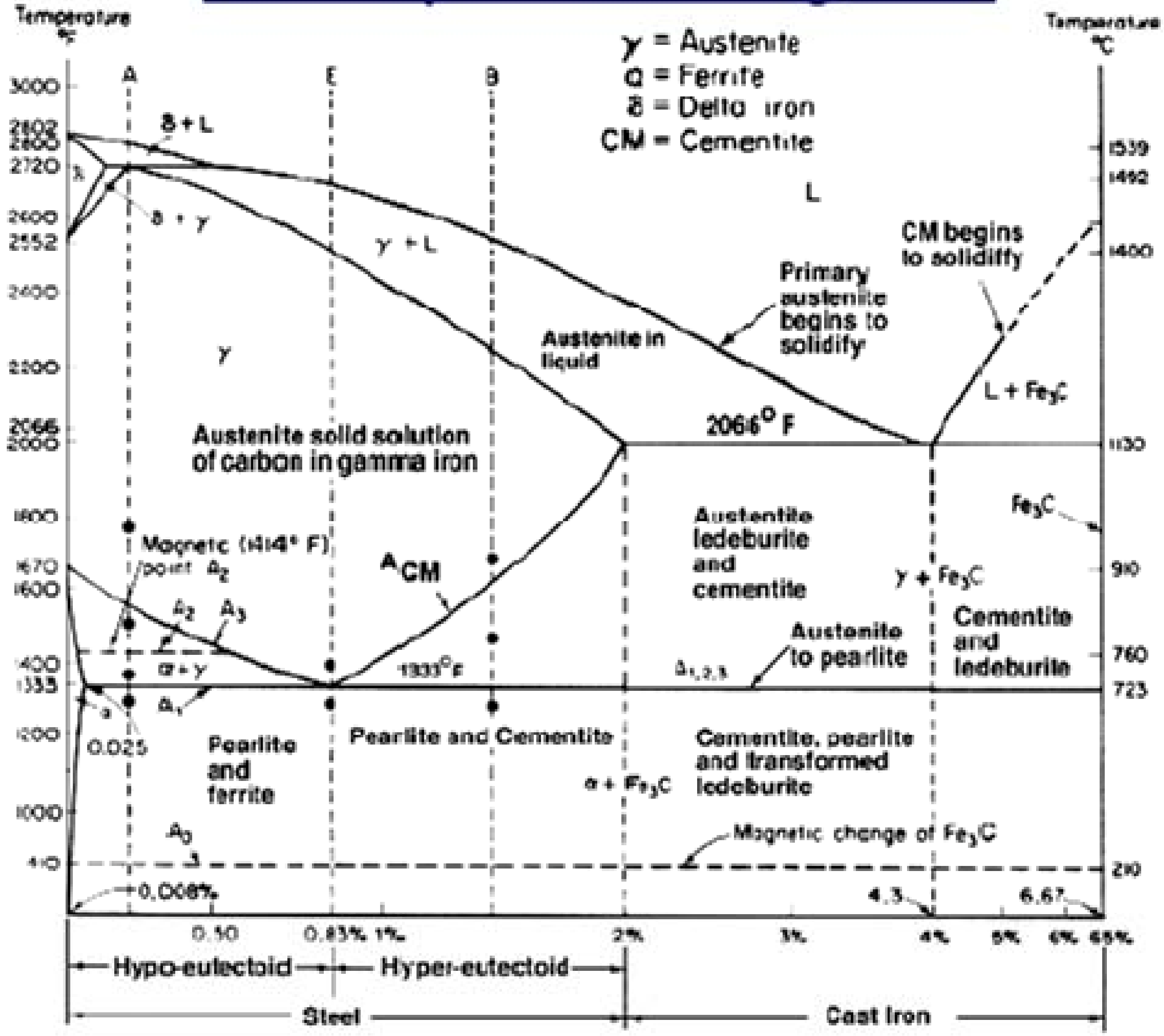
Proeutectoid

- Formed before the eutectoid
- Ferrite that is present in the pearlite is called eutectoid ferrite.
- The ferrite that is formed above the $T_{eutectoid}$ (727°C) is proeutectoid.

