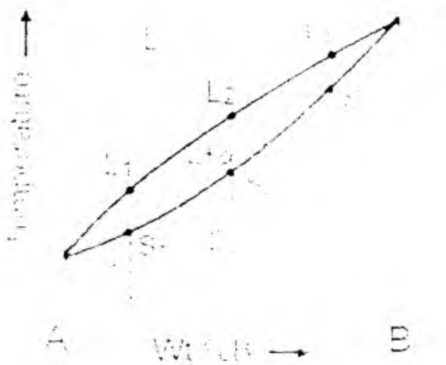
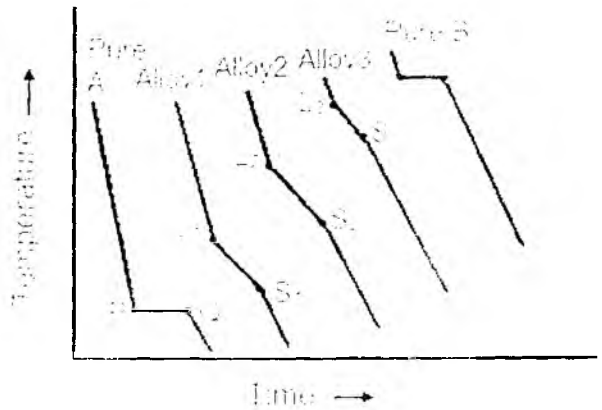
Cooling curves

➢Upon cooling from liquid state, the temperature of the pure metal (A or B) drops continuously till melting point at which solidification starts. Solidification happens at a constant temperature (line PQ) as F =0 (F = 1 – 2 +1 = 0). The temperature drops again on completion of solidification.

➢For any alloy (1, 2, 3 etc.) temp. drops till the liquidus (L_1, L_2, L_3). However, in this case, solidification proceeds over a range of temperature as F = 1 (2 – 2 + 1 = 1). Once solidification completes at the solidus (S_1, S_2, S_3) the temp. drops again.





Phase Equilibria

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

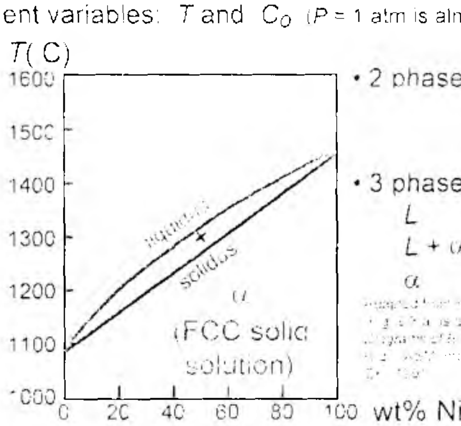
	Crystal Structure		
Ni	FCC	1.9	0.1246
Cu	FCC	1.8	0.1278

- 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.

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).

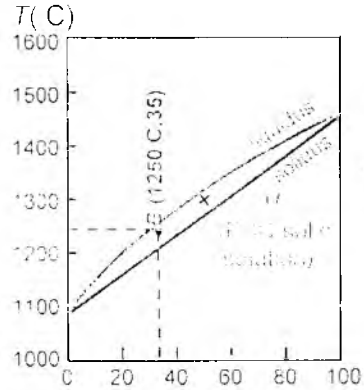
for Cu-Ni system



- 2 phases:
- 3 phase fields:
  - L
  - $L + \alpha$
  - α

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:



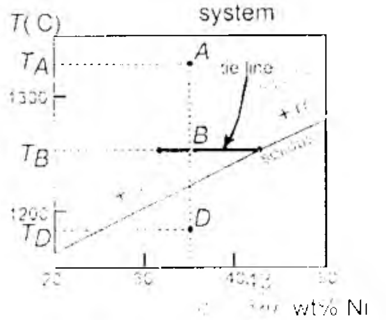
Cu-Ni phase diagram

Phase Diagrams:
composition of phases

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

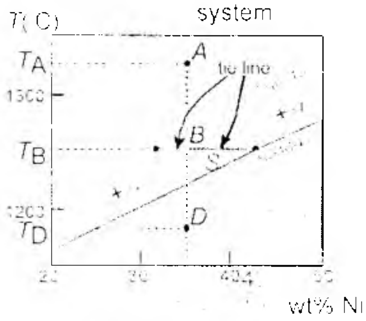
At T_A = 1320 C:
  Only Liquid (L)
  $C_L = C_o$
At T_D = 1190 C:
  Only Solid (α)
  $C_\alpha = C_o$
At T_B = 1250 C:
  Both α and L
  $C_L = C_{liquidus}$
  $C_\alpha = C_{solidus}$ (= 43 wt% Ni here)

Cu-Ni system



Phase Diagrams:
weight fractions of phases

- Rule 3. If we know T and C_0, then we know:
  --the amount of each phase (given in wt%)
- Examples:



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%

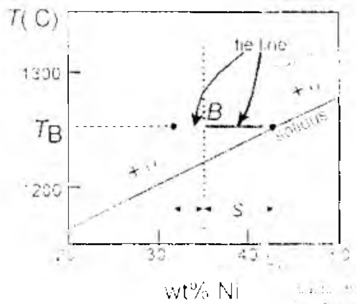
At T_B: Both α and L

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

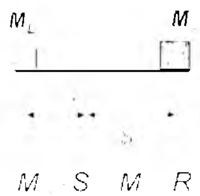
$$W_\alpha = \frac{R}{R+S} = 27\ wt\%$$

The Lever Rule

- Tie line – connects the phases in equilibrium with each other - essentially an isotherm



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

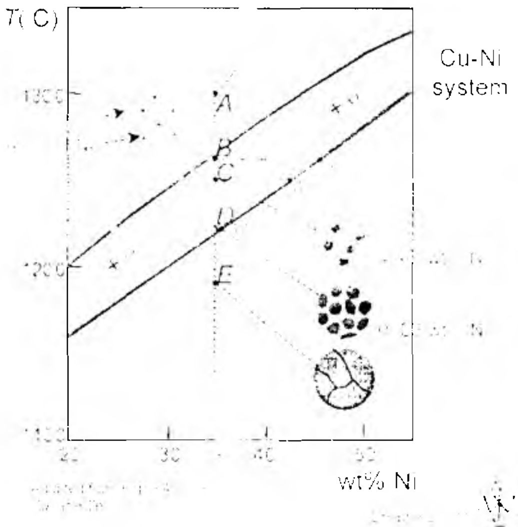


$$W_L = \frac{M_\alpha}{M_L + M_\alpha} = \frac{S}{R+S} = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

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

Ex: Cooling in a Cu-Ni Binary

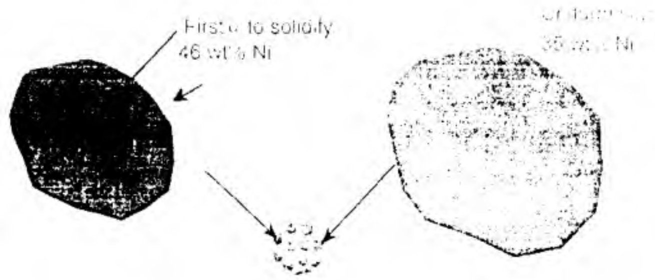
- Phase diagram: Cu-Ni system.
- System is:
  - --
    i.e., 2 components: Cu and Ni.
  - --
    i.e., complete solubility of one component in another; α phase field extends from 0 to 100 wt% Ni.
- Consider



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.

