Materials: Alloys, Ceramics, Glasses and Composites

PRRE1003
Resources, Processes & Materials Engineering

LECTURE Materials M2

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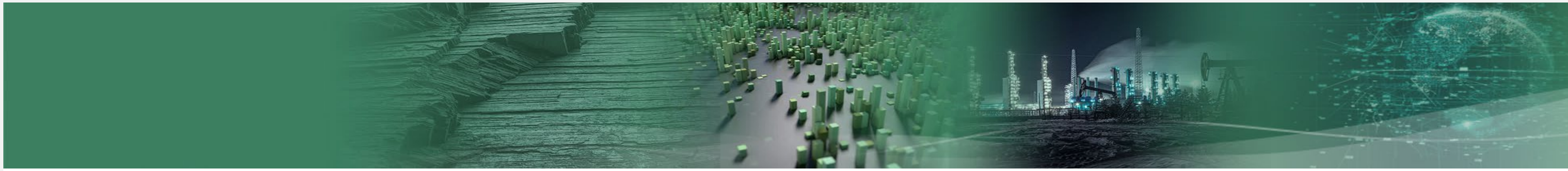

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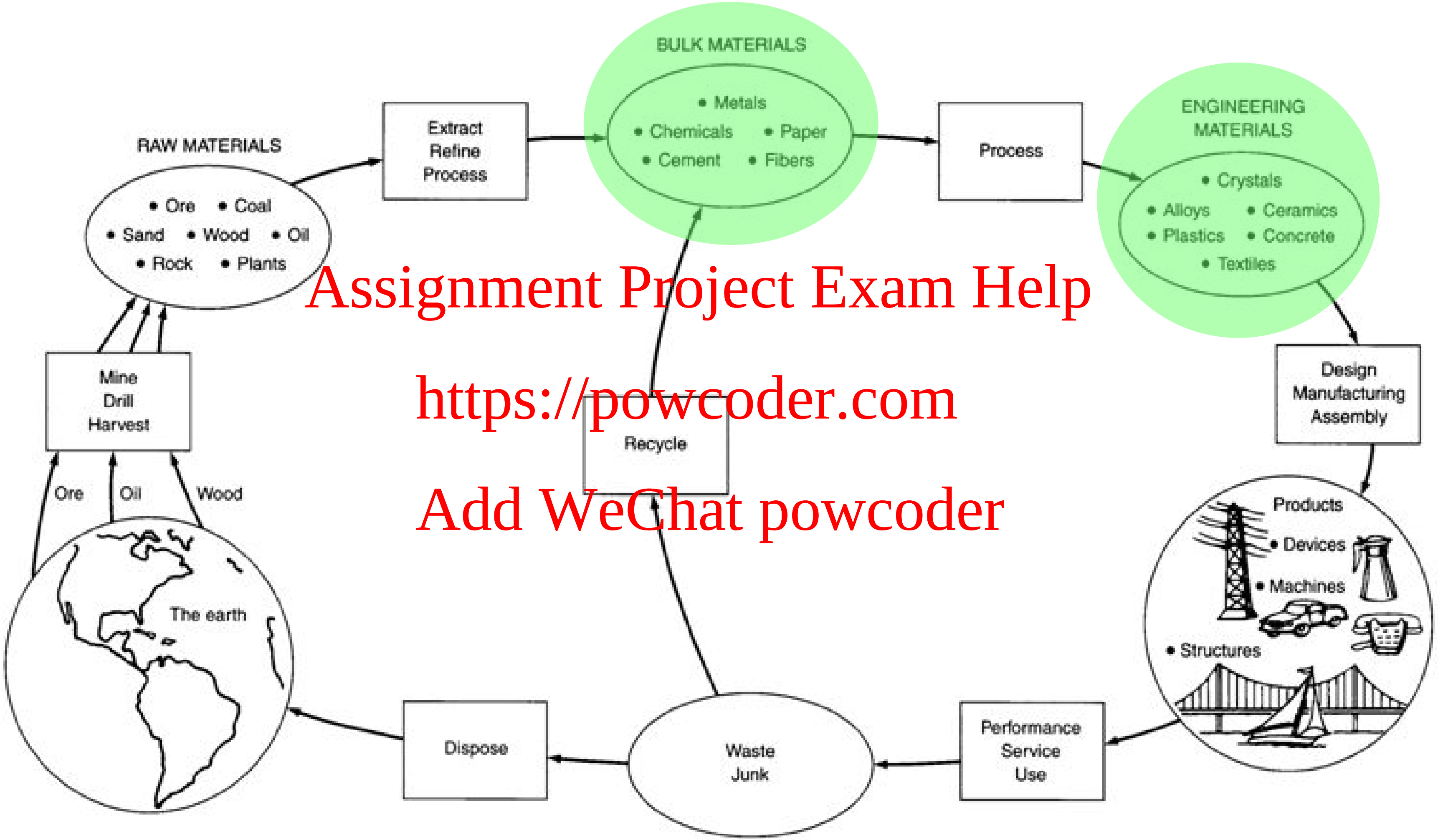
Lecture focus



Reproduced from "Materials and Man's Needs", National Academy of Sciences, Washington D.C., 1974.

Lecture Outline

- Alloy development and Phase Equilibrium Diagrams
  - Phase equilibrium diagrams
  - Heat treatments and case studies – steel and aluminium alloys in the transport and aerospace industries

- Non-Metals
  - Polymers – types and properties
  - Ceramics and Glasses - types properties, limitations, Weibull statistics
  - Strengthening and toughening
  - Composites – Law of Mixtures, design of properties
  - Examples and case studies - GFRP, CFRP, concrete

Alloy Systems

Definition: a metallic alloy is a mixture of a metal with other metals or non- metals.

Alloy System – that which describes all possible permutations of alloys, phases, compositions and temperatures for mixtures of two or more elements.

- usually represented by a phase equilibrium diagram.

Alloy components – the chemical elements that make up the alloy. Number of components described by type of alloy or alloy system, for instance, binary alloy – 2 components, ternary alloy – 3 components

- taking only 45 of the most common metals, any combination of two give 890 binary systems.
- since many commercial alloy systems contain many elements, engineers have very many systems available to them.

