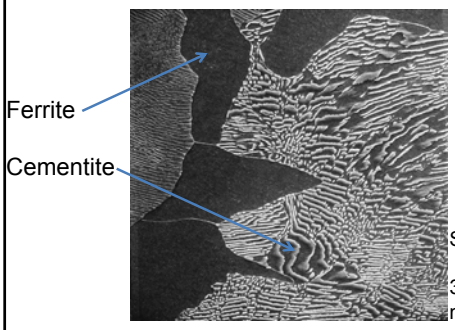
Phase Diagrams & Phase Tranformation

Microstructure - Phases



Plain C steel containing 0.44 wt. % C

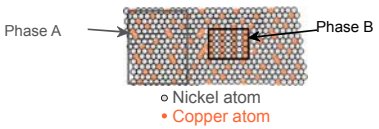
Basic Definitions

- Alloy: A metallic substance that is composed of two or more elements.
- Component: A chemical constituent (element or compound) of an alloy, which may be used to specify its composition.
- Phase: A homogeneous portion of a system that has uniform physical and chemical characteristics.
- Equilibrium: The state of a system where the phase characteristics remain constant over indefinite time periods.
  - At equilibrium the free energy is a minimum.

When we combine two elements

- What equilibrium state do we get?
- If we specify...
  --a composition (e.g., wt% Cu - wt% Ni), and
  --a temperature (T)

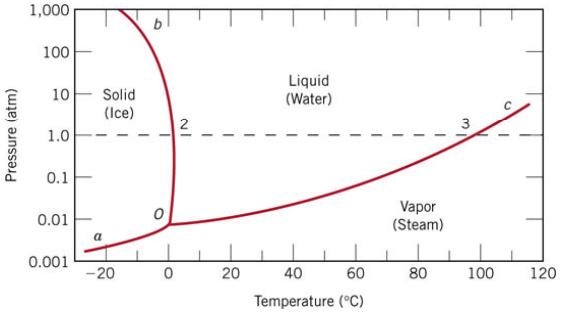
then...
How many phases do we get?
What is the composition of each phase?
How much of each phase do we get?



Phase Diagram

- Three externally controllable parameters that affect phase fraction and composition
  - Temperature
  - Pressure
  - Composition
- Phase diagram is constructed when various combinations of these parameters are plotted against one another

Unary (One component) phase diagram



Phase Equilibria: Solubility Limit

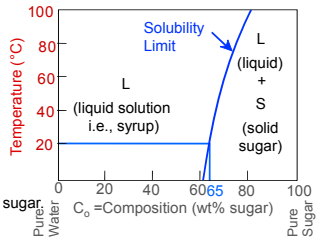
Introduction
- Solutions – solid solutions, single phase
- Mixtures – more than one phase

- Solubility Limit:
  Max concentration for which only a single phase solution occurs.

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

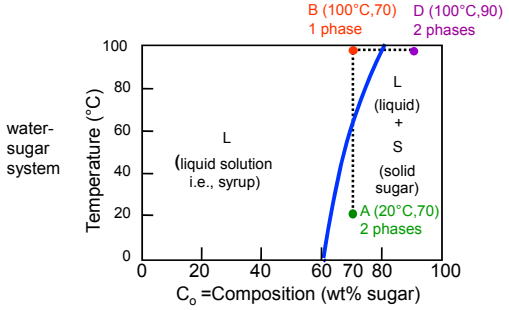
Answer: 65 wt% sugar.
If C_o < 65 wt% sugar: syrup
If C_o > 65 wt% sugar: syrup + sugar.

Sucrose/Water Phase Diagram



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.



Phase Equilibria

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

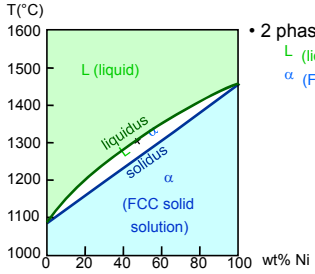
	Crystal Structure	electroneg	*r* (nm)
Ni	FCC	1.9	0.1246
Cu	FCC	1.8	0.1278

- Both have the same crystal structure (FCC) and have similar electronegativities and atomic radii (W. Hume – Rothery rules) suggesting high mutual solubility.
- Ni and Cu are totally miscible in all proportions.

Phase Diagrams

- Indicate phases as function of T, C_o, and P.
- For this course:
  -binary systems: just 2 components.
  -independent variables: T and C_o (P = 1 atm is almost always used).

- Phase Diagram for Cu-Ni system

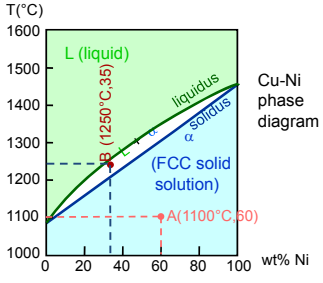


- 2 phases:
  L (liquid)
  α (FCC solid solution)

Phase Diagrams: # and types of phases

- Rule 1: If we know T and C_o, then we know:
  --the # and types of phases present.

- Examples:
  A(1100°C, 60):
  1 phase: α
  B(1250°C, 35):
  2 phases: L + α



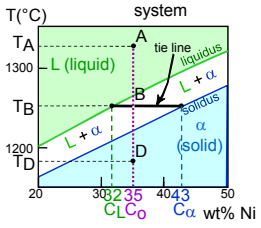
Cu-Ni phase diagram

Phase Diagrams: composition of phases

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

- Examples:
  C_o = 35 wt% Ni
  At T_A = 1320°C:
  Only Liquid (L)
  $C_L = C_o$ (= 35 wt% Ni)
  At T_D = 1190°C:
  Only Solid (α)
  $C_\alpha = C_o$ (= 35 wt% Ni)
  At T_B = 1250°C:
  Both α and L
  $C_L = C_{liquidus}$ (= 32 wt% Ni here)
  $C_\alpha = C_{solidus}$ (= 43 wt% Ni here)

Cu-Ni system



Gibbs Phase Rule

$$F = C - P + 2$$

- Degrees of Freedom: How many number of intensive variables we have to specify to completely define/ specify the system
- Number of components
- Number of phases: How many number of intensive variables that can be independently changed without changing the number of phases

Intensive variables of the system:

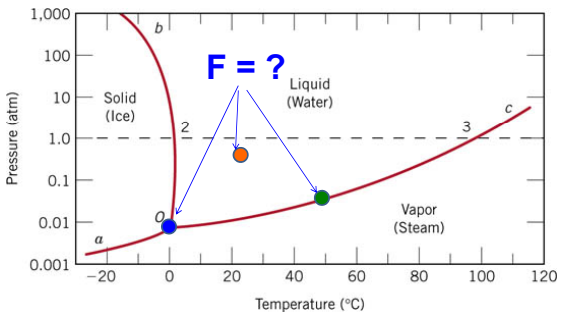
- Temperature of each phase
- Pressure of each phase
- Composition of each phase = Relative concentration of each component in that phase