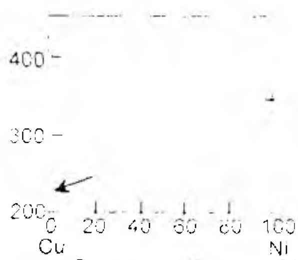
- Fast rate of cooling: Cored structure
- Slow rate of cooling: Equilibrium structure



Mechanical Properties: Cu-Ni System

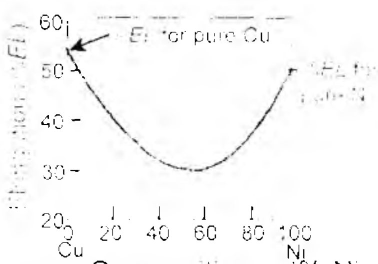
- Effect of solid solution strengthening on:

--Tensile strength (*TS*)



--Peak as a function of C_o

--Ductility (%*EL*,%*AR*)



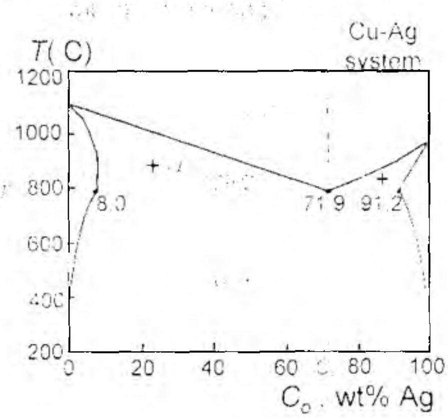
--Min. as a function of C_o

Binary-Eutectic Systems

Ex.: Cu-Ag system

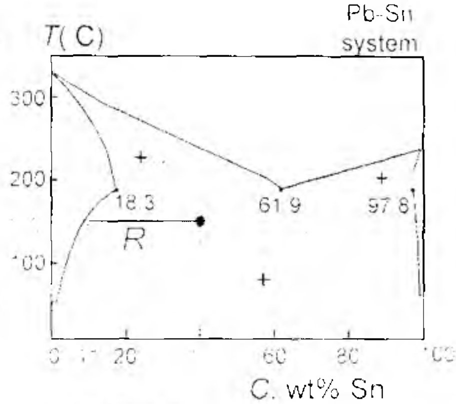
- 3 single phase regions (L, α, β)
- Limited solubility:
  - α: mostly Cu
  - β: mostly Ag
- T_E: No liquid below T_E
- C_E: Min. melting T_E composition
- **Eutectic transition**

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



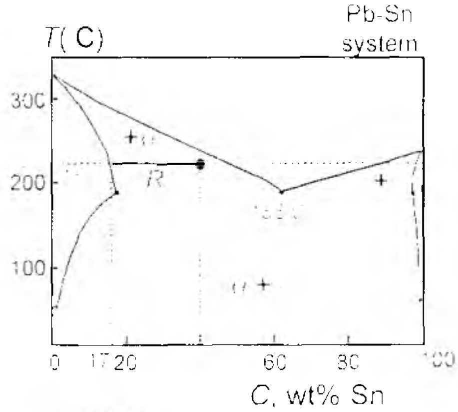
EX: Pb-Sn Eutectic System (1)

- For a 40 wt% Sn-60 wt% Pb alloy at 150 C, find...
  - --the phases present: α +
  - --compositions of phases:
  - --the relative amount of each phase:



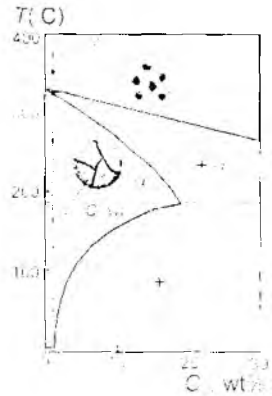
EX: Pb-Sn Eutectic System (2)

- For a 40 wt% Sn-60 wt% Pb alloy at 200 C, find...
  - --the phases present: α +
  - --compositions of phases:
  - --the relative amount of each phase:



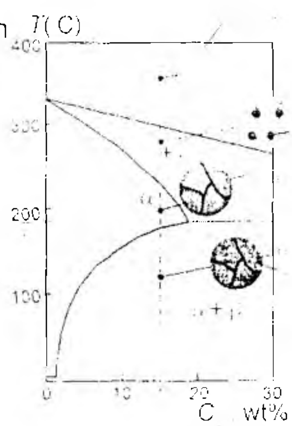
Microstructures in Eutectic Systems: I

- $C_0 < 2$ wt% Sn
- Result:
  - --at extreme ends
  - --polycrystal of α grains
    - i.e., only one solid phase



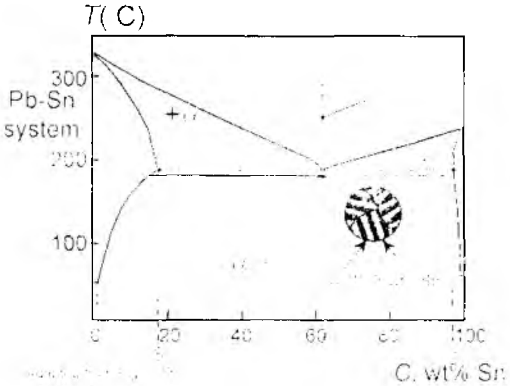
Microstructures in Eutectic Systems: II

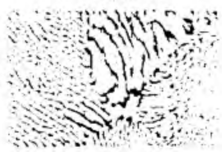
- 2 wt% Sn < C_0 < 18.3 wt% Sn
- Result:
  - Initially liquid + α
  - then α alone
  - finally two phases
    - α polycrystal
    - fine β-phase inclusions



Microstructures in Eutectic Systems: III

- $C_0 = C_E$
- Result: Eutectic microstructure (lamellar structure) --alternating layers (lamellae) of α and β crystals

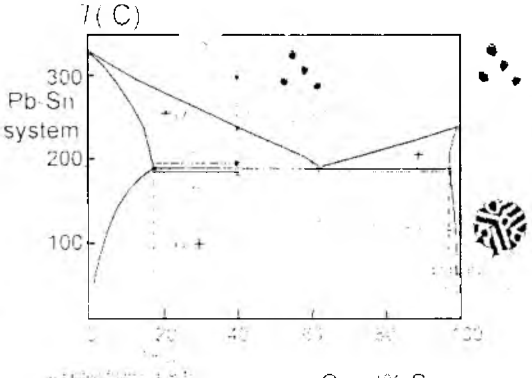




Lamellar Eutectic Structure

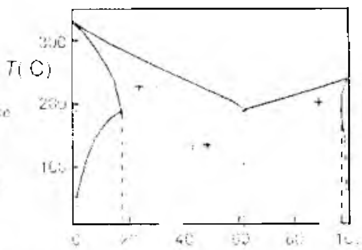
Microstructures in Eutectic Systems: IV

- 18.3 wt% Sn < C_0 < 61.9 wt% Sn
- Result: α crystals and a eutectic microstructure



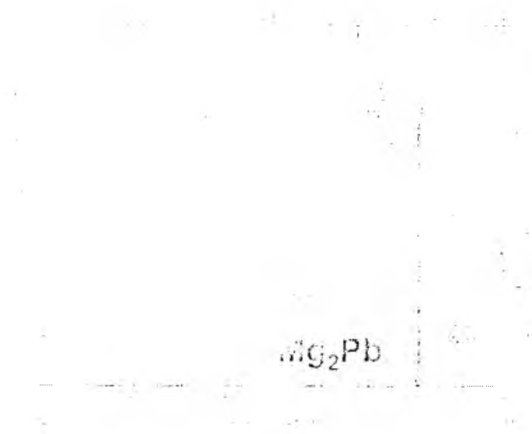
- Just above T_E:
  - C_α = 18.3 wt% Sn
  - = 61.9 wt% Sn
  - $W_\alpha = \frac{}{R+}$ = 50 wt%
  - = $(1 - W_\alpha)$ = 50 wt%
- Just below T_E:
  - C_α = 18.3 wt% Sn
  - = 97.8 wt% Sn
  - $W_\alpha = \frac{}{R+}$ = 73 wt%
  - W = 27 wt%

