



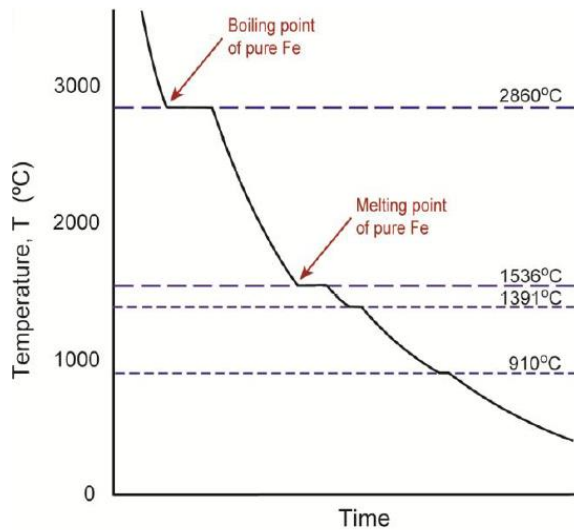
Lecture 2B



Phase Transformations and TTT Diagrams

Thursday 12th November 2020

Learning Outcome



- Knowledge of solidification and solid state transformations.
- Understanding of the principles of transformation and conditions of structure under which it occurs.
- Ability to interpret TTT-diagrams

Study guide for lecture 2B

Minimum reading:

- Lecture slides 2B
- Teach yourself Phase Diagrams and Phase Transformations, part 5-8 and exercises within

Supplementary recommended resources:

- Phase diagram tool within GRANTA EduPack MS&E database
- Ashby Ch 5, 9
- Callister (any edition): Chapter on Phase Transitions
- Youtube links (if you have time):

Advanced but good lecture by Prof. Harry Bhadeshia

<https://www.youtube.com/watch?v=YxO8kezITbo>

Recommended extra exercises:

Micro-projects 2A-B (same as last lecture)

Outline

- Introduction to Phase Transformations
- Iron – Carbon Phase diagram features
- Cooling and Solidification processes
 - ✓ Near equilibrium
 - ✓ Non-equilibrium
- TTT diagrams

Introduction to Phase Transformations

When the temperature varies in a process, the equilibrium condition of the material keeps changing (e.g. as boundaries on the phase diagram are crossed) – hence *phase transformations* take place. These transformations determine which phases are present after processing, and how they are distributed amongst one another - that is, the final *microstructure*. This in turn controls the material properties.

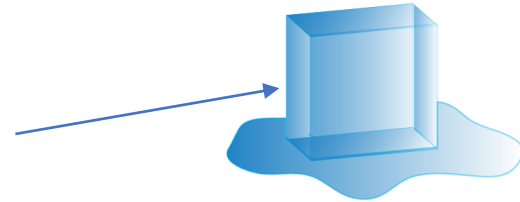
Phase diagrams give important information needed to predict the phase transformations and final microstructure which result from a given thermal history. The real microstructure may not be at equilibrium, but phase diagrams give a starting point from which other (non-equilibrium) microstructures can often be inferred.

Phase Transformations

DEF: where one or more phases within a system change into new phase(s)

Common phase transformation example: ice melting

Phase transformation from solid to liquid



Ice melting and other single component system changes are considered *congruent transitions*

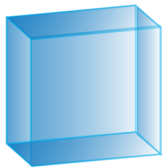
Congruent transitions:
a phase transformation with
no compositional change