Temperature of each phase is equal and is equal to the temperature of the system

Pressure of each phase is equal and is equal to the pressure of the system

To completely define the system means: specifying temperature, pressure and relative concentrations of each component in each phase of the system

Application of Gibbs Phase Rule: Unary phase diagram



Gibbs Phase Rule when Pressure is constant

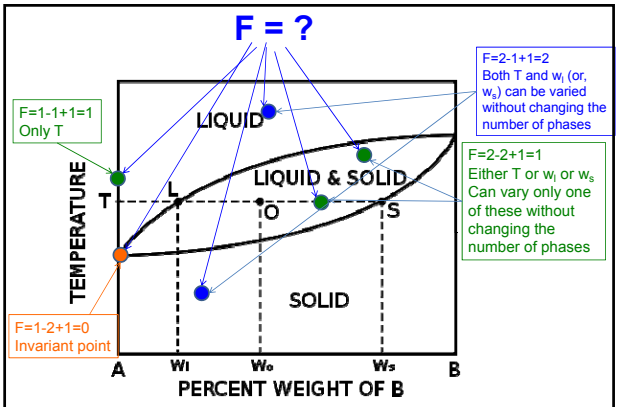
$$F = C - P + 1$$

If Pressure is fixed at a particular value

$F = C - P + 2$

- Degrees of Freedom
- Number of components
- Number of phases

Phase diagrams for metals and ceramics are drawn at 1 atm. fixed pressure



Phase Diagrams:

weight fractions of phases

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

C_o = 35 wt% Ni

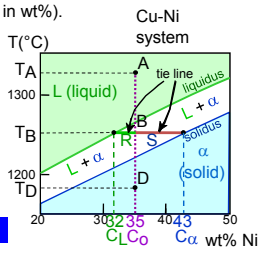
At T_A: Only Liquid (L)
W_L = 100 wt%, W_α = 0

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

At T_B: Both α and L

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

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



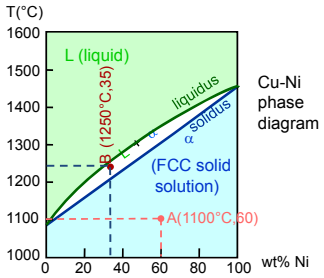
Phase Diagrams:

and types of phases

- Rule 1: If we know T and C_o, then we know:
  --the # and types of phases present.
- Examples:

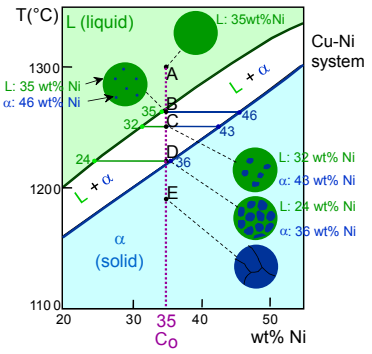
A(1100°C, 60):
1 phase: α

B(1250°C, 35):
2 phases: L + α

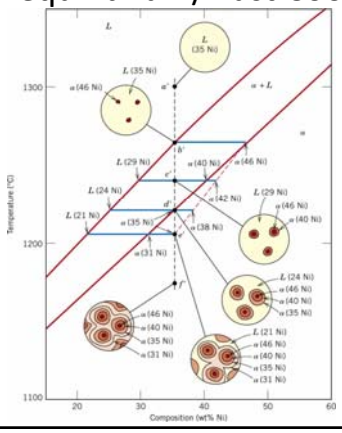


Ex: Cooling in a Cu-Ni Binary

- Phase diagram:
  Cu-Ni system.
- Consider
  C_o = 35 wt%Ni.

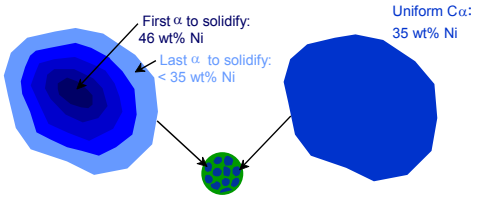


Non-equilibrium/ Fast Cooling



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



Binary-Eutectic Systems

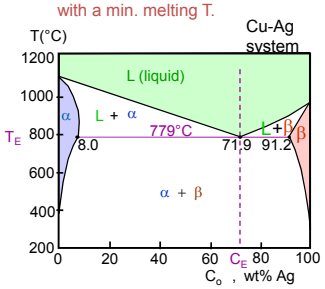
2 components

has a special composition with a min. melting T.

Ex.: Cu-Ag system

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

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

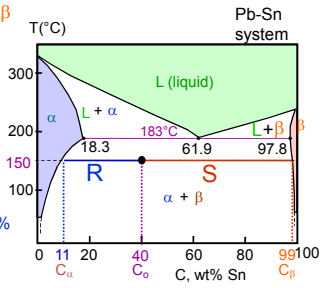


EX: Pb-Sn Eutectic System (1)

- For a 40 wt% Sn-60 wt% Pb alloy at 150°C, find...
  --the phases present: α + β
  --compositions of phases:
  C_o = 40 wt% Sn
  C_α = 11 wt% Sn
  C_β = 99 wt% Sn
  --the relative amount of each phase:

$$W_\alpha = \frac{S}{R+S} = \frac{C_\beta - C_o}{C_\beta - C_\alpha} = \frac{99-40}{99-11} = \frac{59}{88} = 67\ \text{wt\%}$$

$$W_\beta = \frac{R}{R+S} = \frac{C_o - C_\alpha}{C_\beta - C_\alpha} = \frac{40-11}{99-11} = \frac{29}{88} = 33\ \text{wt\%}$$

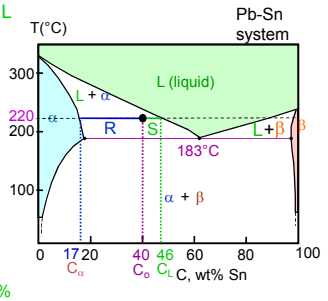


EX: Pb-Sn Eutectic System (2)

- For a 40 wt% Sn-60 wt% Pb alloy at 200°C, find...
  - --the phases present: α + 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:

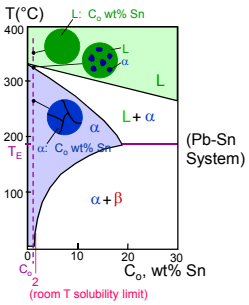
$$W_\alpha = \frac{C_L - C_O}{C_L - C_\alpha} = \frac{46 - 40}{46 - 17} = \frac{6}{29} = 21 \text{ wt\%}$$

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



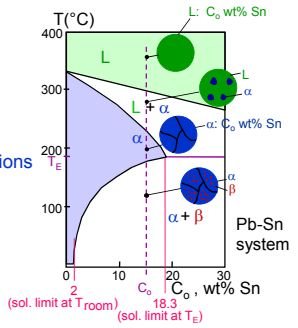
Microstructures in Eutectic Systems: I

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



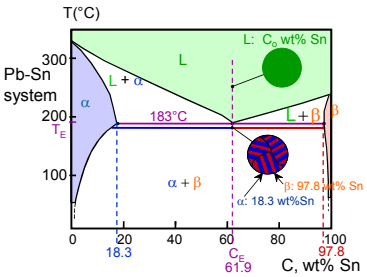
Microstructures in Eutectic Systems: II

- 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

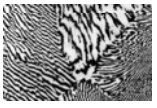


Microstructures in Eutectic Systems: III

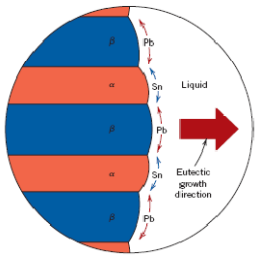
- C_O = C_E
- Result: Eutectic microstructure (lamellar structure)
  --alternating layers (lamellae) of α and β crystals.