Alloy Development and Phase Equilibrium Diagrams (Ashby GL2 1-27)

Phase Equilibrium Diagrams

Alloy composition (concentration) – an alloy's composition is described by presenting the concentration of each component in weight% (or atomic%)

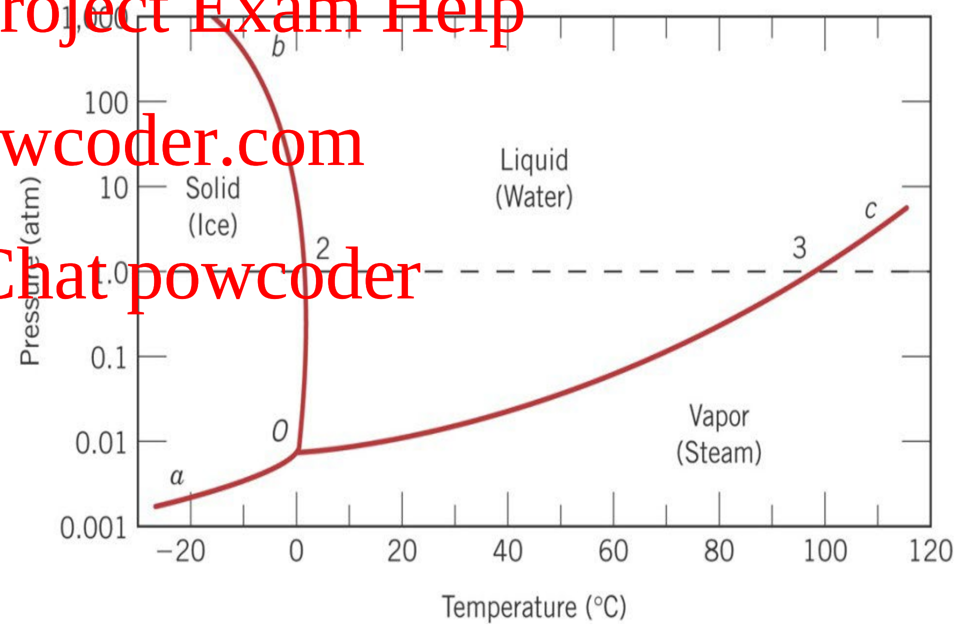
Alloy Constitution – described by:

- Phases present
- Weight fraction of each phase
- Composition of each phase

Phase is a portion/region of material that has **uniform physical and chemical characteristics**

e.g.,

- water, brine, ice
- pure iron, pure copper
- solid solution of Zn in Cu
- solid solution of C in Fe



Phase Equilibrium Diagrams

- The various alloy systems are graphically represented by diagrams know as equilibrium or phase diagrams.

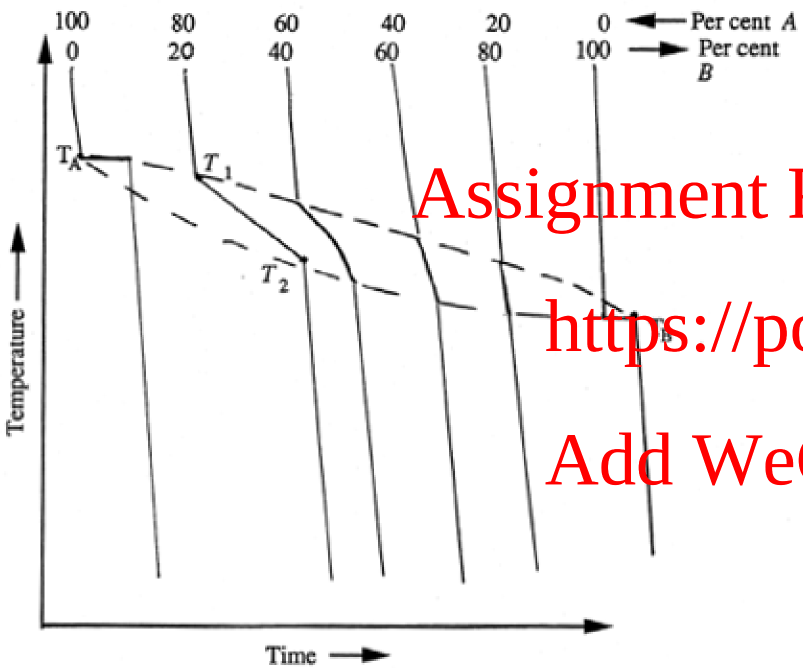
- Basically, the diagrams are cooling curves derived under equilibrium conditions, i.e., under extremely slow heating and cooling conditions.

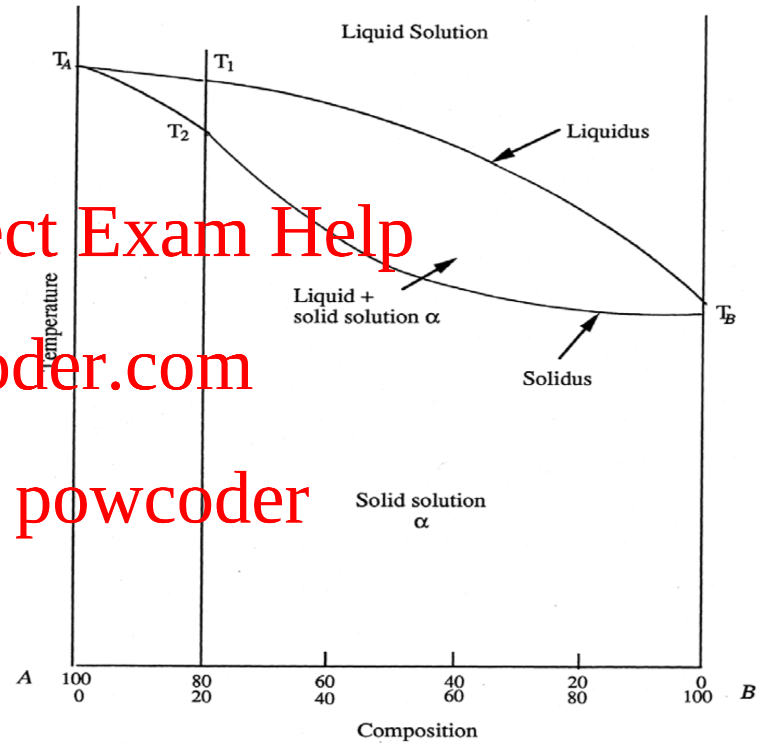
- The diagram also indicates the solubility of elements in each other and structure of phase changes, which occur for various alloy compositions

- *The information gained by the understanding of these diagrams is therefore essential for materials engineers, particularly when considering heat treatment and structural aspects of alloys*