Hypoeutectic & Hypereutectic



(Pb-Sn System)

Intermetallic Compounds



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

Eutectoid & Peritectic

- liquid in equilibrium with two solids

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

- solid phase in equation with two solid phases

$$S_2 \rightleftarrows S_1 + S_3$$

intermetallic compound - cementite

$$\gamma \underset{heat}{\overset{cool}{\rightleftarrows}} \alpha + Fe_3C \qquad (727°C)$$

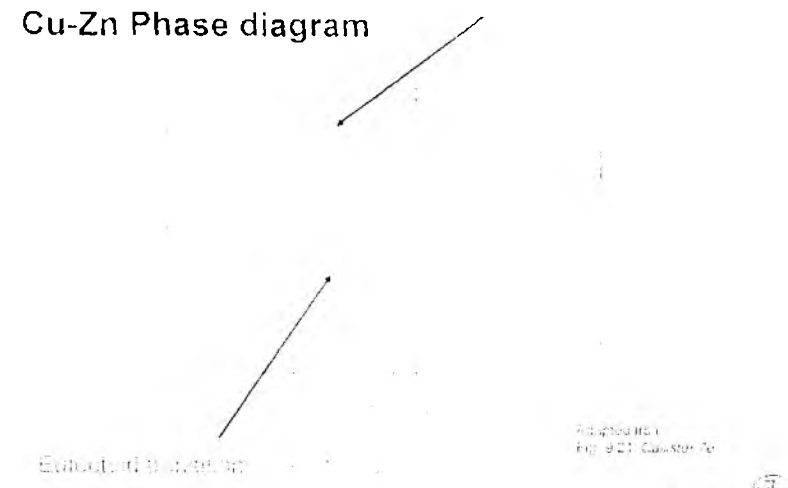
- liquid + solid 1 → solid 2 (Fig 9.21)

$$S_1 + L \rightleftarrows S_2$$

$$\delta + L \underset{heat}{\overset{cool}{\rightleftarrows}} \gamma \qquad (1493°C)$$