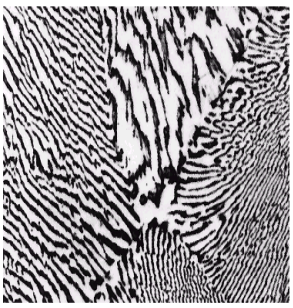


Micrograph of Pb-Sn eutectic microstructure



Lamellar Eutectic Structure





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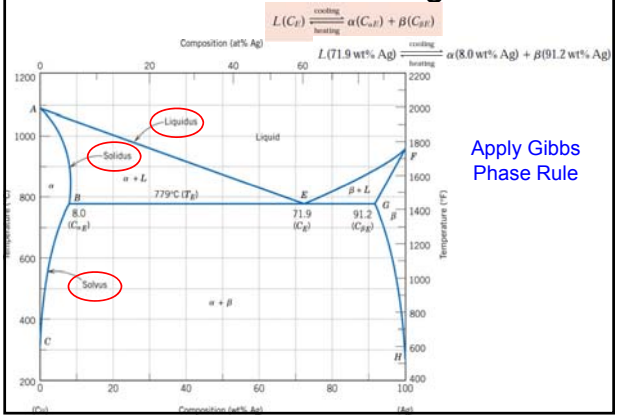
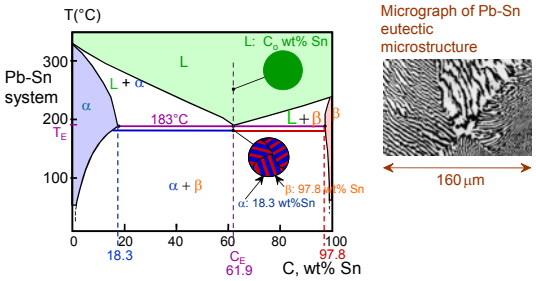
Eutectic Phase Diagram



Apply Gibbs Phase Rule

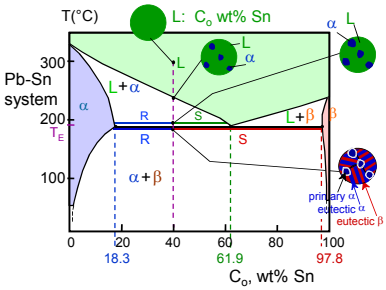
Microstructures in Eutectic Systems: III

- **If the Liquid composition is Euctectic composition**
- Result: Eutectic microstructure (lamellar structure)
  --alternating layers (lamellae) of α and β crystals.



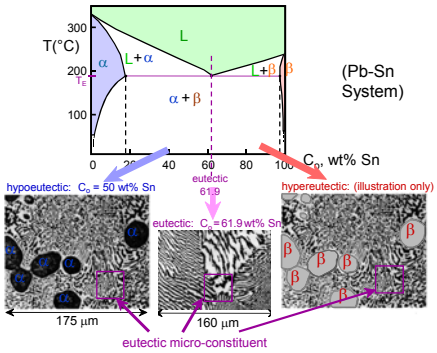
Microstructures in Eutectic Systems: IV

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

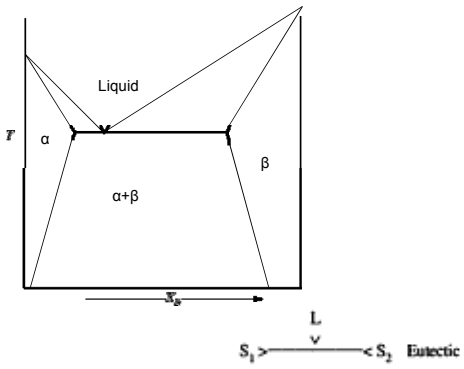


- Just above T_E :
  - $C\alpha$ = 18.3 wt% Sn
  - C_L = 61.9 wt% Sn
  - $W\alpha = \frac{S}{R+S}$ = 50 wt%
  - W_L = (1-Wα) = 50 wt%
- Just below T_E :
  - $C\alpha$ = 18.3 wt% Sn
  - $C\beta$ = 97.8 wt% Sn
  - $W\alpha = \frac{S}{R+S}$ = 73 wt%
  - $W\beta$ = 27 wt%

Hypoeutectic & Hypereutectic

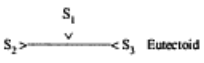


You can draw Eutectic phase diagram stating from the eutectic reaction

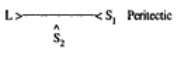


Other Phase Diagrams

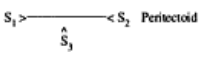
Eutectoid $\delta \rightleftharpoons \gamma + \varepsilon$



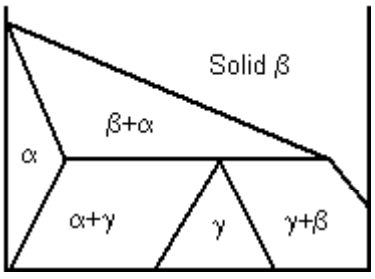
Peritectic $\gamma + L \rightleftharpoons \delta$