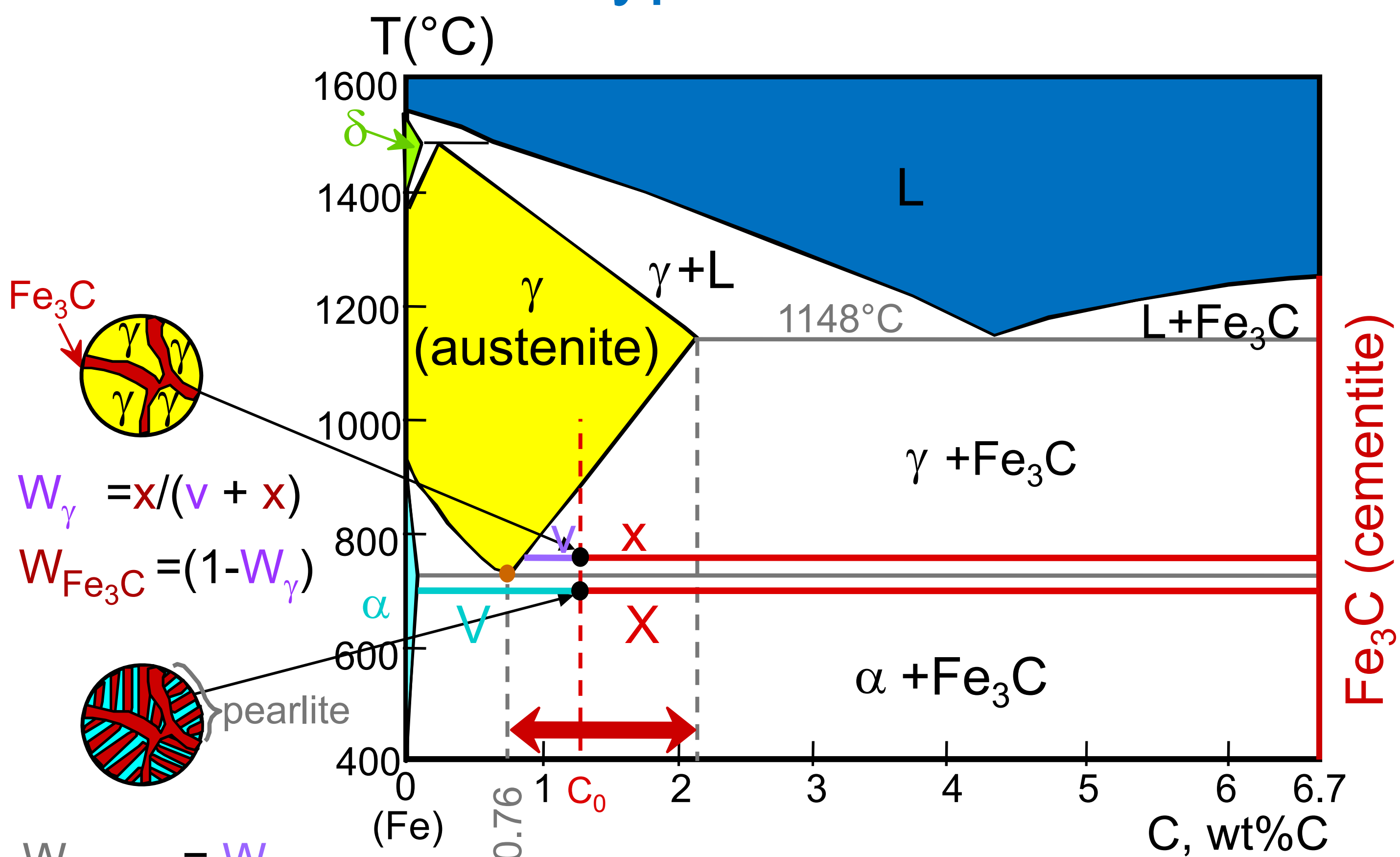




Fe-C phase diagram



Hypereutectoid Steel



$W_\gamma = x/(v + x)$

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

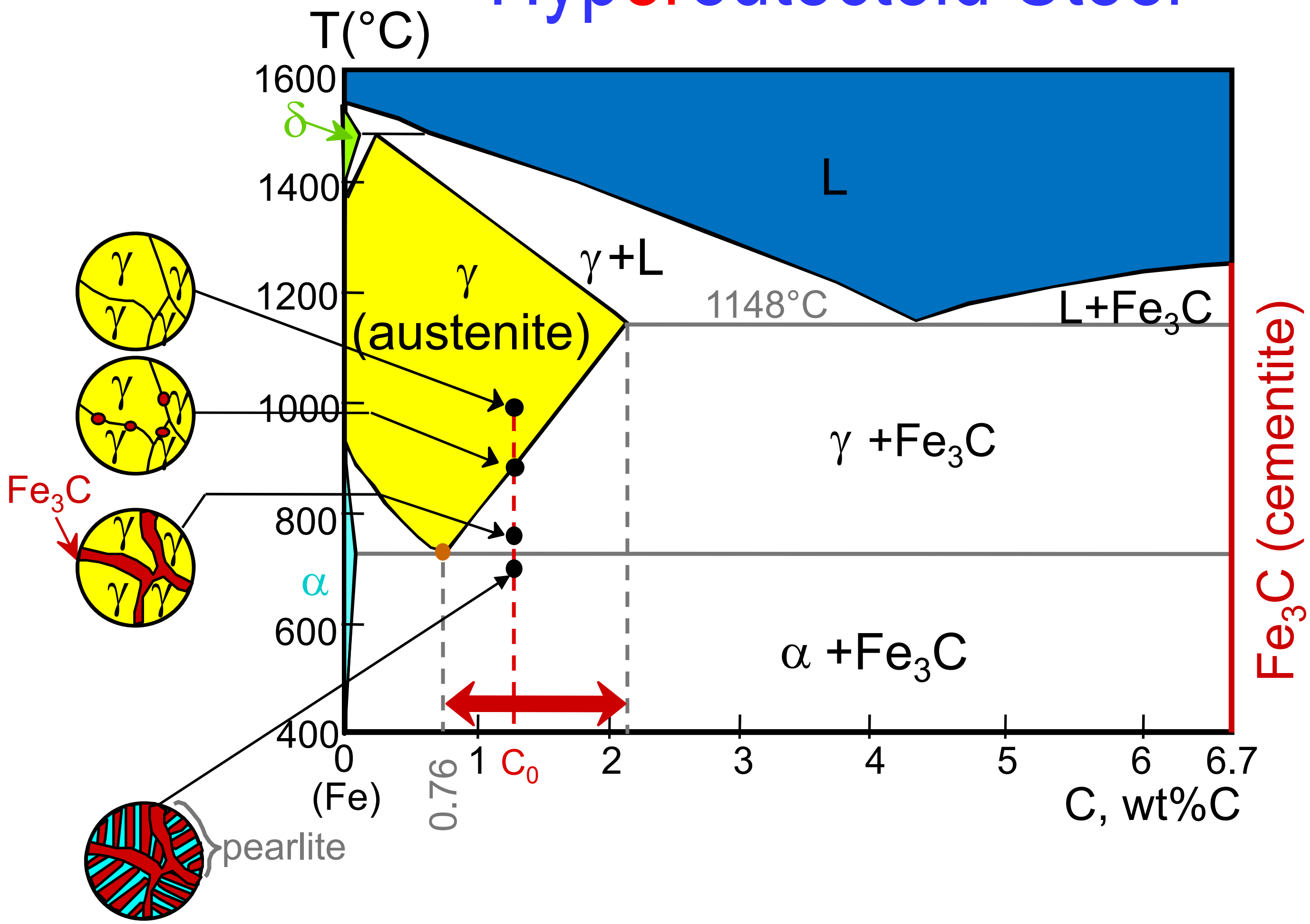
$W_{pearlite} = W_\gamma$

$W_\alpha = X/(V + X)$