Alloy Development and Phase Equilibrium Diagrams

Complete solid solubility

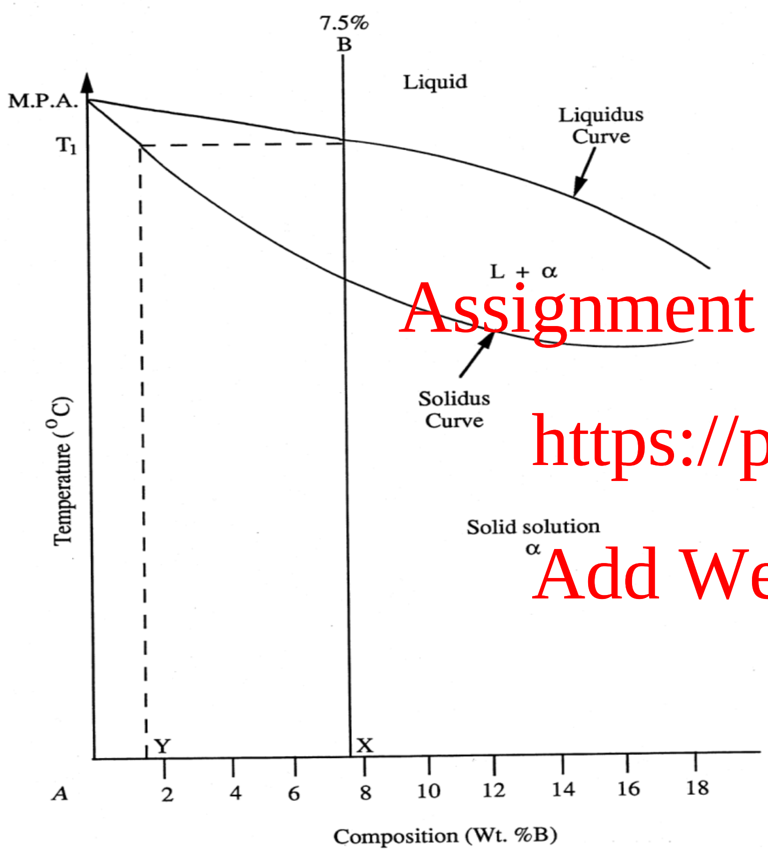


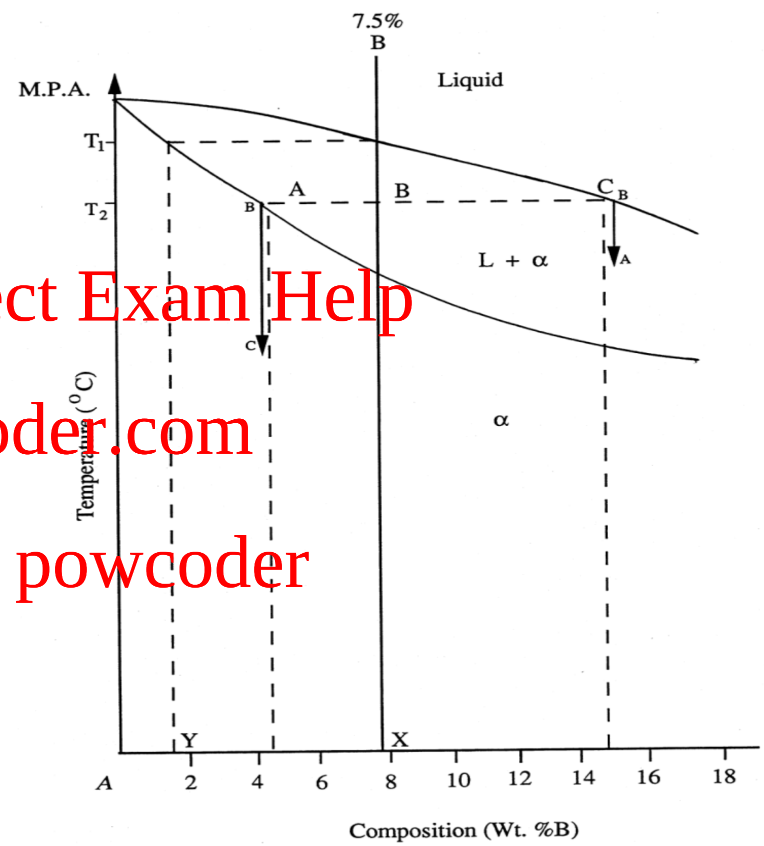


A **substitutional solid solution** is the only phase formed with this system. The cooling curves and the equilibrium diagram are shown in the figures above. The letters A and B represent the pure metals.

Between the liquidus and solidus lines there exists a two-phase region. Any alloy in this region will consist of a mixture of A and B in liquid form and a solid solution.

Alloy Development and Phase Equilibrium Diagrams





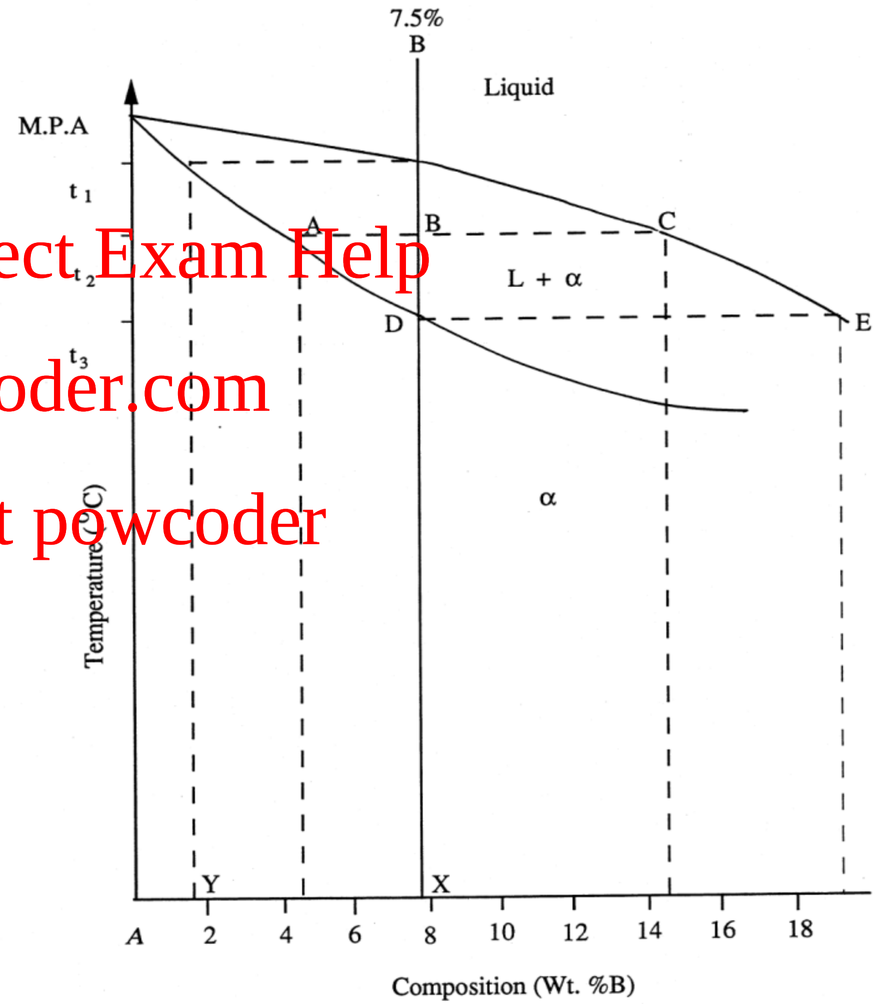
By understanding the concepts of alloy phase equilibrium diagrams and being able to read and extract data, important information about the specific alloys can be obtained.