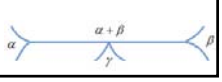


Peritectoid $\alpha + \gamma \rightleftharpoons \delta$

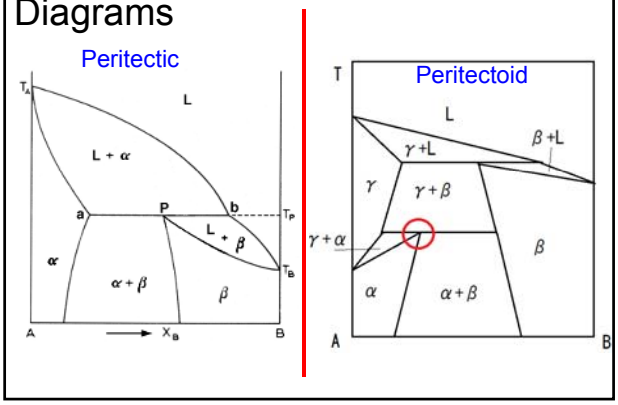


Peritectoid Phase diagram

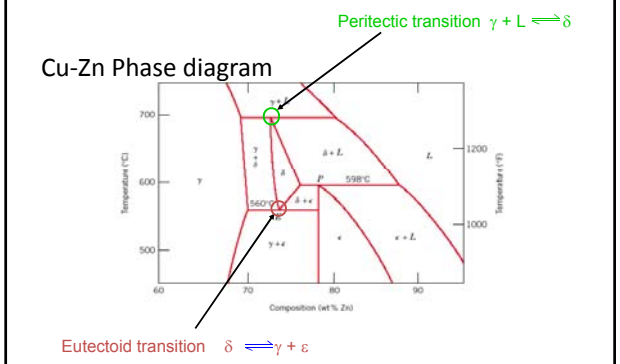


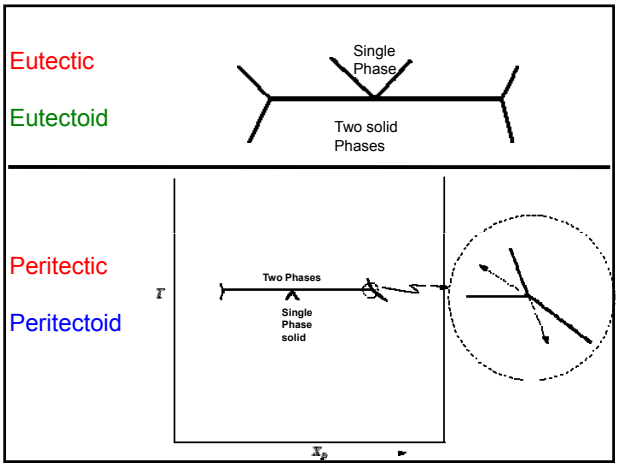


Peritectic and Peritectoid Phase Diagrams

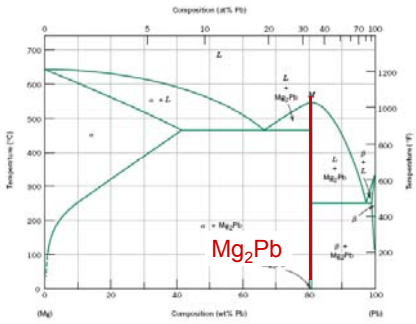


Eutectoid & Peritectic





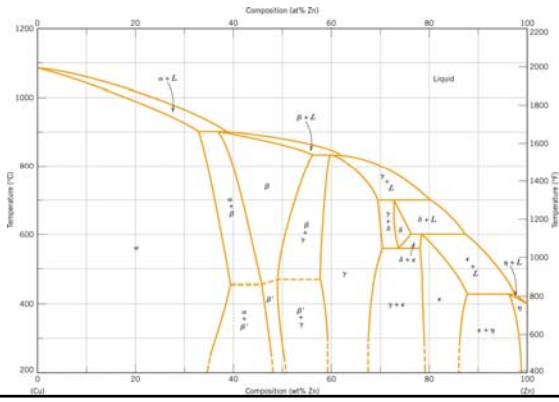
Intermediate/ Intermetallic Compounds



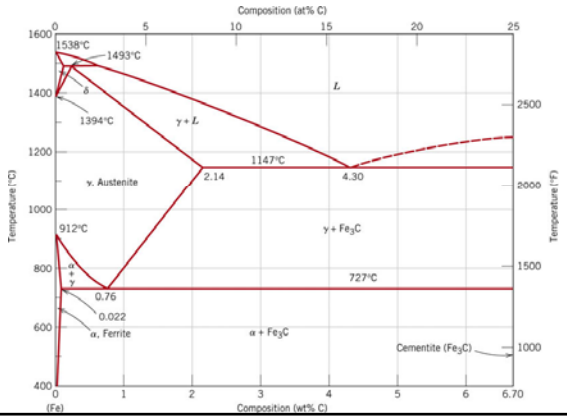
Note: intermetallic compound forms a line - not an area - because stoichiometry (i.e. composition) is exact.

- Not isomorphous with either of the components of the alloy system
- Congruently melting intermediate phases → Intermetallic phase

Cu-Zn : Intermediate Phases



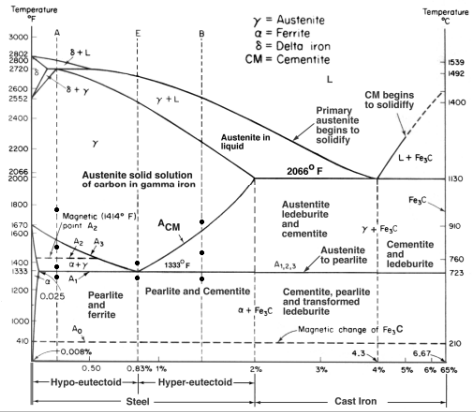
Fe-Cementite Phase Diagram



Few Principles about Phase Diagrams

1. One phase regions may touch each other only at single points (point of congruent transformation), never along a boundary
2. Adjacent one phase regions are seperated from each other by 2 phase regions involving the same 2 phases
3. Three 2 phase regions must originate upon three phase isotherm
4. Two three phase isotherms may be connected by a 2 phase region provided that there are 2 phases which are common to both of the three phase equilibria
5. All boundaries of 2 phase fields must project into 2 phase fields when they join a three phase isotherm

Fe-Cementite Phase Diagram



Iron-Carbon (Fe-C) Phase Diagram

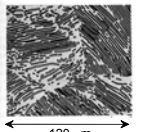
- 2 important points

-Eutectic (A):

$L \Rightarrow \gamma + Fe_3C$

-Eutectoid (B):