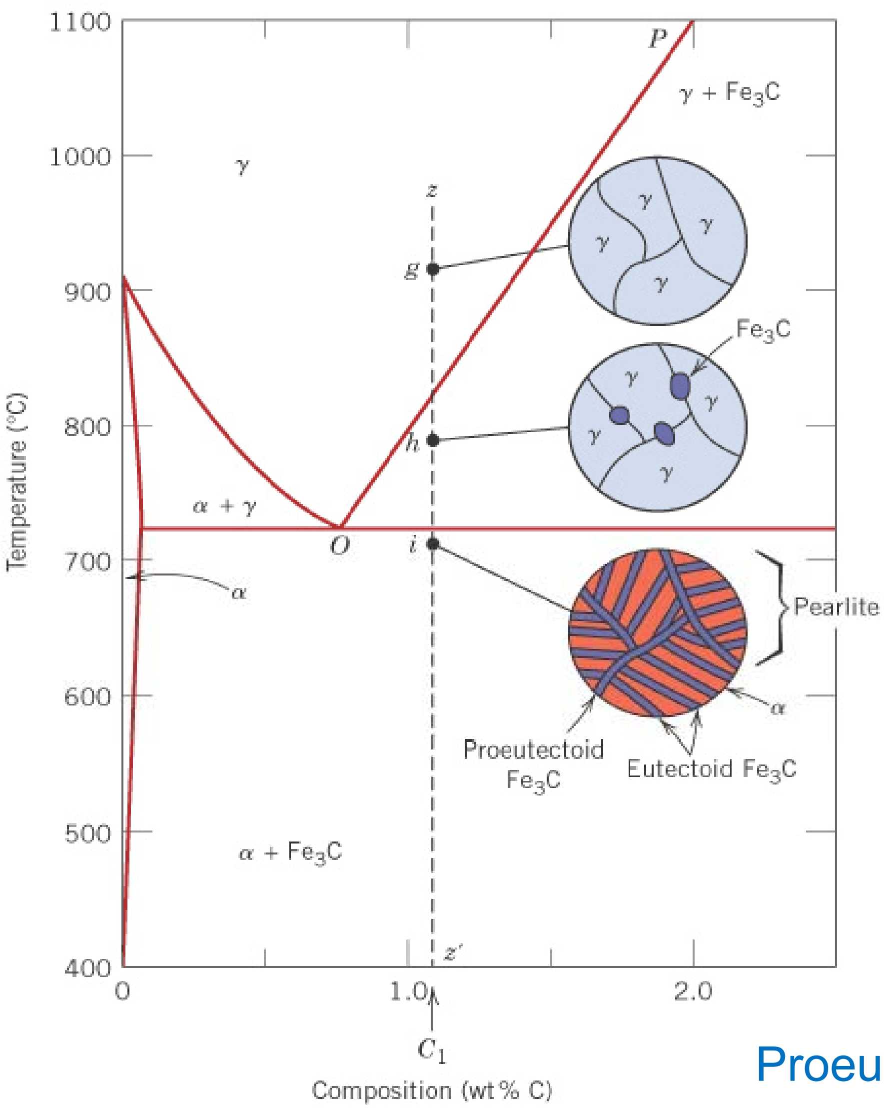
$W_{Fe_3C'} = (1 - W_\alpha)$

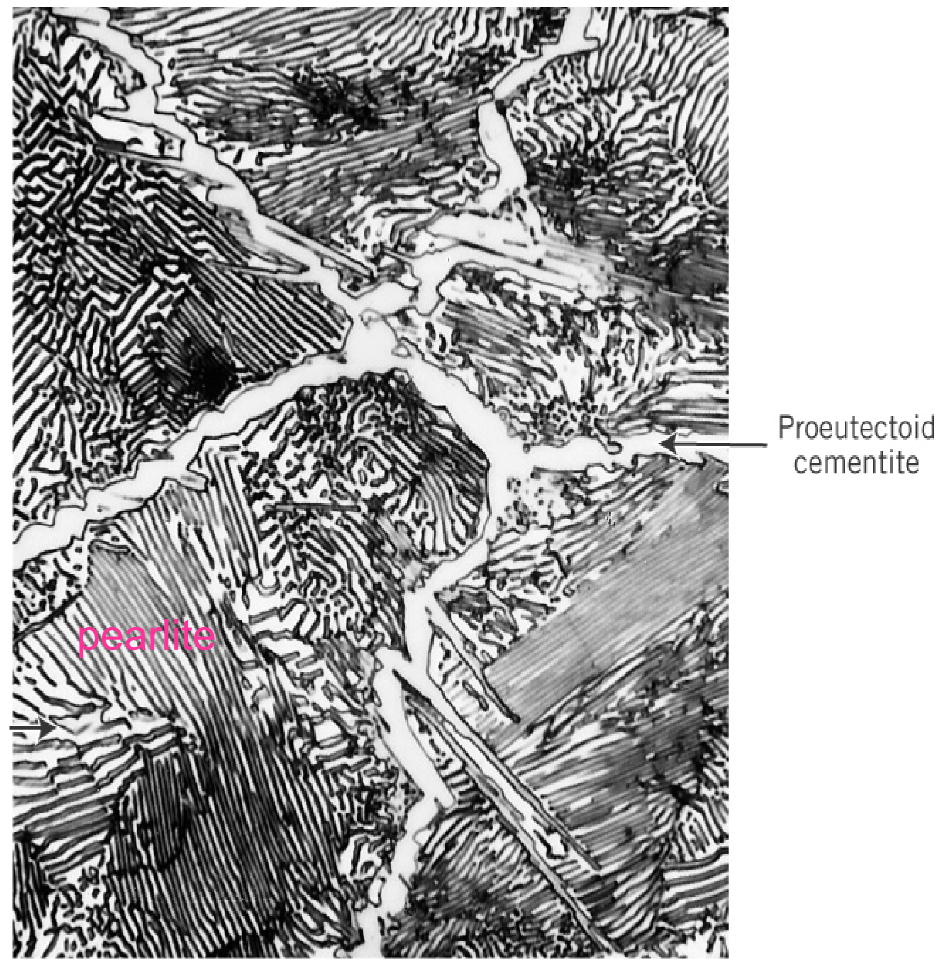
Microstructures for iron-iron carbide alloys that have compositions between 0.76 and 2.14 wt% carbon are hypereutectoid (more than eutectoid).