For example, the alloy constitution in terms of phase compositions and proportions can be determined, and these have a direct influence on the properties of the alloy.

Alloy Development and Phase Equilibrium Diagrams

For Alloy 7.5% B

To determine the relative amounts of the two phases in equilibrium at a specific temperature requires a vertical line to be drawn on the diagram at the particular composition. This is shown in the figure opposite.



At temperature t_2

Two phases present – solid α and Liquid

Solid α Composition 4.5% B

Liquid Composition 14.5% B

Proportion of Solid α BC/AC=(14.5-7.5)/(14.5-4.5)= 70%

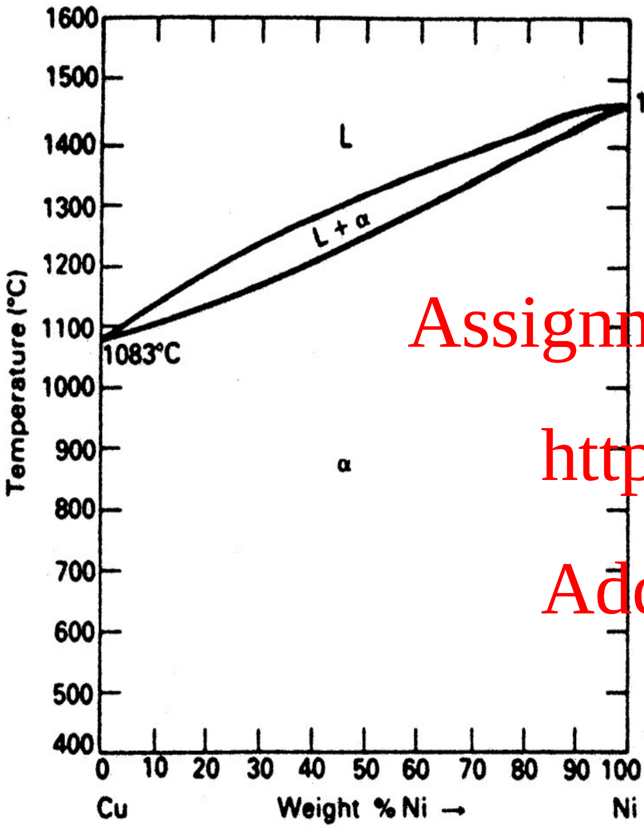
Proportion of Liquid AB/AC= 30%

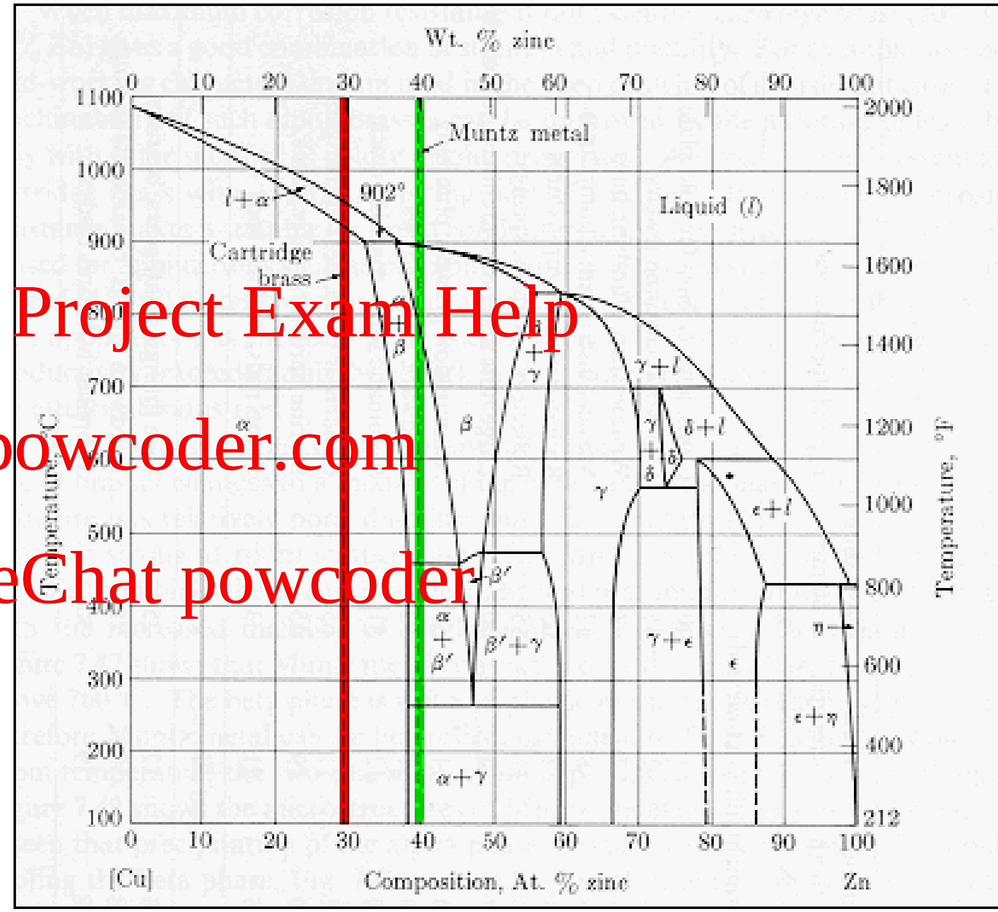
Learning Outcome Check 1

- What does a Phase Equilibrium Diagram represent?
- What are the parameters on the axes of the diagram?
- What is
  - *an alloy component?*
  - *an alloy system?*
  - *a phase?*

- When describing an alloy system, what might be the constituents of the alloy?
- What is the Lever Law?