Eutectoid & Peritectic

Cu-Zn Phase diagram

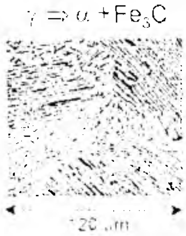


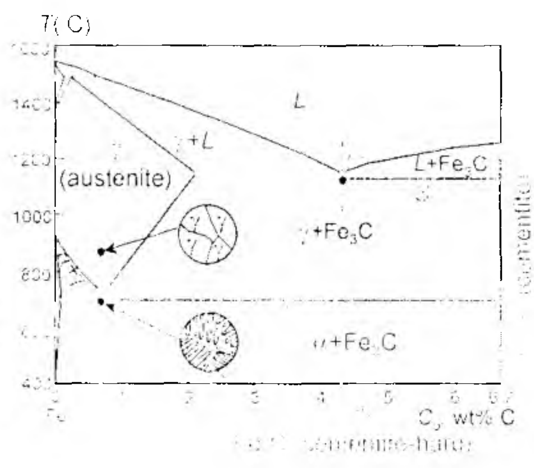
Iron-Carbon (Fe-C) Phase Diagram

- 2 important points

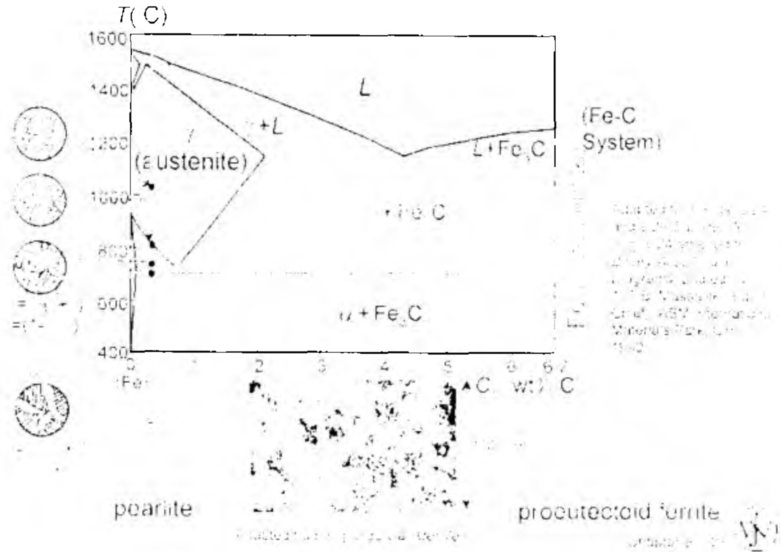
$L \Rightarrow \gamma + Fe_3C$

$\gamma \Rightarrow \alpha + Fe_3C$

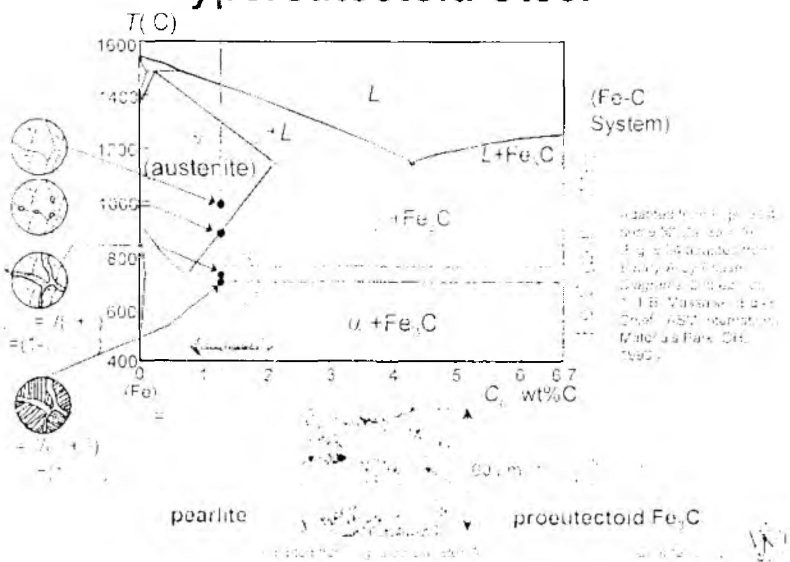




eutectoid Steel



Hypereutectoid Steel



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)

Chapter 9 – Phase Equilibria

Solution: a) composition of Fe_3C and ferrite (α)

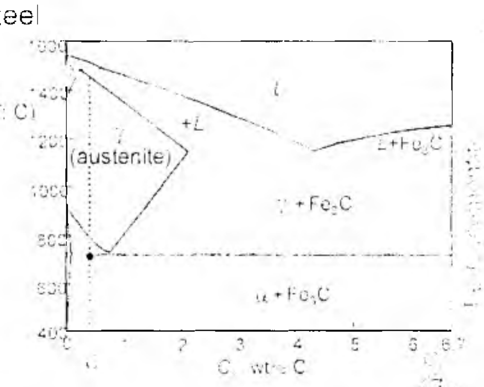
b) the amount of carbide (cementite) in grams that forms per 100 g of steel

$$\frac{Fe_3C}{Fe_3C + \alpha} = \frac{C_0 - C_\alpha}{C_{Fe_3C} - C_\alpha} \times 100$$

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

$Fe_3C = 5.7$ g

$\alpha = 94.3$ g



Chapter 9 – Phase Equilibria

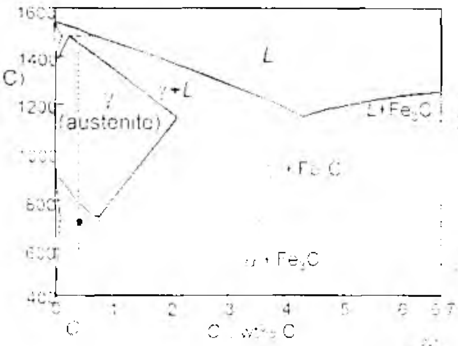
c. the amount of pearlite and proeutectoid ferrite (α)