Hypereutectoid Steel



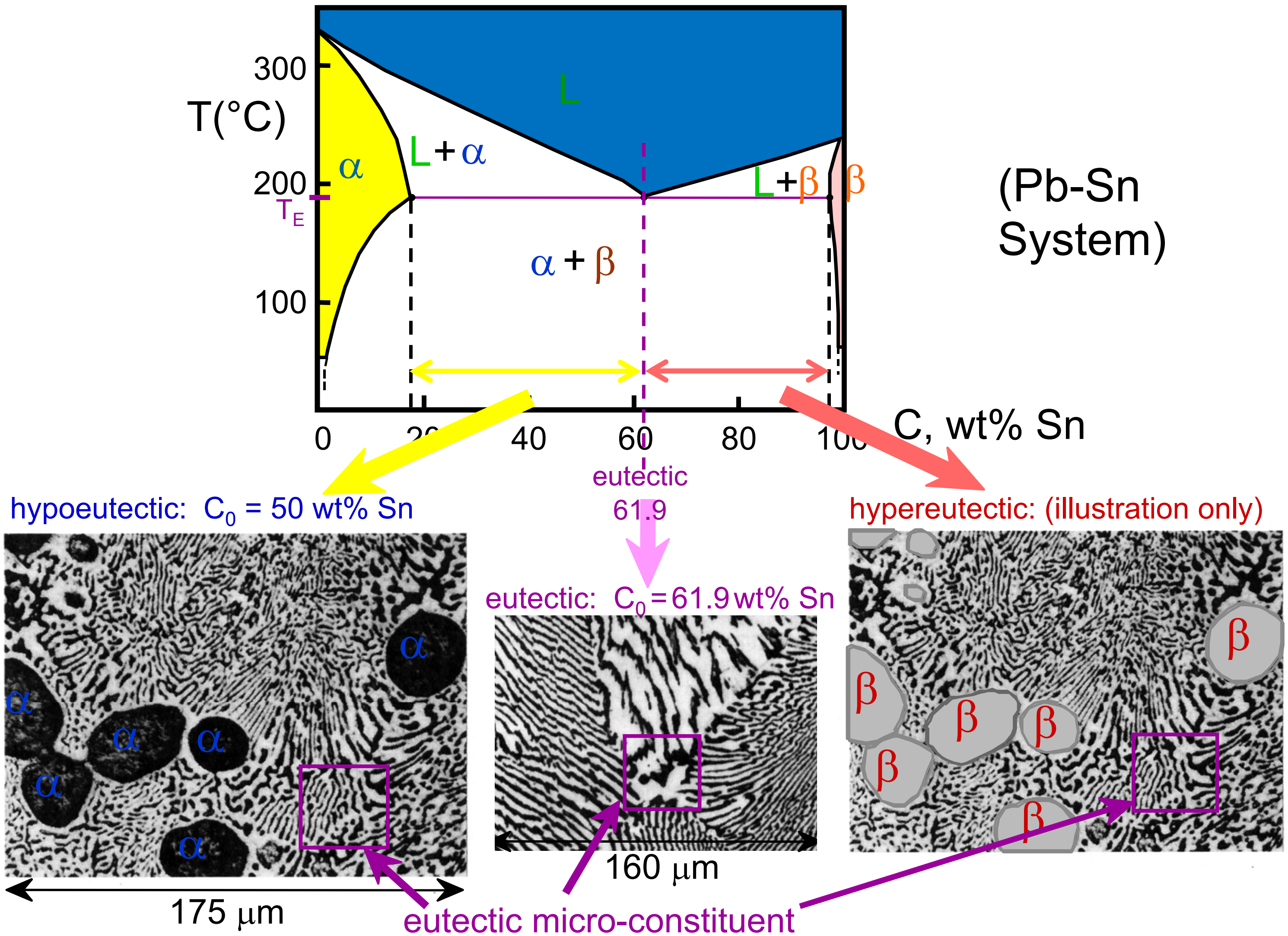
Hypereutectoid Steel (1.2 wt% C)

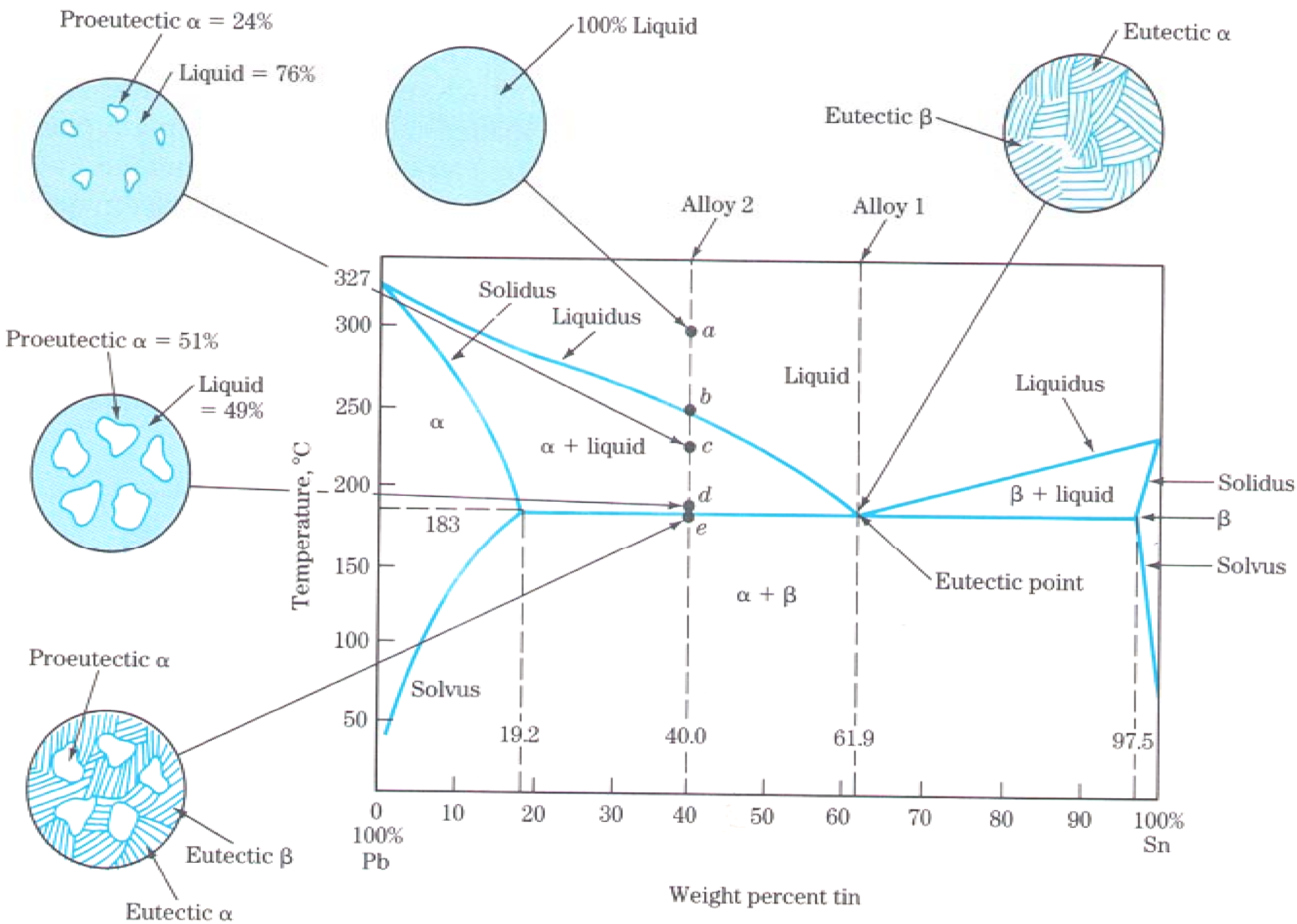




Proeutectoid: formed above the $T_{eutectoid}$ (727°C)