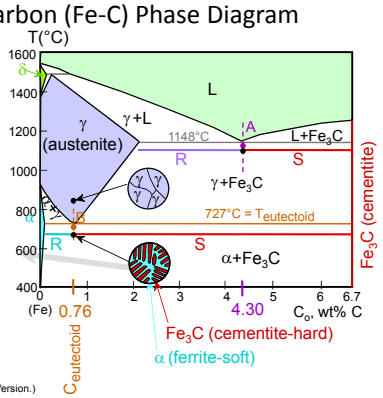
$\gamma \Rightarrow \alpha + Fe_3C$



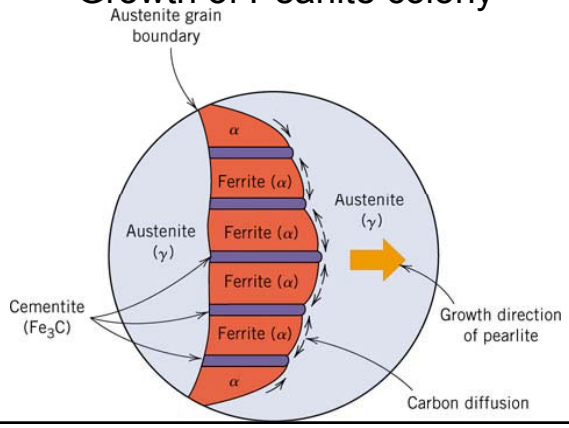
120 μm

Result: Pearlite = alternating layers of α and Fe_3C phases

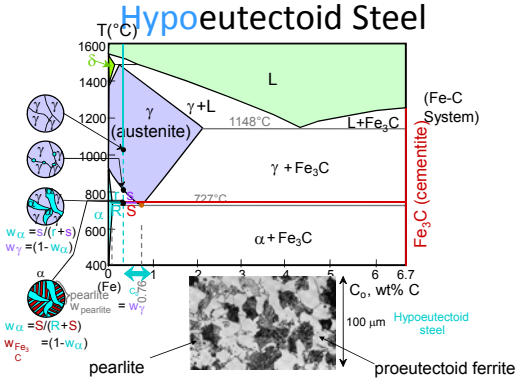
(From Fig. 7.27, Callister Adapted Version.)



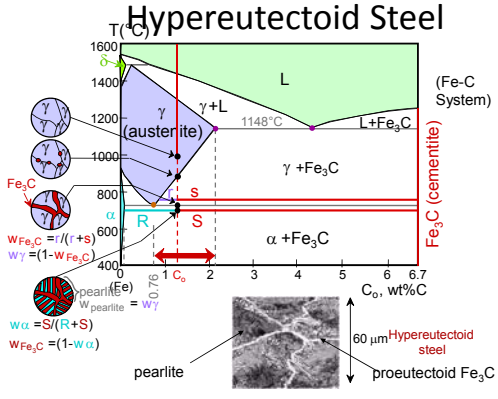
Growth of Pearlite colony



Hypoeutectoid Steel



Hypereutectoid Steel



Class Work/ Class Test
Do it now on your own notebook

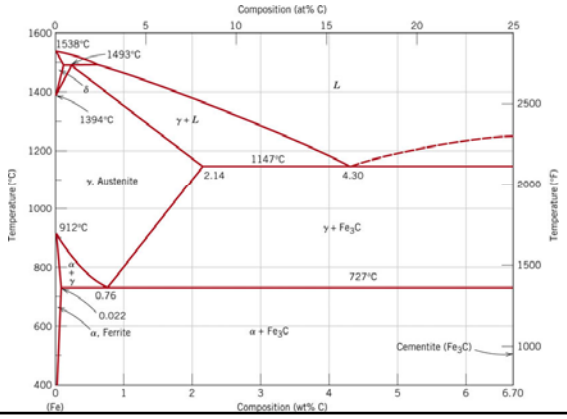
For an alloy, Fe-0.40 wt% C at a temperature just below the eutectoid, determine the following

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)

Fe-Cementite Phase Diagram



Phase Equilibria

Solution:

a) composition of Fe_3C and ferrite (α)

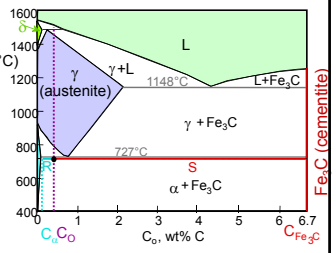
b) the amount of carbide (cementite) in grams that forms per 100 g of steel

C_O = 0.40 wt% C
C_α = 0.022 wt% C
C_{Fe_3C} = 6.70 wt% C

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

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

$Fe_3C = 5.7$ g
$\alpha = 94.3$ g



Phase Equilibria

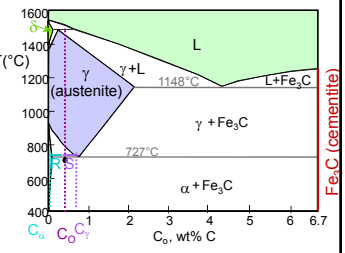
c. the amount of pearlite and proeutectoid ferrite (α)

Amount of pearlite = amount of γ just above T_E

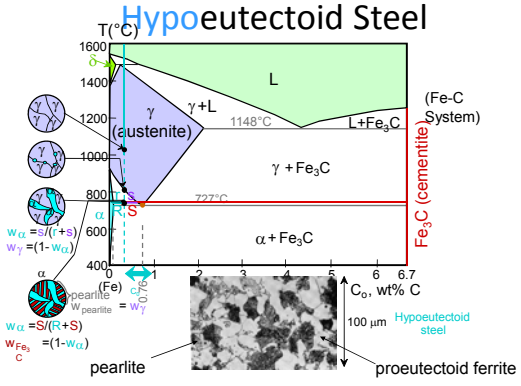
C_o = 0.40 wt% C
C_α = 0.022 wt% C
$C_{pearlite} = C_\gamma$ = 0.76 wt% C

$$\frac{\gamma}{\gamma+\alpha} = \frac{C_o - C_\alpha}{C_\gamma - C_\alpha} x\,100 = 51.2\ g$$

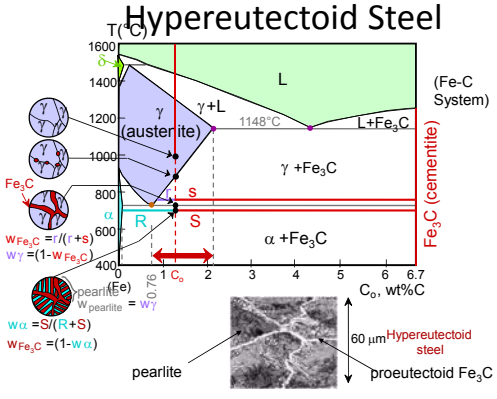
pearlite = 51.2 g
proeutectoid α = 48.8 g



Recap of μstructure evolution in steel
Hypoeutectoid Steel



Recap of μstructure evolution in steel
Hypereutectoid Steel



Phase Transformation

Phase transformations (change of the microstructure) can be divided into three categories:

- **Diffusion-dependent with no change in phase composition or number of phases present** (e.g. melting, solidification of pure metal, allotropic transformations, recrystallization, etc.)
- **Diffusion-dependent with changes in phase compositions and/or number of phases** (e.g. eutectic or eutectoid transformations)
- **Diffusionless phase transformation** - by cooperative small displacements of all atoms in structure, (e.g. martensitic transformation)

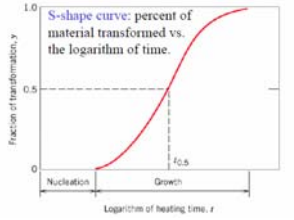
Diffusion-dependent phase transformations can be rather slow and the final structure often depend on the rate of cooling/heating.

Kinetics of phase transformations

Phase transformations involve change in structure and (for multi-phase systems) composition ⇒ rearrangement and redistribution of atoms via diffusion is required.