Simple to Complex Phase Equilibrium Diagrams

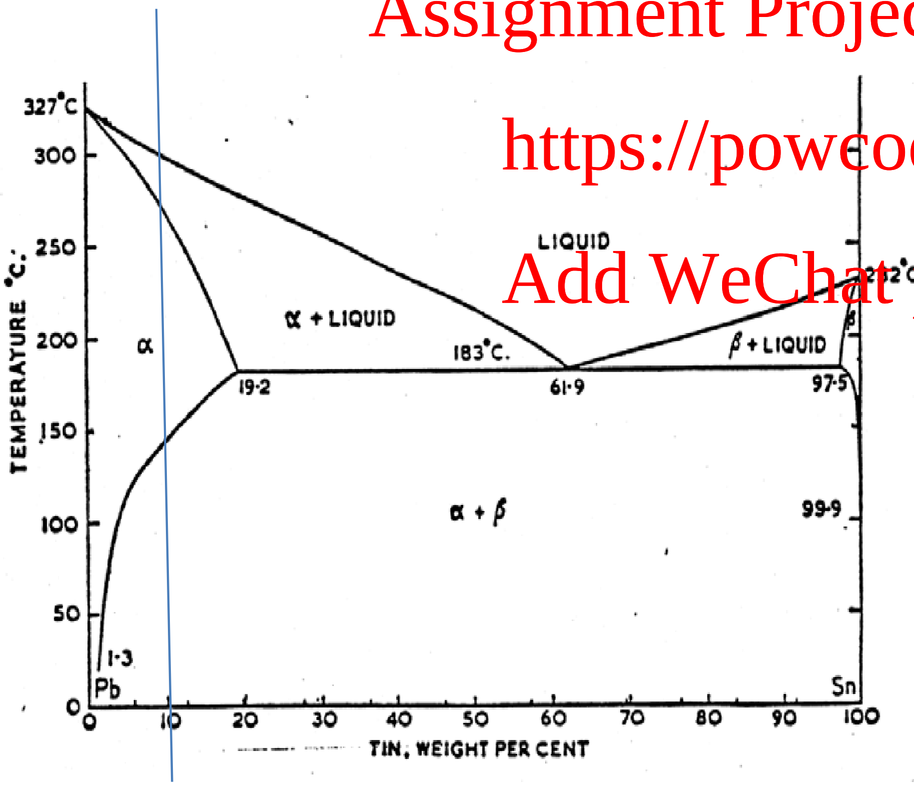




Partial solubilities and Multi-Phase Alloys

This is the Lead-Tin alloy system – *Solder*.

A heat treatment process known as ***age hardening*** or ***precipitation hardening*** can be applicable which will provide a strengthening effect.



PB-SN ALLOY SYSTEM

FOR ALLOY 90 /10 (Pb/Sn).

~300°C – STARTS TO SOLIDIFY

~260°C – ALL SOLID α (CORED)

~183°C – ALL SOLID α (REDUCED CORING - DIFFUSION)

MAX SOLID SOLUBILITY 19.2. SOLUTION NOT SATURATED.

~150°C – ALL SOLID α - AT MAX S. SOLUBILITY FOR TEMP AND COMP. (10% Sn)

~100°C – CONSTITUTION NOW α + β MUCH MORE α THAN β.

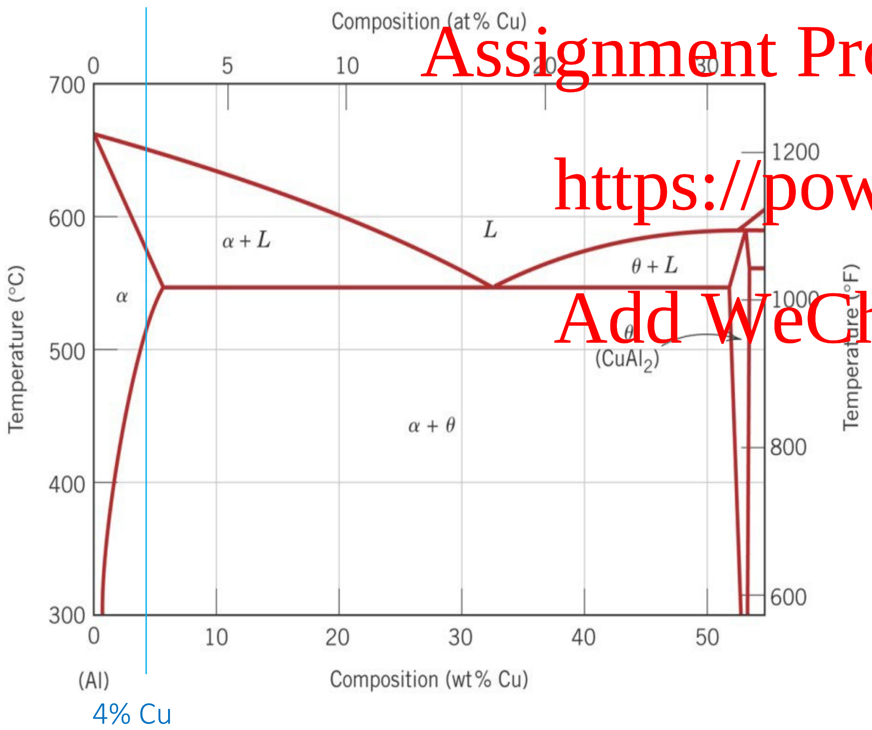
~0°C – α + β   α COMP 1.3% Sn 98.7 Pb; β COMP ~100% Sn.

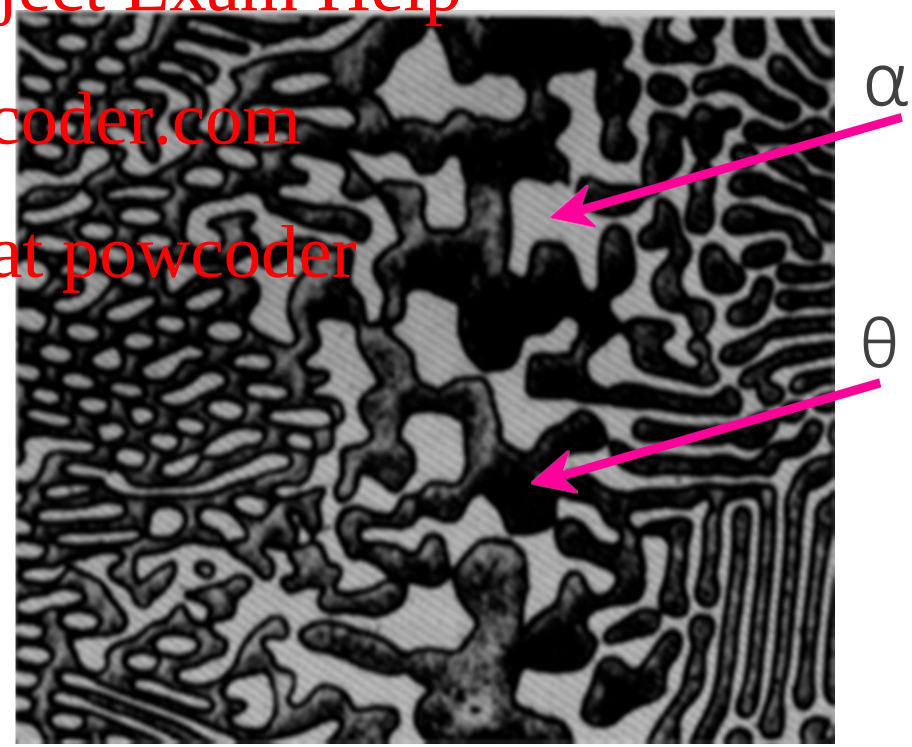
PROP α = $\frac{100-10}{100-1.3} = \frac{90}{98.7} = 91.1\%$