Hypoeutectic & Hypereutectic





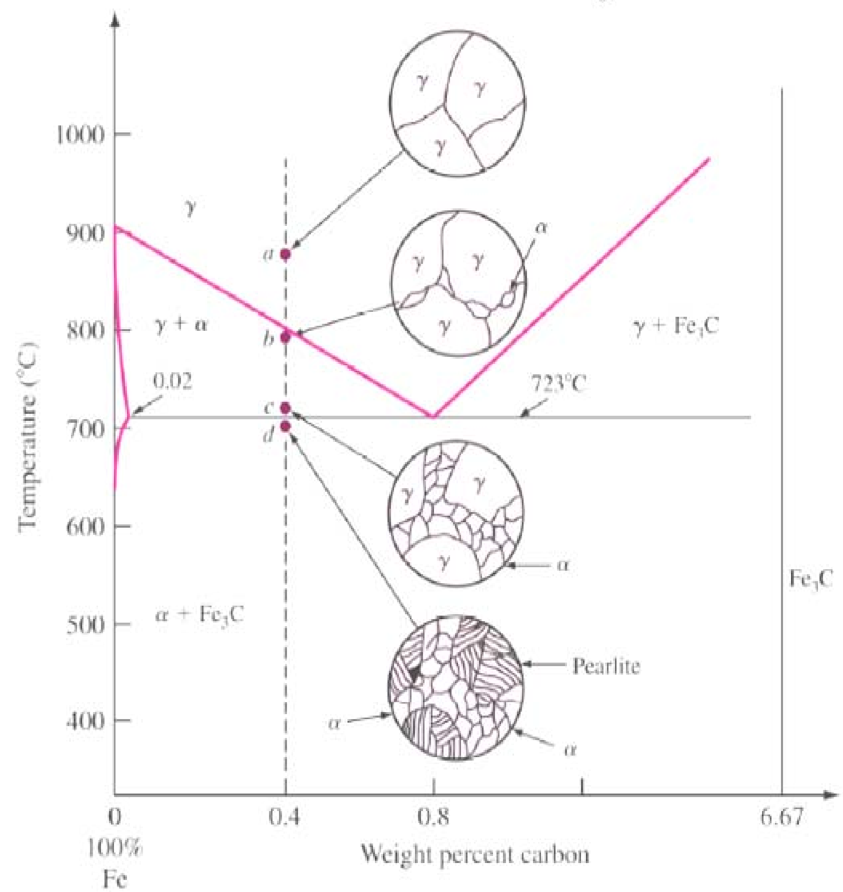
Proeutectic α = 24%
Liquid = 76%
100% Liquid
Eutectic α
Eutectic β
Alloy 2
Alloy 1
327
300
250
200
150
100
50
Solidus
Liquidus
a
b
c
d
e
Liquid
Liquidus
Proeutectic α = 51%
Liquid = 49%
α
α + liquid
183
β + liquid
Solidus
β
Solvus
Eutectic point
α + β
Temperature, °C
Proeutectic α
Solvus
19.2
40.0
61.9
97.5
Eutectic β
Eutectic α
0
100% Pb
10
20
30
40
50
60
70
80
90
100% Sn
Weight percent tin

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.



Solution to Example Problem

a) Using the RS tie line just below the eutectoid

C_α = 0.022 wt% C
C_{Fe_3C} = 6.70 wt% C

b) Using the lever rule with the tie line shown

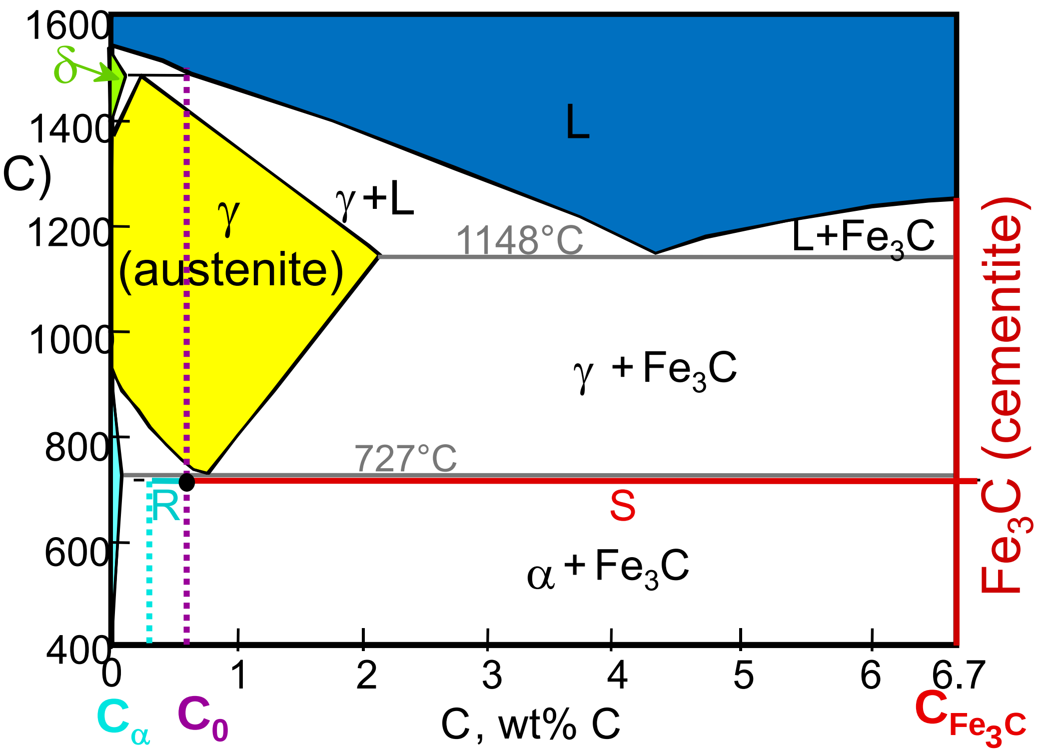
$$W_{Fe_3C} = \frac{R}{R+S} = \frac{C_0 - C_\alpha}{C_{Fe_3C} - C_\alpha}$$