Reaction:
 $L \leftrightarrow \alpha$

Phase transformations in different environments

Example: Water

1 atmosphere



Solid phase: ice

0°C
↔



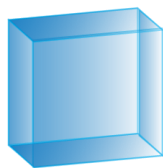
Liquid phase: water

100°C
↔



Gas phase: water vapor

Approx. 0.005 atmosphere



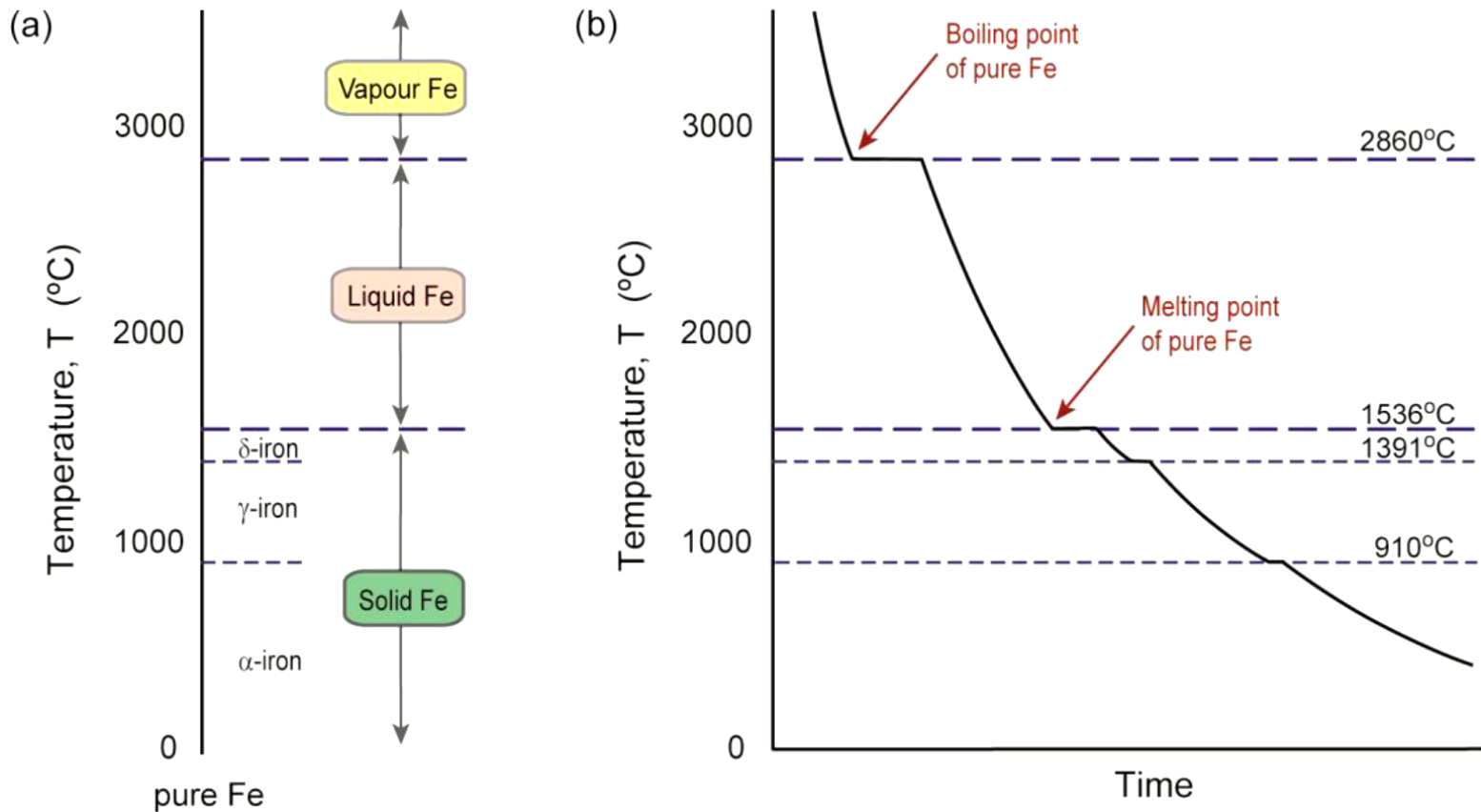
Solid phase: ice

approx. 0°C
←→



Gas phase: water vapor

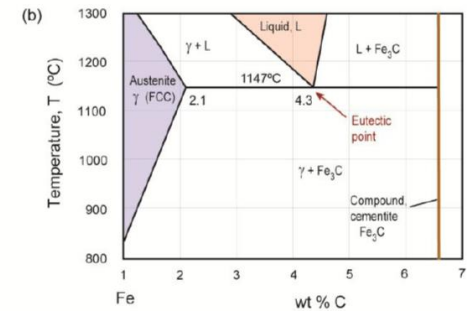
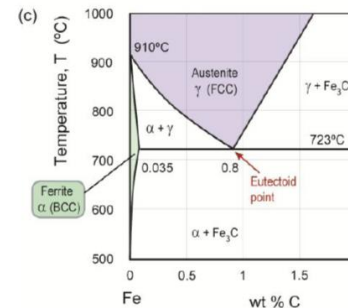
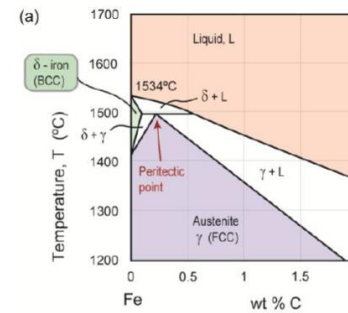
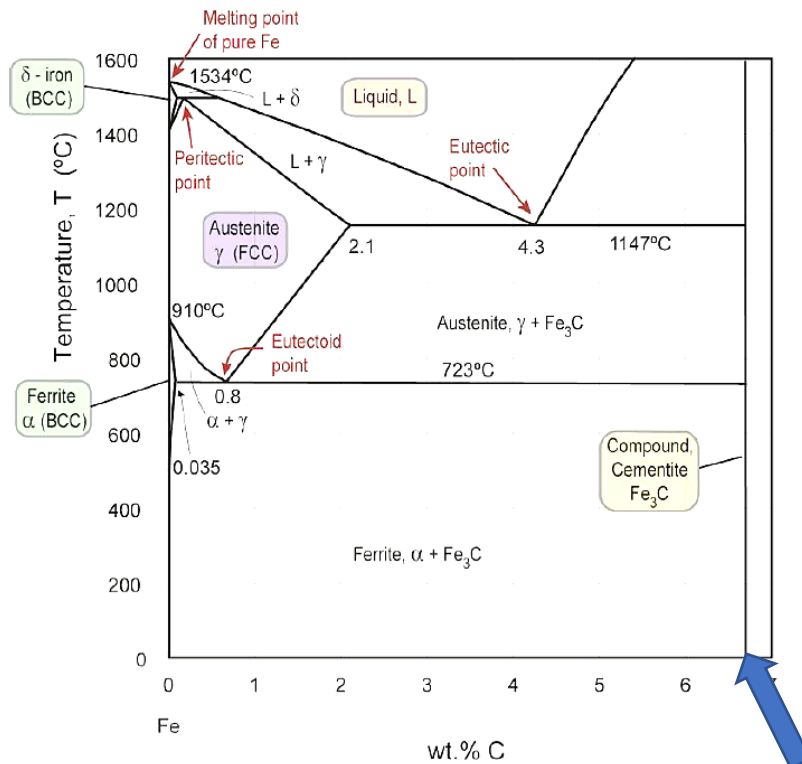
Equilibrium solidification (in 1 atmosphere)