PROP β = $\frac{10-1.3}{100-1.3} = 9.9\%$

Partial Solubilities and Multi-Phase Alloys

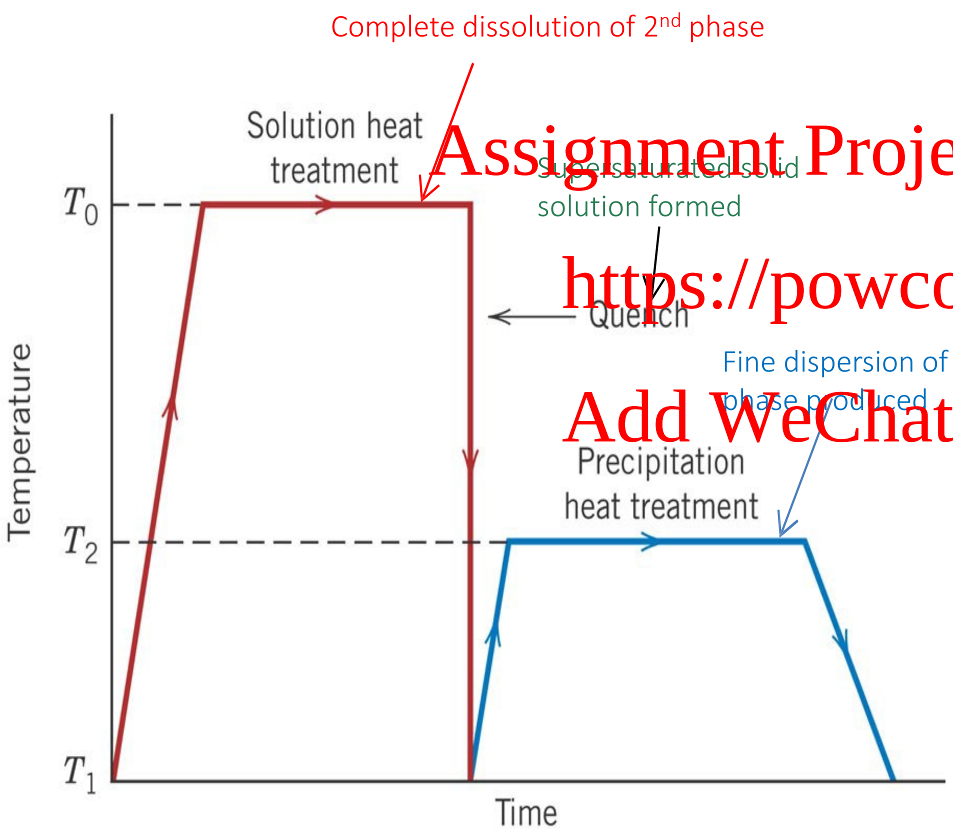
Using phase equilibrium diagrams to develop improved properties by heat treatments
This is from the Ai-Cu alloy system, commonly used in aircraft manufacture