The process of phase transformation involves:

- **Nucleation** of the new phase(s) - formation of stable small particles (nuclei) of the new phase(s). Nuclei are often formed at grain boundaries and other defects.
- **Growth** of the new phase(s) at the expense of the original phase(s).



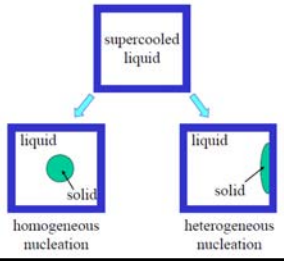
Nucleation

Nucleation can be

Heterogeneous – the new phase appears on the walls of the container, at impurity particles, etc.

Homogeneous – solid nuclei spontaneously appear within the undercooled phase.

Let's consider solidification of a liquid phase undercooled below the melting temperature as a simple example of a phase transformation.



Gibbs free energy in analysis of phase transitions

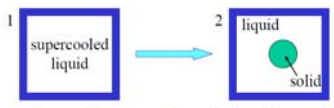
It is convenient to analyze phase transformations occurring under conditions of constant temperature (T) and pressure (P) by using **Gibbs free energy (G)**.

G = H – TS, where H is the enthalpy and S is the entropy

H = U + PV, where U is the internal energy

Gibbs free energy (G = H – TS):
Equilibrium is trade-off between minimization of enthalpy and maximization of entropy

A phase transformation occurs spontaneously only when G decreases in the course of the transformation



Is the transition from undercooled liquid to a solid spherical particle in the liquid a spontaneous one?

The formation of a solid nucleus leads to a Gibbs free energy change of

$$\Delta G = V_S(G_v^S - G_v^L) + A_{SL}\gamma_{SL} = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{SL}$$

at $T < T_m$, $G_v^S < G_v^L$ – solid is the equilibrium phase

negative below T_m

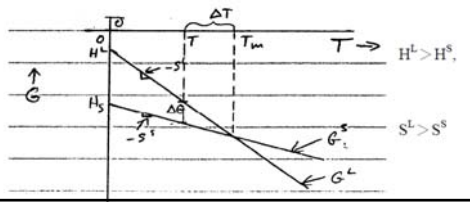
always positive

Free energy change per unit volume. Below T_m, it is -ve

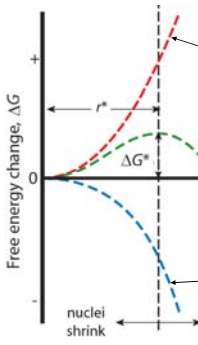
V_S is the volume of the solid sphere

A^{SL} is the solid/liquid interfacial area

γ^{SL} is the solid/liquid interfacial energy



Homogeneous Nucleation & Energy Effects



Surface Free Energy- Energy needed to make an interface)

$\Delta G_S = 4\pi r^2 \gamma_{SL}$

γ = surface tension

ΔG_T = Total Free Energy = $\Delta G_S + \Delta G_V$

Volume (Bulk) Free Energy – releases of energy due to formation of solid

$\Delta G_V = \frac{4}{3}\pi r^3 \Delta G_v$

r^* = critical nucleus: nuclei < r^* shrink; nuclei>r^* grow (to reduce energy)

at r=r*, $\frac{\partial \Delta G}{\partial r} = 0$

Homogeneous nucleation

at r=r*, $\frac{\partial \Delta G}{\partial r} = 0$

$$\Delta G = V_S(G_v^S - G_v^L) + A_{SL}\gamma_{SL} = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{SL}$$

$$r^* = \frac{-2\gamma_{SL}}{\Delta G_v} \qquad \Delta G^* = \frac{16\pi(\gamma_{SL})^3}{3(\Delta G_v)^2}$$

$$\Delta G_v = \frac{\Delta H_v \Delta T}{T_m} = \frac{L_v \Delta T}{T_m} \qquad \Delta T = T_m - T = Undercooling$$

ΔH_v=L_v is latent heat of solidification

$\Delta G_v, \Delta H_v = L_v < 0$

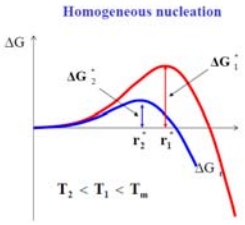
Therefore,

$$r^* = \frac{-2\gamma_{SL}}{\Delta G_v} = \left(\frac{-2\gamma_{SL}T_m}{\Delta H_v}\right)\frac{1}{\Delta T}$$

$$\Delta G^* = \frac{16\pi(\gamma_{SL})^3}{3(\Delta G_v)^2} = \left(\frac{16\pi(\gamma_{SL})^3 T_m^2}{3(\Delta H_v)^2}\right)\frac{1}{(\Delta T)^2}$$

Both r and ΔG* decrease with increasing undercooling*

Homogeneous nucleation



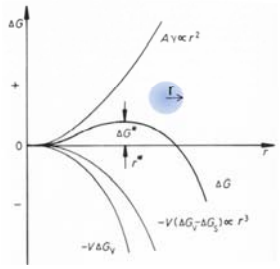
$$r^* = \frac{-2\gamma_{SL}}{\Delta G_v} = \left(\frac{-2\gamma_{SL}T_m}{\Delta H_v}\right)\frac{1}{\Delta T}$$

$$\Delta G^* = \frac{16\pi(\gamma_{SL})^3}{3(\Delta G_v)^2} = \left(\frac{16\pi(\gamma_{SL})^3 T_m^2}{3(\Delta H_v)^2}\right)\frac{1}{(\Delta T)^2}$$

Both r and ΔG* decrease with increasing undercooling*

Homogeneous nucleation in solid

$$\Delta G = V_S \Delta G_v + A_{SL}\gamma_{SL} + V_S \Delta G_{strain} = \frac{4}{3}\pi r^3(\Delta G_v + \Delta G_{strain}) + 4\pi r^2 \gamma_{SL}$$



$$r^* = \frac{-2\gamma_{SL}}{(\Delta G_v + \Delta G_{strain})}$$

$$\Delta G^* = \frac{16\pi(\gamma_{SL})^3}{3(\Delta G_v + \Delta G_{strain})^2}$$

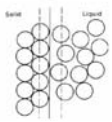
Both r and ΔG* increase because of strain energy involved in solid state transformation*

Rate of Homogeneous nucleation

There is an energy barrier of ΔG* for formation of a solid nucleus of critical size r*. The probability of energy fluctuation of size ΔG* is given by the Arrhenius equation and the rate of homogeneous nucleation is

$$\dot{N} \sim \nu_d \exp\left(-\frac{\Delta G^*}{kT}\right) \quad \text{nuclei per m}^3 \text{ per s}$$

where ν_d is the frequency with which atoms from liquid attach to the solid nucleus. The rearrangement of atoms needed for joining the solid nucleus follow the same temperature dependence as the diffusion coefficient:



$$\nu_d \sim \exp\left(-\frac{Q_d}{kT}\right)$$

$$\Delta G^* \propto \frac{1}{(\Delta T)^2}$$

$$\Delta T = T_m - T$$

As T ↓ → ΔT ↑ → ΔG* ↓

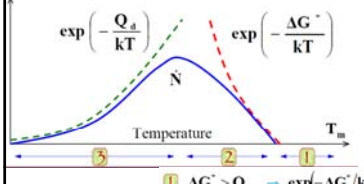
→exp(-(ΔG*)/kT) ↑

→ ν_d ↓

Therefore: $\dot{N} \sim \exp\left(-\frac{Q_d}{kT}\right)\exp\left(-\frac{\Delta G^*}{kT}\right)$