Techniques to observe phases and microstructures

Technique	Physical basis
Dilatometry	Measurement of dimensional changes at high resolution to detect changes of density and symmetry caused by phase change.
Electrical resistivity	Measurement of electrical resistivity changes associated with difference in electron mean free path before and after phase change.
Calorimetry: differential thermal analysis	Sensitive differential measurement of release or take-up of latent heat associated with phase change.
Optical microscopy	Differential reflection of light, either in color or intensity, by phases or by a surface film created by chemical or electro-etching.
X-ray diffraction	Diffraction of X-radiation by the crystal lattice of each phase, giving diffraction patterns from which crystal structure and volume fraction of phases can be inferred.
Scanning electron microscopy (SEM)	Differential back-scattering of electrons by differing phases giving both an image and compositional information
Transmission electron microscopy (TEM)	Diffraction of an electron beam by the crystal lattice of each phase, giving both an image of the structure and, from the diffraction pattern, its crystal structure.

The Iron – Carbon phase diagram (EduPack MS&E)



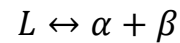
DEF: intermediate phases, compounds which form between components (intermetallics)

Phase Transformations

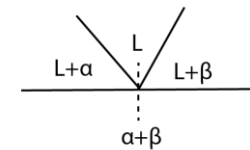
Eutectic transformation:

the composition and temperature at which two liquidus lines meet. The liquid transforms to two intermixed solid phases

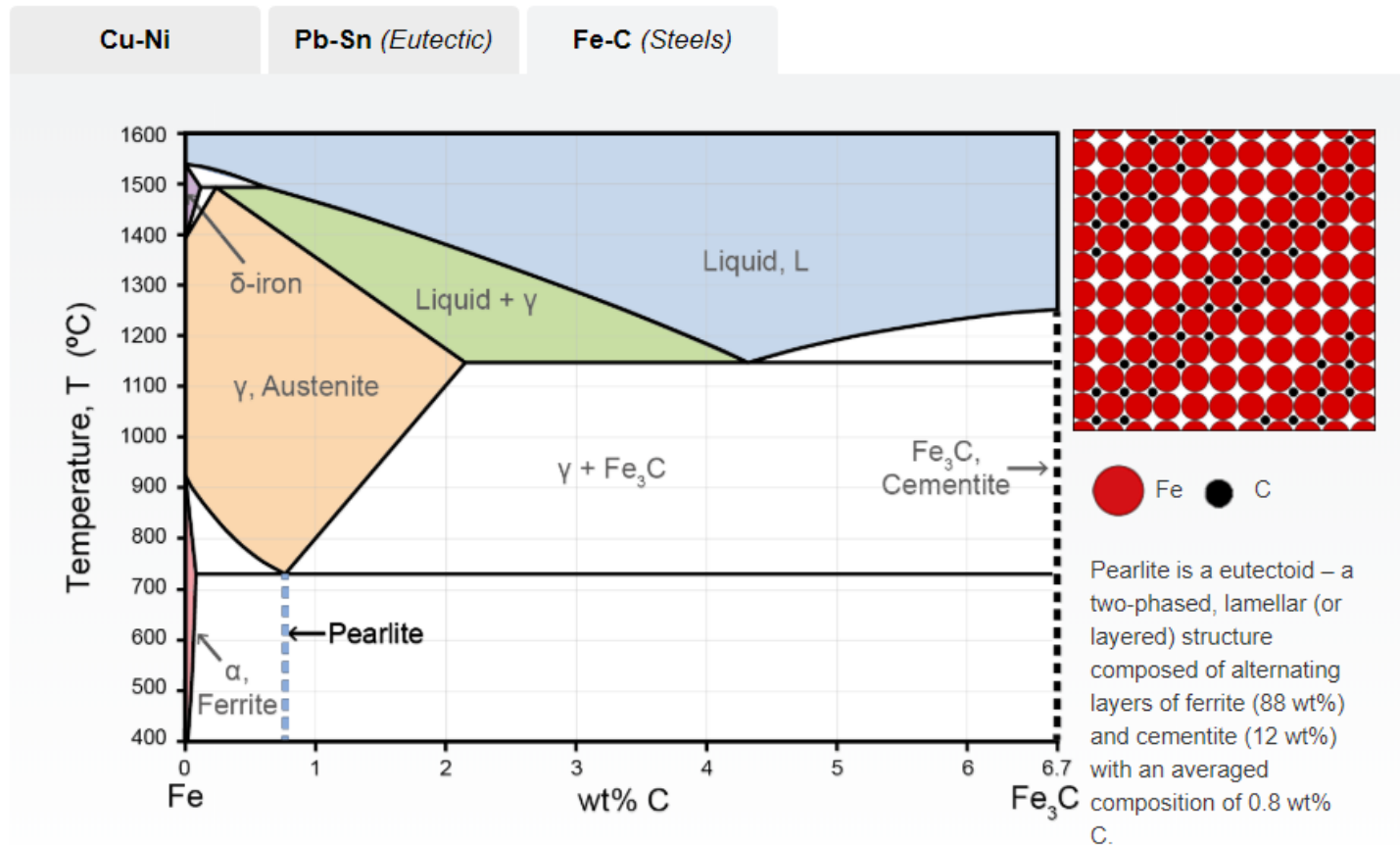
Reaction:



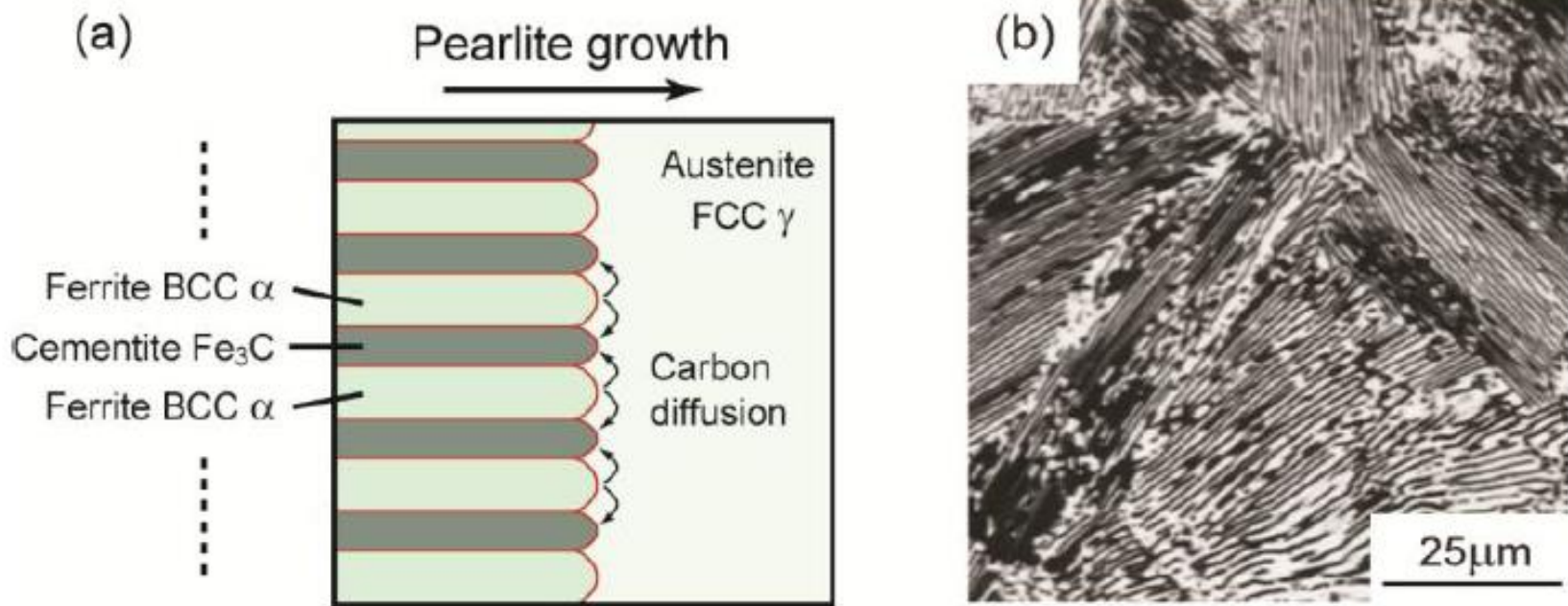
Reaction visual within a phase diagram



EduPack MS&E: Phases

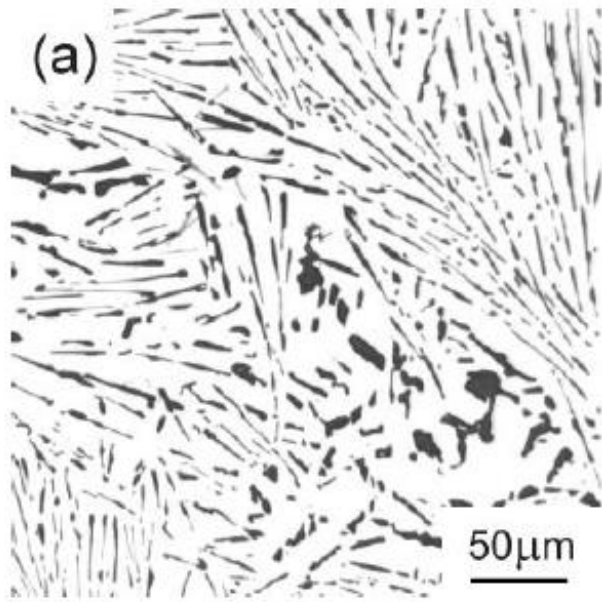


Phase transformations and microstructure



- (a) Schematic illustration of the eutectoid transformation from austenite to pearlite;
- (b) micrograph of pearlite. (Image courtesy of ASM Micrograph Center, ASM International)

Eutectics are not always lamellar



The proportions of the phases in a eutectic can vary widely, depending on the position of the “V” along the eutectic tie-line. If the eutectic point is towards the middle of the tie-line, the proportions of the two phases are roughly equal, and neither can be thought of as a matrix containing the other phase. However, if the V is located towards one end of the tie-line, then one phase forms a matrix containing the second phase as isolated particles. This is the case in eutectic Al-Si alloy here

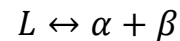
(Images courtesy of ASM Micrograph Center, ASM International)

Phase Transformations

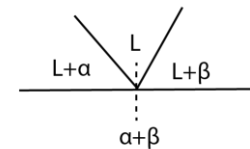
Eutectic transformation:

the composition and temperature at which two liquidus lines meet. The liquid transforms to two intermixed solid phases

Reaction:



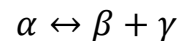
Reaction visual within a phase diagram



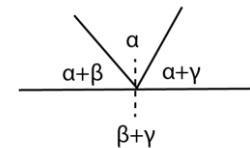
Eutectoid transformation:

one solid phase transforming isothermally and reversibly into two intermixed solid phases

Reaction:



Reaction visual within a phase diagram

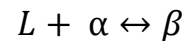


Phase Transformations

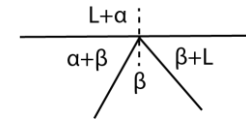
Peritectic transformation:

reaction where a solid and a liquid transform into a solid phase with a different composition