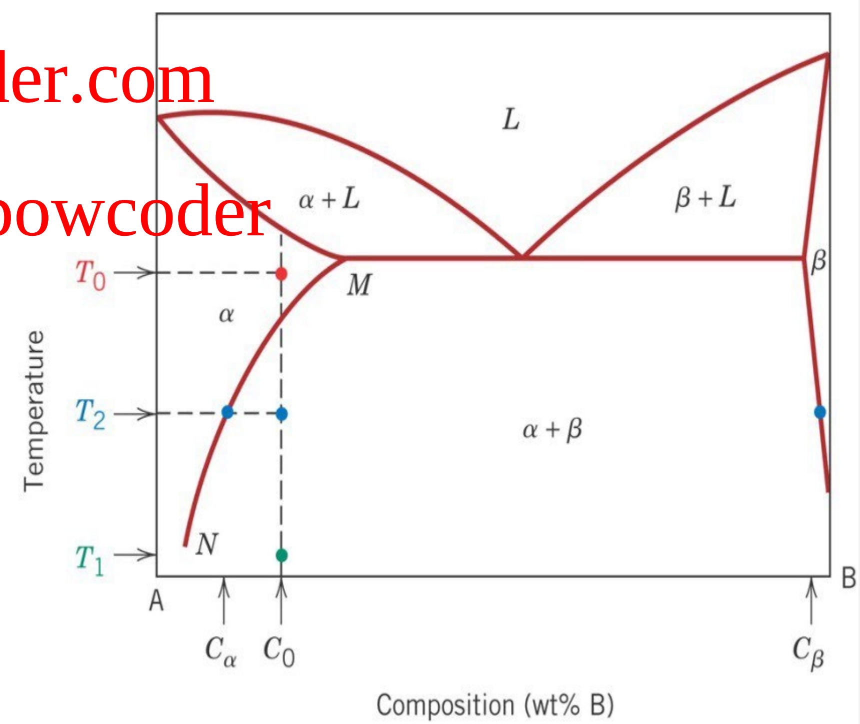




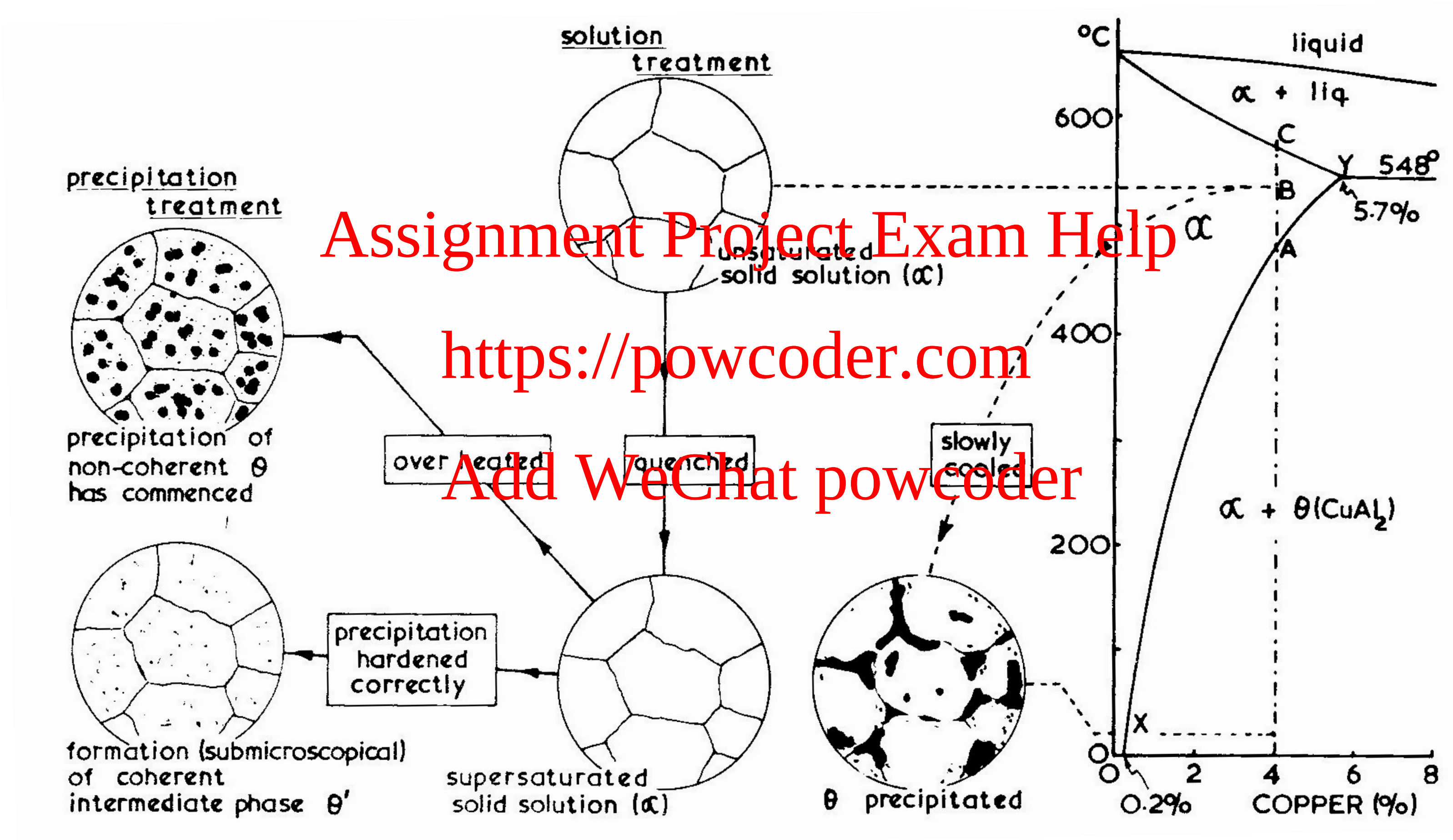
Typical two phase microstructure

Precipitation or Age Hardening Heat Treatment





Case Study – Precipitation Hardening in Aircraft Alloys



Schematic representation of the precipitation hardening process and stages
(after Higgins: Engineering Metallurgy)

Case Study – Precipitation Hardening in Aircraft Alloys

As it turns out, Cu in aluminum do not simply precipitate out according to the phase diagram, but rather it forms metastable precipitate phase, before finally forming the equilibrium phase, such as Al_2Cu. For Al-Cu, the first phase to form is a fully coherent precipitate called a GP (Guinier Preston) zone. This is followed by intermediate θ" and θ' phases before the stable θ (Al_2Cu) phase forms. As these reactions occur, the hardness changes, at first increasing as the precipitates nucleate and grow (or age), and changing from coherent to incoherent phases. Eventually the strength decreases as the incoherent precipitates grow in size but decrease in number (i.e., overaged), see Fig. 3.

Make the aircraft components from this condition alloy

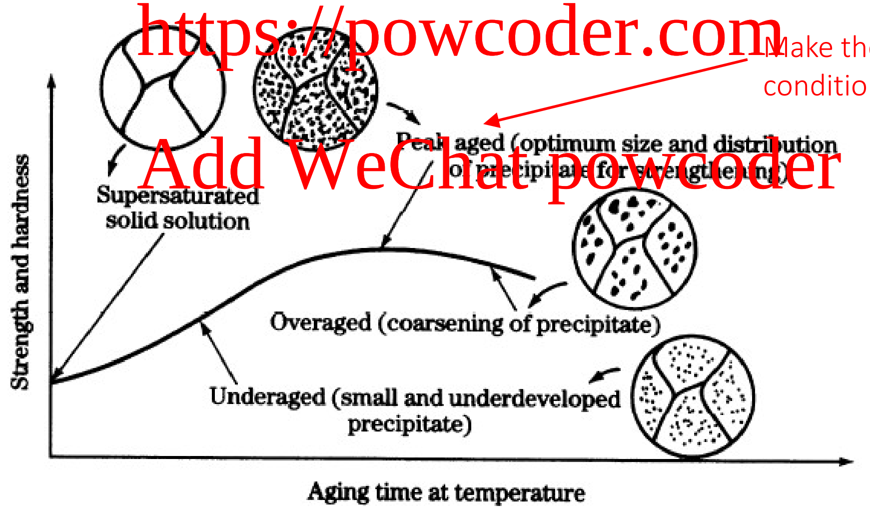


Figure 3. Microstructural development with aging time [1].

Learning Outcome Check 2

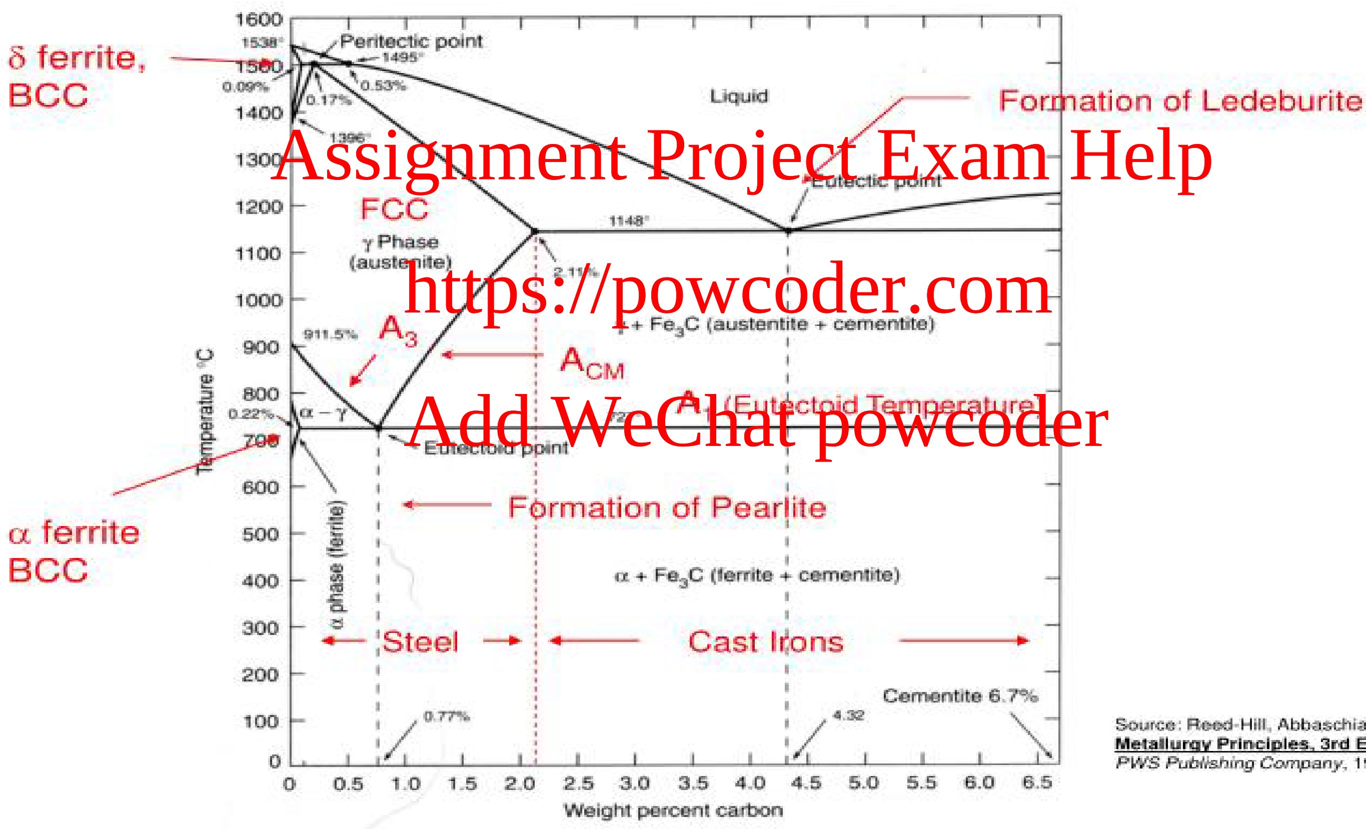
- What is complete solid solubility?
- What is partial solid solubility?