Rate of Homogeneous nucleation

$$\dot{N} \sim \exp\left(-\frac{Q_d}{kT}\right)\exp\left(-\frac{\Delta G^*}{kT}\right)$$



1 $\Delta G^* > Q_d \Rightarrow \exp(-\Delta G^*/kT) << \exp(-Q_d/kT)$

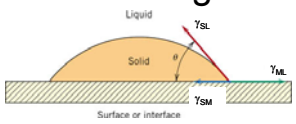
ΔG* is too high - nucleation is suppressed

2 $\Delta G^* \le Q_d \Rightarrow \exp(-\Delta G^*/kT) > \exp(-Q_d/kT)$

ΔG*~ $1/\Delta T^2$ – decreases with T – sharp rise of homogeneous nucleation (diffusion is still active)

3 $\exp(-Q_d/kT)$ – too small – low atomic mobility suppresses the nucleation rate

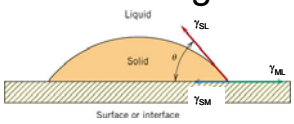
Heterogeneous nucleation



$$\Delta G = V_S \Delta G_v + A_{SL}\gamma_{SL} + A_{SM}\gamma_{SM} - A_{SM}\gamma_{ML}$$

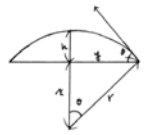
$$\gamma_{SM} - \gamma_{ML} = -\gamma_{SL}\cos\theta$$

Heterogeneous nucleation



$$\Delta G = V_S \Delta G_v + A_{SL}\gamma_{SL} + A_{SM}\gamma_{SM} - A_{SM}\gamma_{ML}$$

$$\gamma_{SM} - \gamma_{ML} = -\gamma_{SL}\cos\theta$$



$A_{SM} = \pi y^2 = \pi r^2 \sin^2\theta$

$A_{SL} = 2\pi r^2(1-\cos\theta)$

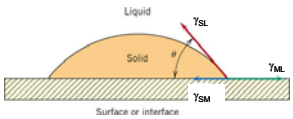
$V = \pi \int_{R-h}^{R} (R^2 - x^2)\,dx = \frac{\pi h^2}{3}(3R-h).$

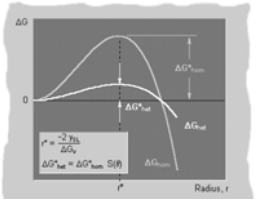
$V_S = 1/3\pi h^2(3r-h) = 1/3\pi r^2[1-\cos\theta]^2[2r+r\cos\theta] = 1/3\pi r^3[1-\cos\theta]^2[2+\cos\theta]$

$$V_S = \frac{4}{3}\pi r^3 S(\theta) \qquad S(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

$$\Delta G = \left(\frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{SL}\right) S(\theta)$$

Heterogeneous nucleation



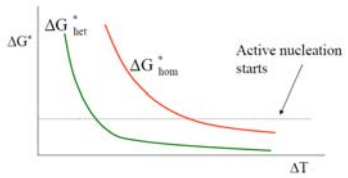


$$\Delta G_{het} = \left\{\frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma_{SL}\right\} S(\theta)$$

$$r^*_{het} = \frac{-2\gamma_{SL}}{\Delta G_v} = r^*_{hom} \qquad S(\theta) = \frac{(2+\cos\theta)(1-\cos\theta)^2}{4}$$

$$\Delta G^*_{het} = \frac{16\pi\gamma_{SL}^3}{3\Delta G_v^2} S(\theta) = \Delta G^*_{hom} S(\theta)$$

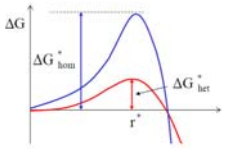
Solidification: Nucleation Processes



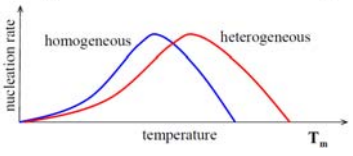
- Homogeneous nucleation
  - nuclei form in the bulk of liquid metal
  - requires supercooling (typically 80-300°C max)
- Heterogeneous nucleation
  - Nuclei form on mold wall or inoculants
  - allows solidification with only 0.1-10ºC supercooling

Nucleation rate

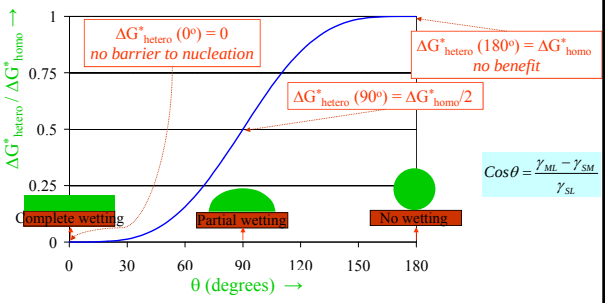
if $\theta = 10^\circ$ $S(\theta) = (2+\cos\theta)(1-\cos\theta)^2/4 \approx 10^{-4}$



heterogeneous nucleation starts at a lower undercooling



Variation of S(θ) with θ



Nucleation rate: Homogeneous vs. Heterogeneous

$$I_{homo} \propto I^0_{homo}\, e^{-\left(\frac{\Delta G^*_{homo}}{kT}\right)} \qquad I_{hetero} \propto I^0_{hetero}\, e^{-\left(\frac{\Delta G^*_{hetero}}{kT}\right)}$$

= f(number of nucleation sites) ~ 10^{42}

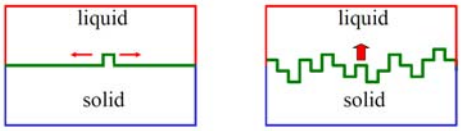
= f(number of nucleation sites) ~ 10^{26}

BUT
the exponential term dominates

$I_{hetero} > I_{homo}$

Growth

Once a stable nucleus of the new phase exceeding the critical size r* is formed, it starts to grow. Atomically rough interfaces migrate by continuous growth, whereas atomically flat interfaces migrate by ledge formation and lateral growth.