$$= \frac{0.40 - 0.022}{6.70 - 0.022} = 0.057$$

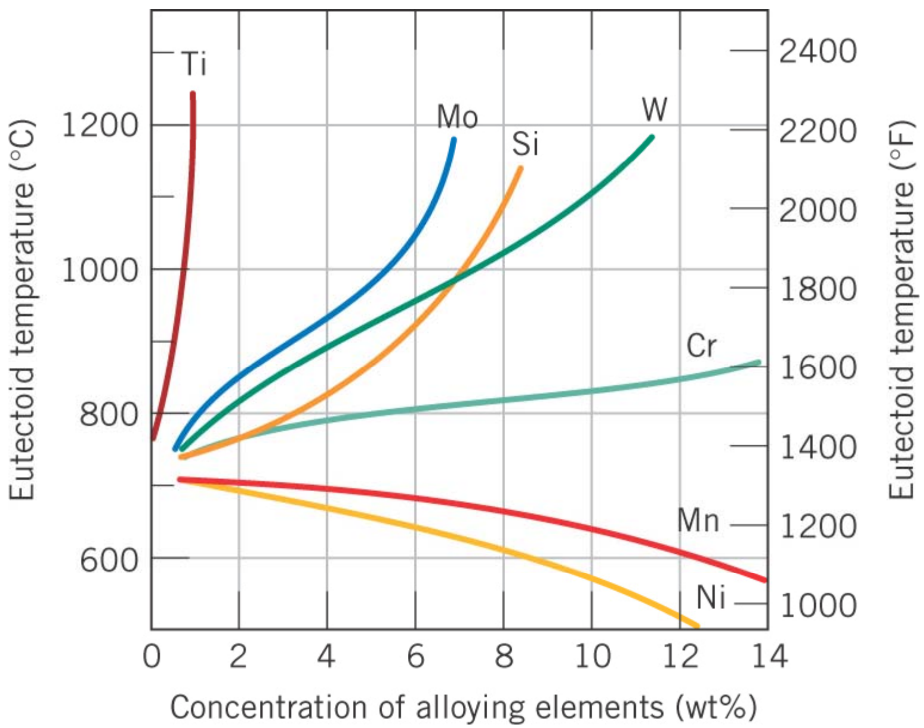
Amount of Fe_3C in 100 g

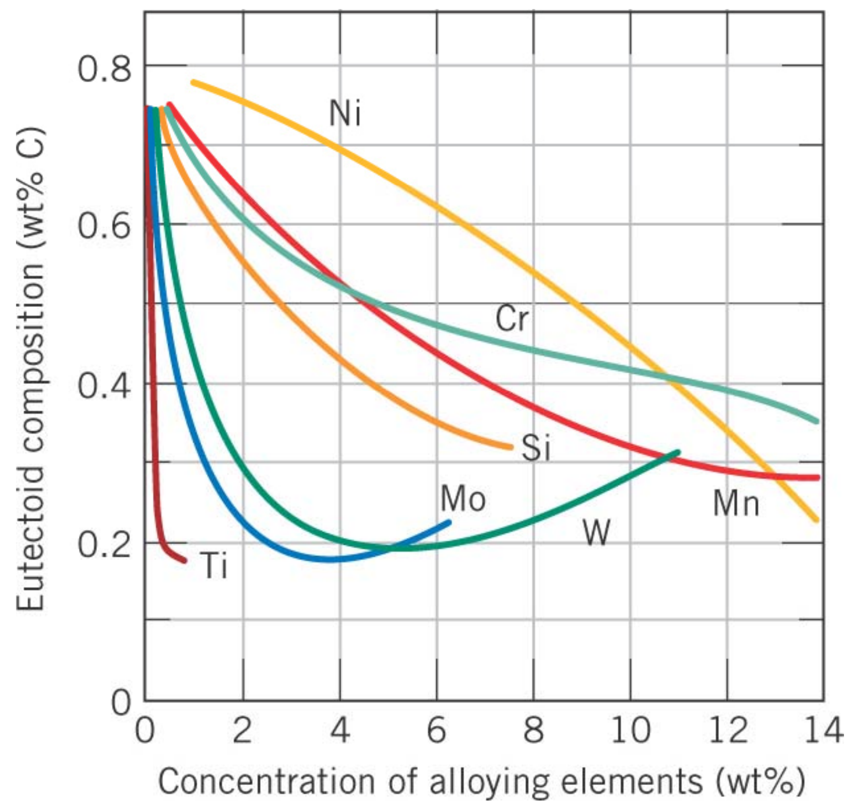
= (100 g)W_{Fe_3C}

= (100 g)(0.057) = 5.7 g



Alloying steel with other elements changes the Eutectoid Temperature, Position of phase boundaries and relative Amounts of each phase





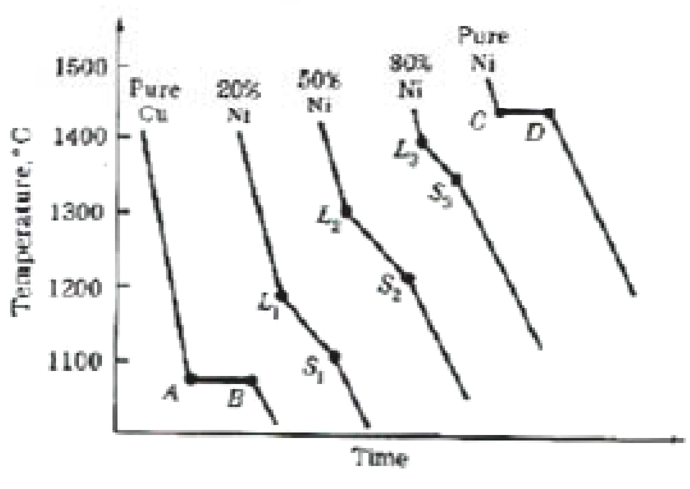
Working with Phase Diagrams

- Overall Composition
- Solidus
- Liquidus
- Limits of Solid Solubility
- Chemical Composition of Phases at any temperature
- Amount of Phases at any temperature
- Invariant Reactions
- Development of Microstructure
- Chemical Activity

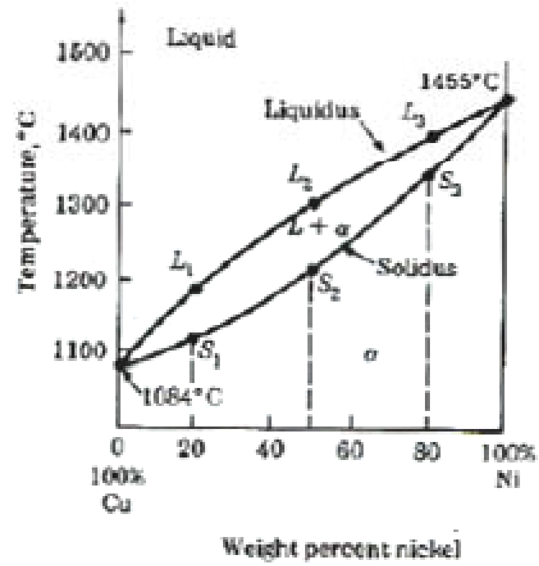
Determination of Phase Diagrams

- Cooling Curves
- Differential Scanning Calorimetry
- Thermomechanical Analysis
- Differential Thermal Analysis
- Metallography/Petrography
- Energy Dispersive X-ray Spectroscopy
- Electron Microprobe Analyzer
- X-ray Diffraction
- Transmission Electron Microscopy

Cooling Curves



(a)



(b)

Using Phase Diagrams to determine Heat Treatability

- Heat Treatment is based on "controlling" the solid state transformation rate
  - Heat treatment of steels: control of the eutectoid reaction
  - Age hardening (precipitation strengthening) of aluminum alloys: control of precipitation reaction