Reaction:



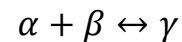
Reaction visual within a phase diagram



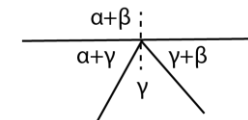
Peritectoid transformation:

reaction where two solid phases transform reversibly into a solid phase with a different composition

Reaction:



Reaction visual within a phase diagram

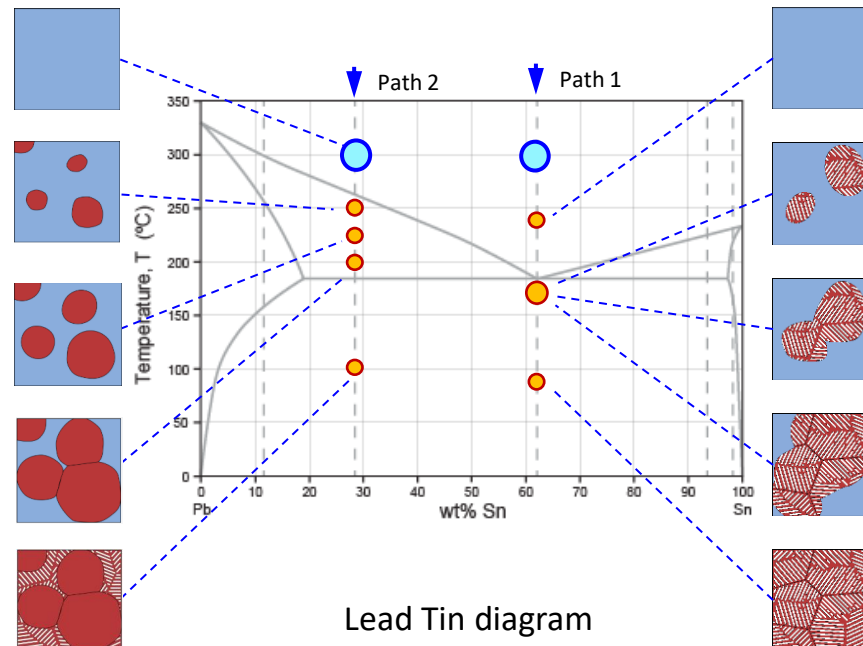


Key concepts in phase transformations (booklet)

- Phase transformations are driven by the resulting change in free energy, also known as the *driving force*;
- At the phase boundaries, the free energies of the states on either side of the boundary are equal – the driving force $\Delta G = 0$;
- Phase changes almost always involve diffusion as the kinetic mechanism by which atomic rearrangement occurs;
- Phase transformations occur via a two-stage process of *nucleation* and *growth*, in which nucleation may be spontaneous (homogeneous), or take place on some kind of interface (heterogeneous);
- *TTT diagrams* capture the extent of an isothermal transformation as a function of hold temperature and time, giving characteristic C-curves for diffusion-controlled phase transformations;
- In continuous cooling, there is a *critical cooling rate* which will just avoid the onset of the diffusional transformations.

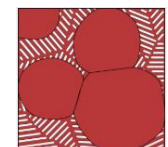
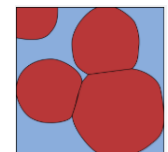
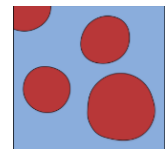
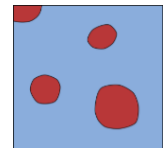
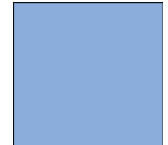
Microstructure Evolution

- As alloys solidify, their microstructure will evolve based on the composition
- Phase diagrams can help give insight as to what microstructure will form

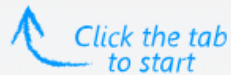


Reminder from EduPack

- Phase fractions
- Composition



Lever rule



This is a simple binary (A-B) phase diagram.
The composition of the cooling path is **51 wt% A, 49.0 wt% B**.

1. Above the **Liquidus** line the alloy is fully liquid. It is a single-phase region with the starting composition C_0 . Solidification begins when the liquidus line is crossed.
2. Between the **Liquidus** and the **Solidus** lines, liquid and solid co-exist at equilibrium. The relative amounts of each are given by the **Lever rule**.
3. Below the **Solidus** line solidification is complete. It is a single-phase region with the (average) composition C_0 although the center of each grain (which solidified first) will be richer in B and the outside (the last to solidify) somewhat depleted – an effect called **coring**.

The Lever rule

In the two-phase region between the liquidus and the solidus, the compositions split into those at the ends of the tie line, C_S and C_L , with weight fractions W_S and W_L .

The fractions must sum to unity:

$$W_S + W_L = 1$$

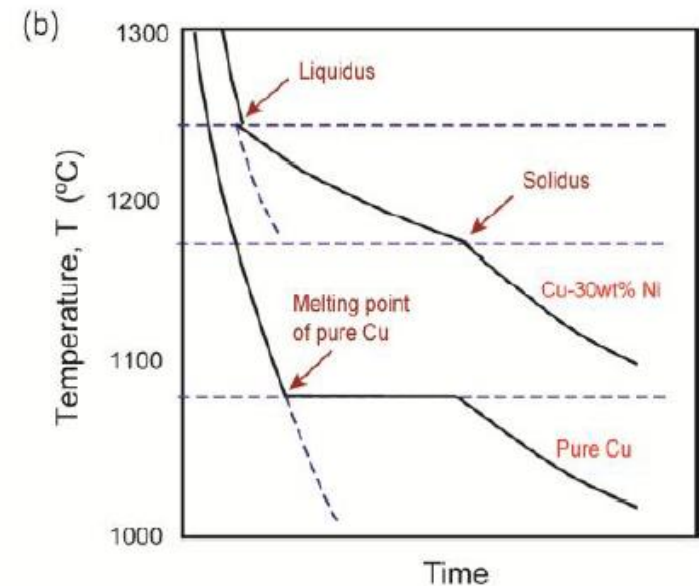
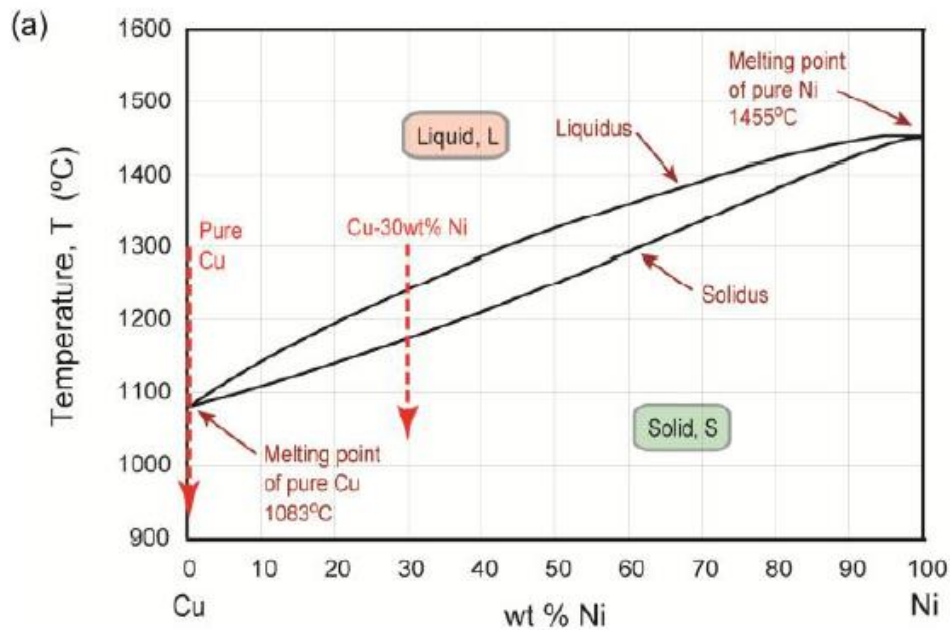
Conservation of matter requires that

$$W_S C_S + W_L C_L = C_0$$

Solving for W_L and W_S gives

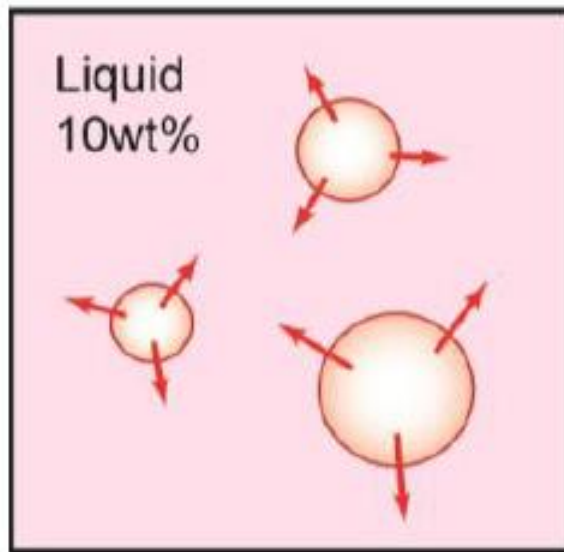
$$W_L = (C_0 - C_S) / (C_L - C_S) \text{ and } W_S = (C_L - C_0) / (C_L - C_S)$$