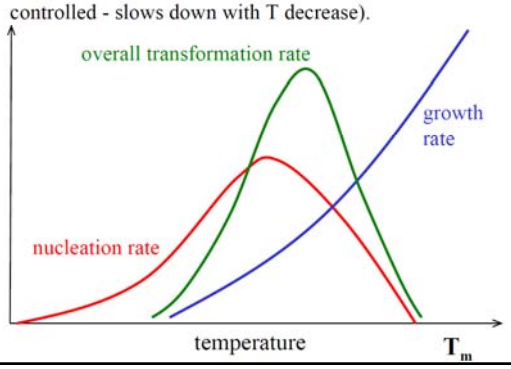


Growth rate = C exp ($-Q_A$/kT) = C exp ($-Q_m$/ RT)

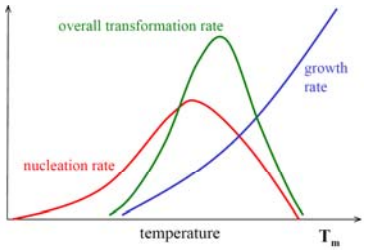
per atom — per mole

Rate of phase transformations

Total rate of a phase transformation induced by cooling is a product of the nucleation rate and growth rate (diffusion controlled - slows down with T decrease).



Rate of Phase Transformation



high T (close to T_m): low nucleation and high growth rates → coarse microstructure with large grains

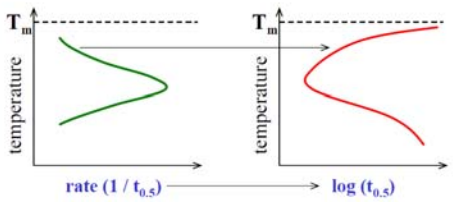
low T (strong undercooling): high nucleation and low growth rates → fine structure with small grains

Rate of phase transformations

To quantitatively describe the rate of a phase transformation, it can be defined as reciprocal of time for transformation to proceed halfway to completion:

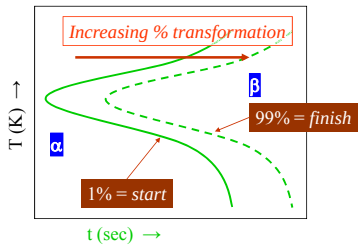
rate = $1 / t_{0.5}$

Plotting the transformation time vs temperature results in a characteristic C-shaped curves:



Time – Temperature – Transformation (TTT) diagram

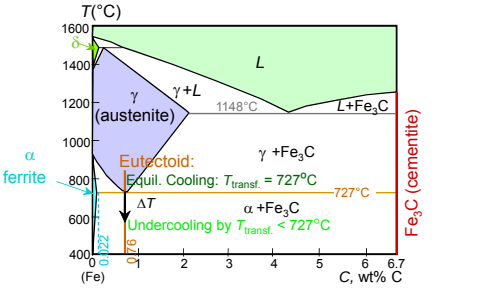
α → β phase transformation



Transformations & Undercooling

- Eutectoid transformation (Fe-Fe_3C system): $\gamma \Rightarrow \alpha + Fe_3C$
- For transformation to occur, must cool to below 727°C

0.76 wt% C, 0.022 wt% C, 6.7 wt% C



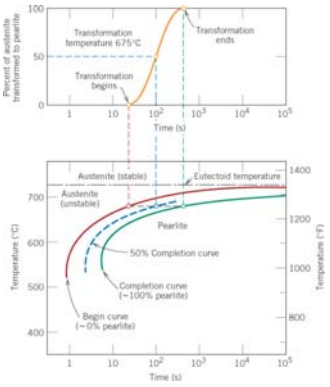
Isothermal Transformation Diagrams

2 solid curves are plotted:

- one represents the time required at each temperature for the start of the transformation;
- the other is for transformation completion.
- The dashed curve corresponds to 50% completion.

The austenite to pearlite transformation will occur only if the alloy is supercooled to below the eutectoid temperature (727°C).

Time for process to complete depends on the temperature.

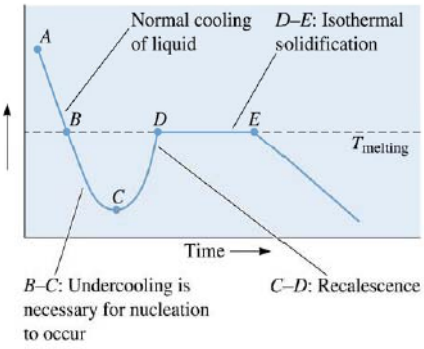


Next class onwards Prof. Sumantra Mandal will teach at the same class timings

Solidification of pure metal:

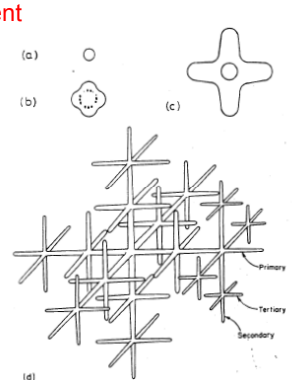
- Cooling curve
- Concept of supercooling
- Homogeneous and heterogeneous nucleation processes,
- Microstructure of pure metals

Cooling Curve for pure metal



Dendritic structure

Development of Thermal Dendrites



a) Spherical Nucleus

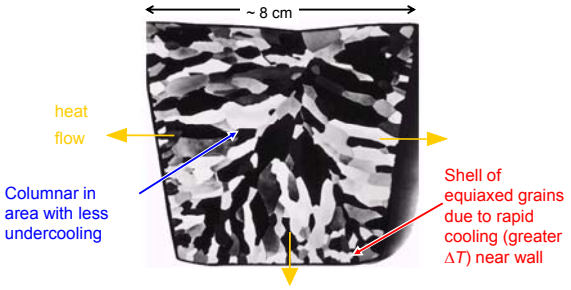
b) The interface becomes unstable

c) Primary arms develop in crystallographic directions <100> in cubic crystals

d) Secondary and tertiary arms develop

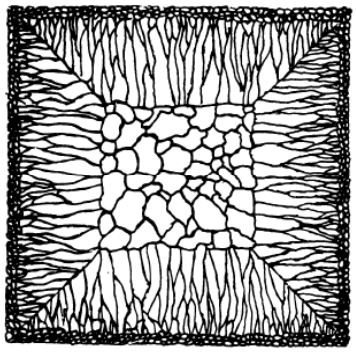
Solidification

Grains can be
- equiaxed (roughly same size in all directions)
- columnar (elongated grains)



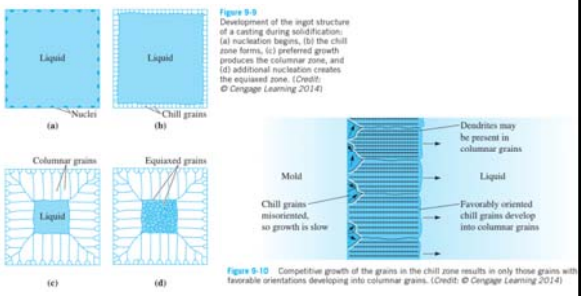
Typical Cast Structure

Cast Grain Structure



Schematic Diagram

Cast Microstructure



Typical Cast Structure