Heat Treatment of Steels

- The eutectoid reaction
- Martensite
- Austenite
- Pearlite
- TTT diagrams

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

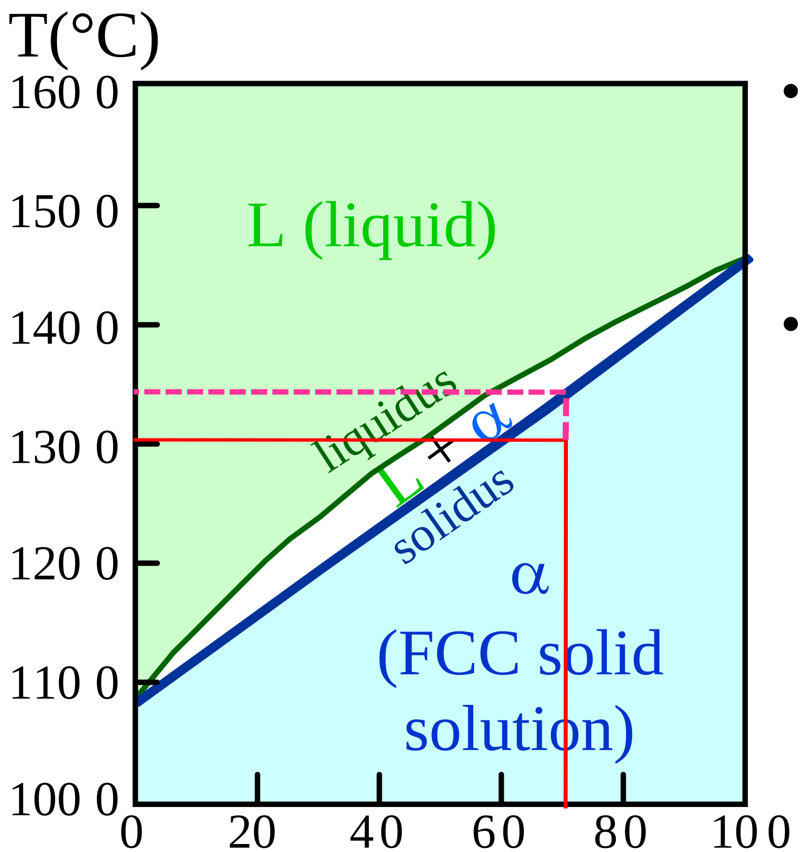
  For a given temperature and composition of the system.

- The microstructure of an alloy depends on

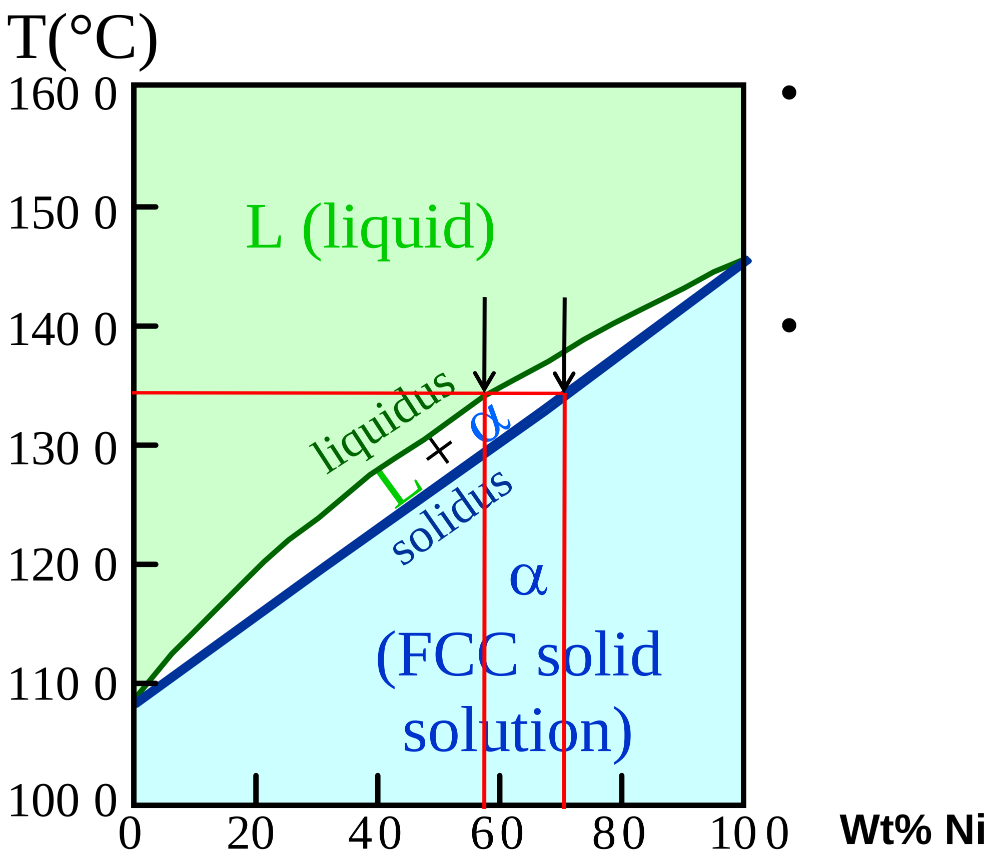
  -- its composition, and
  -- rate of cooling equilibrium

Review

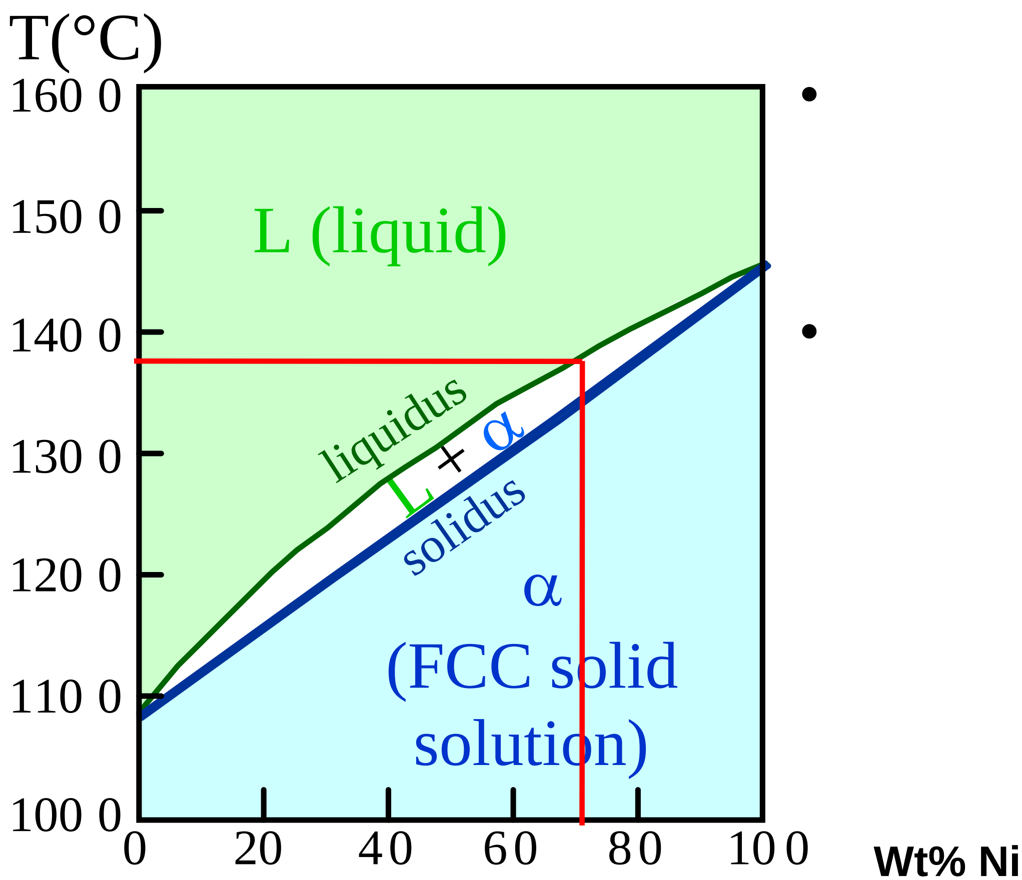
- Heating a copper-nickel alloy of composition 70 wt% Ni-30 wt% Cu from 1300°C. At what temperature does the first liquid phase form?
- Solidus - Temperature where alloy is completely solid. Above this line, liquefaction begins.
- Answer: The first liquid forms at the temperature where a vertical line at this composition intersects the α-(α + *L*) phase boundary--i.e., about 1350°C;