Phase transformations in binary isomorphous alloys

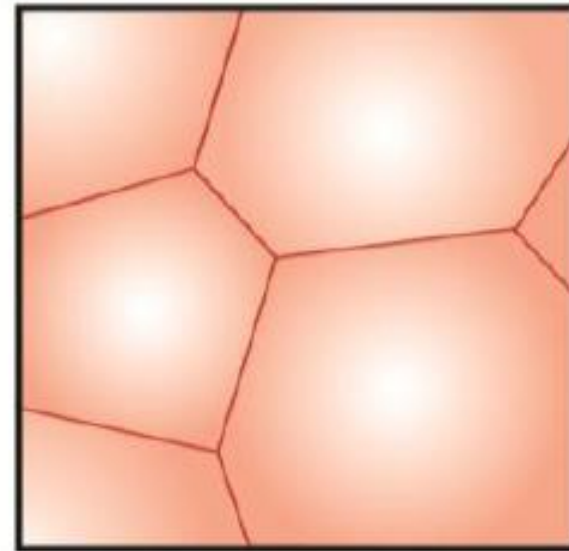


Segregation in solidification of binary alloys

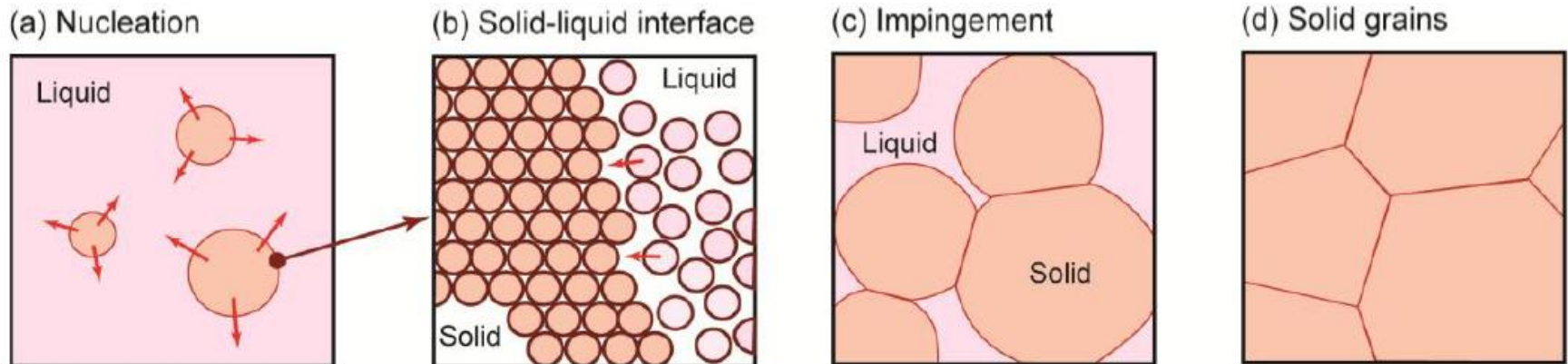
First solid (Pb), 5wt%



Solute gradient
across grains of (Pb)



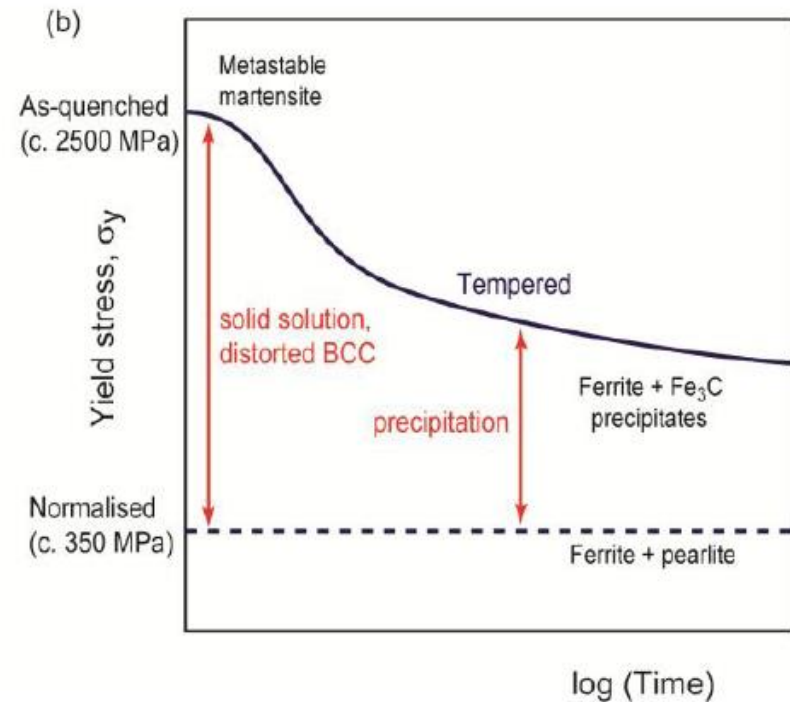
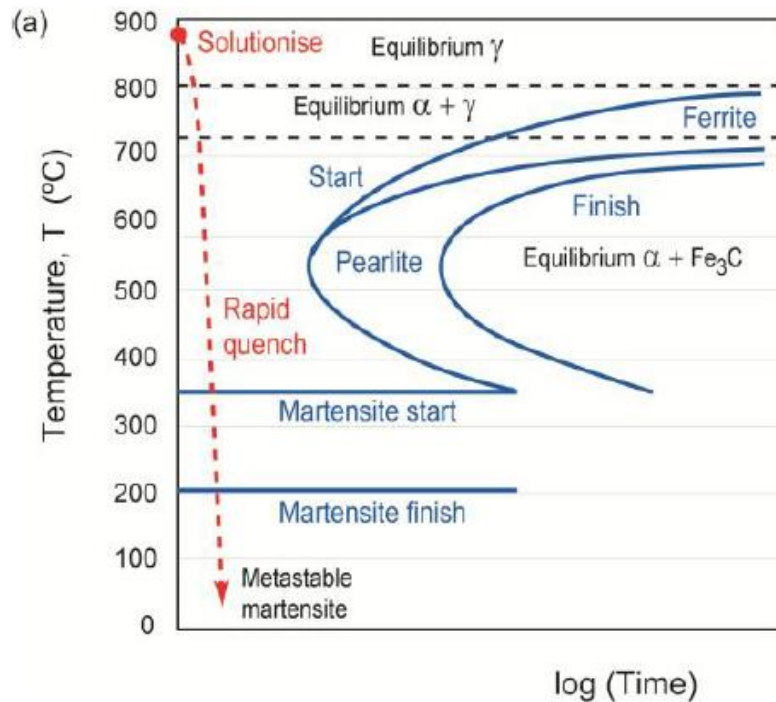
Homogeneous nucleation process and growth



- There can also be *Heterogeneous* nucleation and growth from a pre-existing surface
- Grains form due to differences in orientation at impingement.