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

$$\frac{\gamma}{\gamma+\alpha} = \frac{C_0 - C_\alpha}{C_\gamma - C_\alpha} \times 100 = 51.2 \text{ g}$$

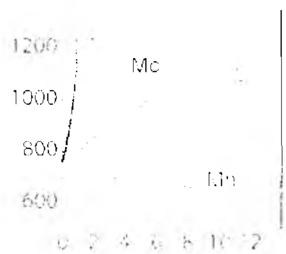
pearlite = 51.2 g

proeutectoid α = 48.8 g

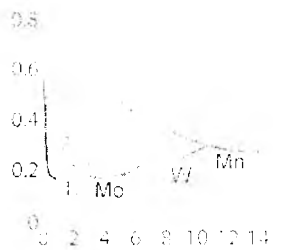


Alloying Steel with More Elements

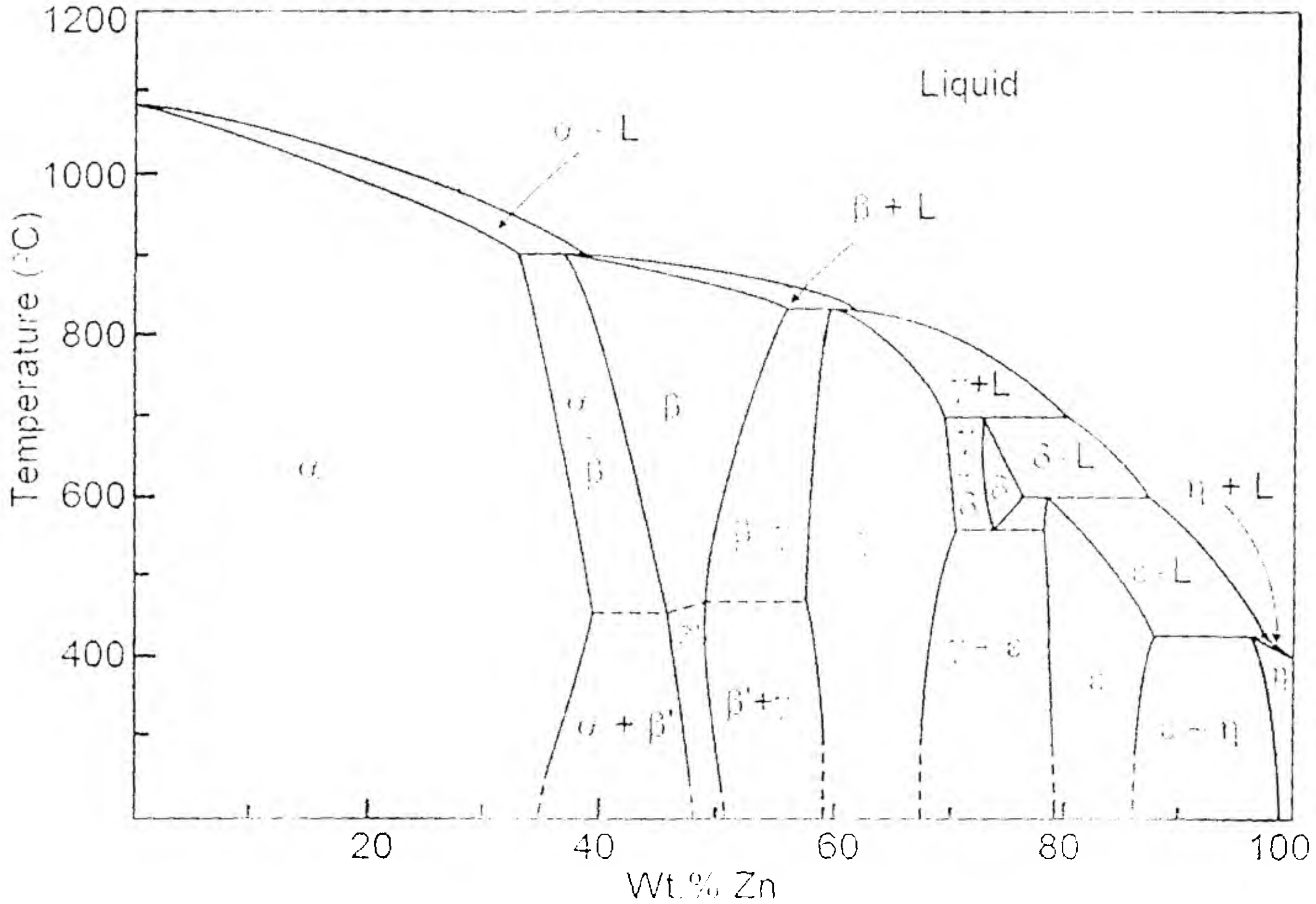
- $T_{eutectoid}$ changes:



- $C_{eutectoid}$ changes:



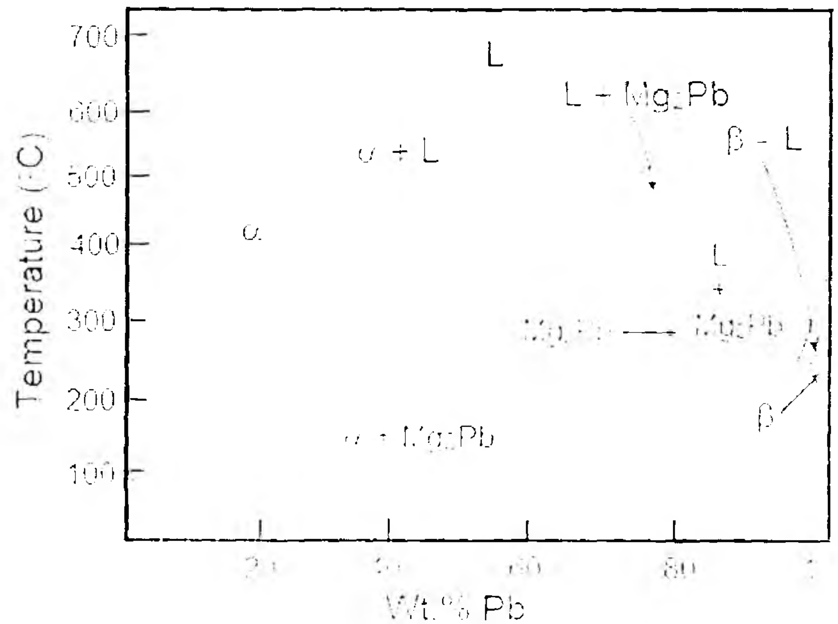
Intermediate phases - Cu-Zn Phase diagram



Cu-Zn phase diagram. α and η are terminal phases and β, γ, δ and ε are intermediate phases.

Phase diagrams with compounds

- Sometimes a crystalline compound called *intermetallic compound* may form between two metals.
- Such compounds generally have a distinct chemical formula or stoichiometry.
- Example – Mg_2Pb in the Mg-Pb system (appear as a vertical line at 81% Pb), Mg_2Ni, Mg_2Si, Fe_3C.



Mg - Pb phase diagram

Peritectic Phase diagram

- $L + \alpha \rightarrow \beta$. An alloy cooling slowly through the peritectic point, *P*, the α phase will crystallize first just below the liquidus line. At the peritectic temperature, T_P all of the liquid and α will convert to β.
- Any composition left of *P* will generate excess α and similarly compositions right of *P* will give rise to an excess of liquid.
- Peritectic systems – Pt - Ag, Ni - Re, Fe - Ge, Sn-Sb (babbit).