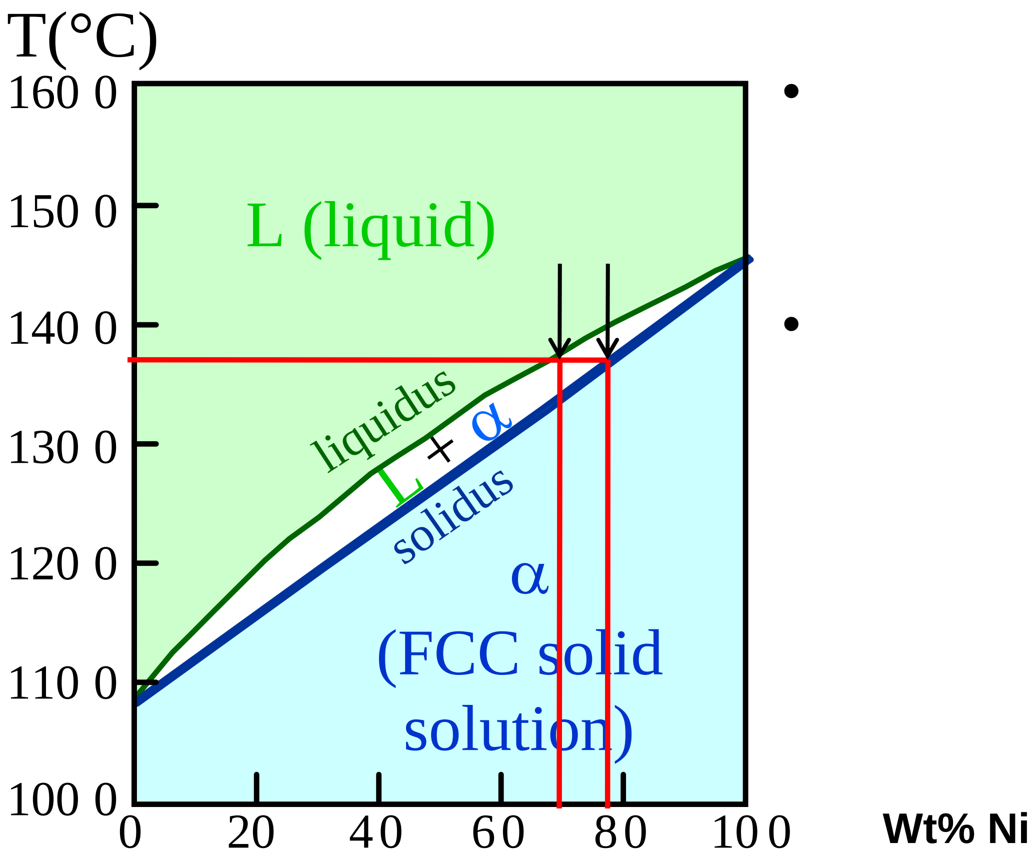
- (b) What is the composition of this liquid phase?
- Answer: The composition of this liquid phase corresponds to the intersection with the (α + *L*)-*L* phase boundary, of a tie line constructed across the α + *L* phase region at 1350°C, 59 wt% Ni;



- (c) At what temperature does complete melting of the alloy occur?
- Liquidus - Temperature where alloy is completely liquid. Below this line, solidification begins.
- Answer: Complete melting of the alloy occurs at the intersection of this same vertical line at 70 wt% Ni with the (α + *L*)-*L* phase boundary--i.e., about 1380°C;



- (d) What is the composition of the last solid remaining prior to complete melting?
- Answer: The composition of the last solid remaining prior to complete melting corresponds to the intersection with α-(α + *L*) phase boundary, of the tie line constructed across the α + *L* phase region at 1380°C--i.e., about 78 wt% Ni.



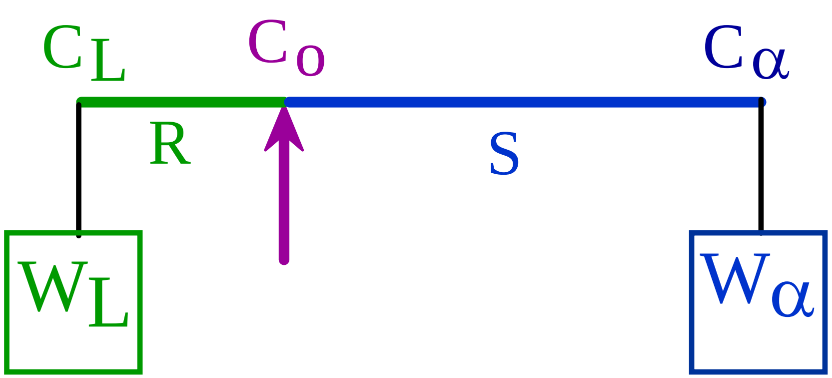
THE LEVER RULE: A PROOF

- Sum of weight fractions: $W_L + W_\alpha = 1$
- Conservation of mass (Ni): $C_o = W_L C_L + W_\alpha C_\alpha$
- Combine above equations:

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

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

- A geometric interpretation:



moment equilibrium:

$$W_L R = W_\alpha S$$

W_L ← $1 - W_\alpha$

solving gives Lever Rule