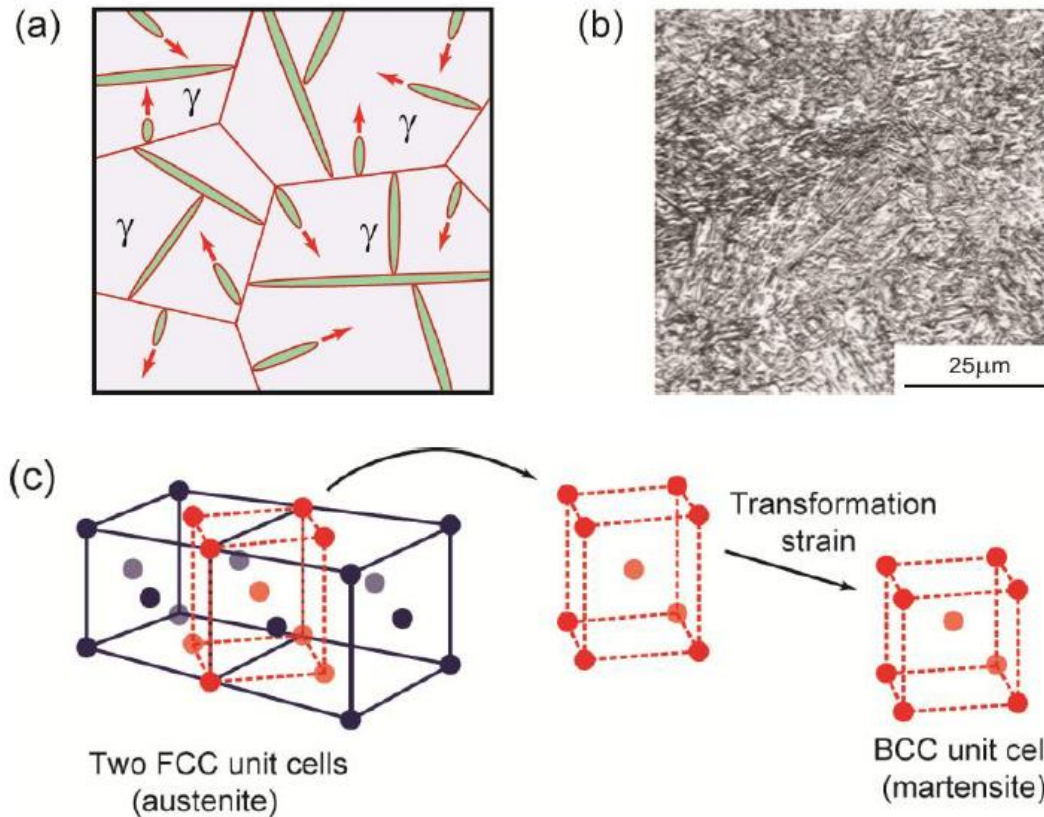
Non-equilibrium solid-state phase changes

Martensite start and finish on a TTT diagram

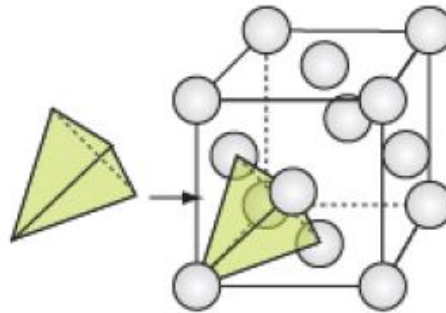


Evolution of yield stress during tempering of carbon steels after quenching

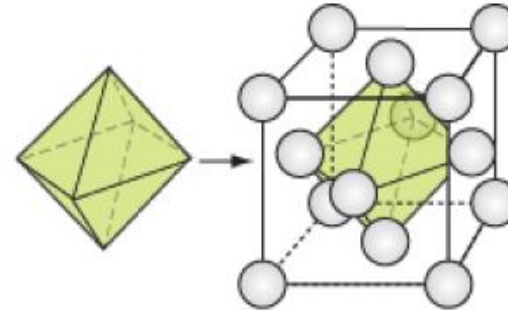
Martensite transformation



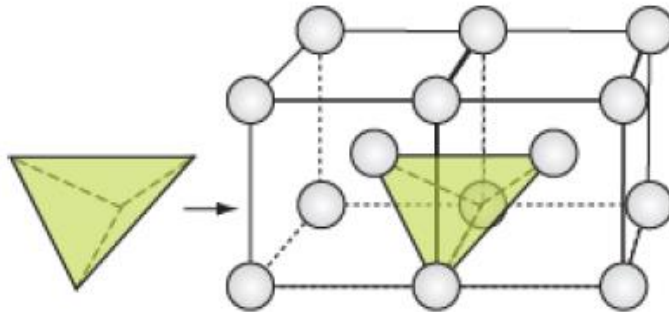
The importance of Interstitial holes...



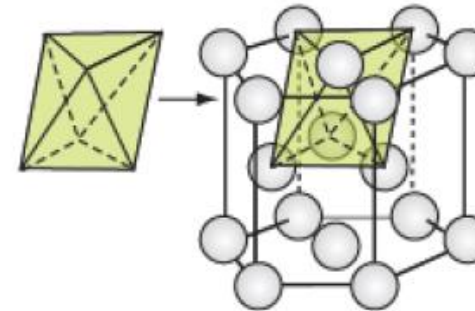
(a) FCC tetrahedral hole



(b) FCC octahedral hole



(c) BCC tetrahedral hole



(d) HCP octahedral hole

Quiz question

2. Which statement is true about unit cells and interstitial holes, relevant for impurity defects?
- a) The tetrahedral holes in BCC and FCC have the same size
 - b) The octahedral hole of FCC is larger than the tetrahedral hole of BCC
 - c) The octahedral hole of HCP is larger than the octahedral hole of FCC
 - d) Octahedral and tetrahedral holes all have the same size in BCC, FCC and HCP structures.

Any Questions ???