- What is a dual-phase (duplex) alloy?

- Why might a duplex alloy be stronger than a single phase alloy?

- What process is used to create precipitation hardening?

Iron Carbon Phase Diagram



Source: Reed-Hill, Abbaschian, **Physical Metallurgy Principles, 3rd Edition**, *PWS Publishing Company*, 1994.

Case Study – Heat Treatment of Steels

Iron – Carbon phase diagram

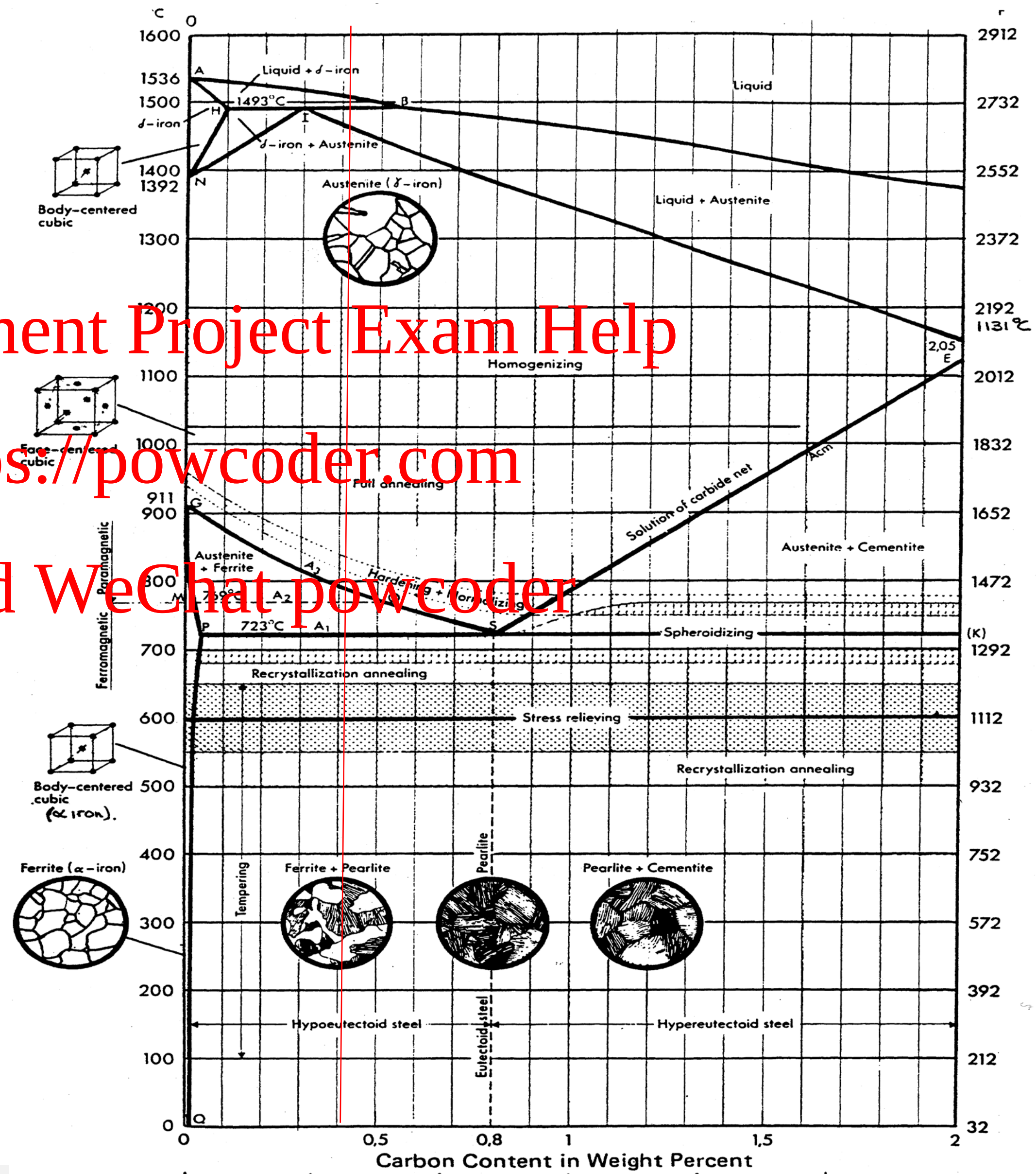
The Steel part

α-ferrite – solid solution of C in BCC Fe
Stable form of iron at room temperature.
The maximum solubility of C is 0.022 wt%
Transforms to FCC γ-austenite at 912 °C

γ-austenite – solid solution of C in FCC Fe
The maximum solubility of C is 2.14 wt %.
Transforms to BCC δ-ferrite at 1394°C
Is not stable below the eutectic temperature
(723 °C) unless stabilized with alloying additions

δ-ferrite - solid solution of C in BCC Fe
The same structure as α-ferrite
Stable only at high T, above 1394 °C
Melts at 1538 °C

cementite (iron carbide or Fe3C)
An intermetallic compound
of iron and carbon with the chemical
formula Fe_3C. C content is around 6.67%.
It is metastable, it remains as a compound
indefinitely at room T, but decomposes
(very slowly, within several years)
into α-Fe and C (graphite) at 650 - 700 °C.
It is hard and brittle



Five basic heat treatments for steel

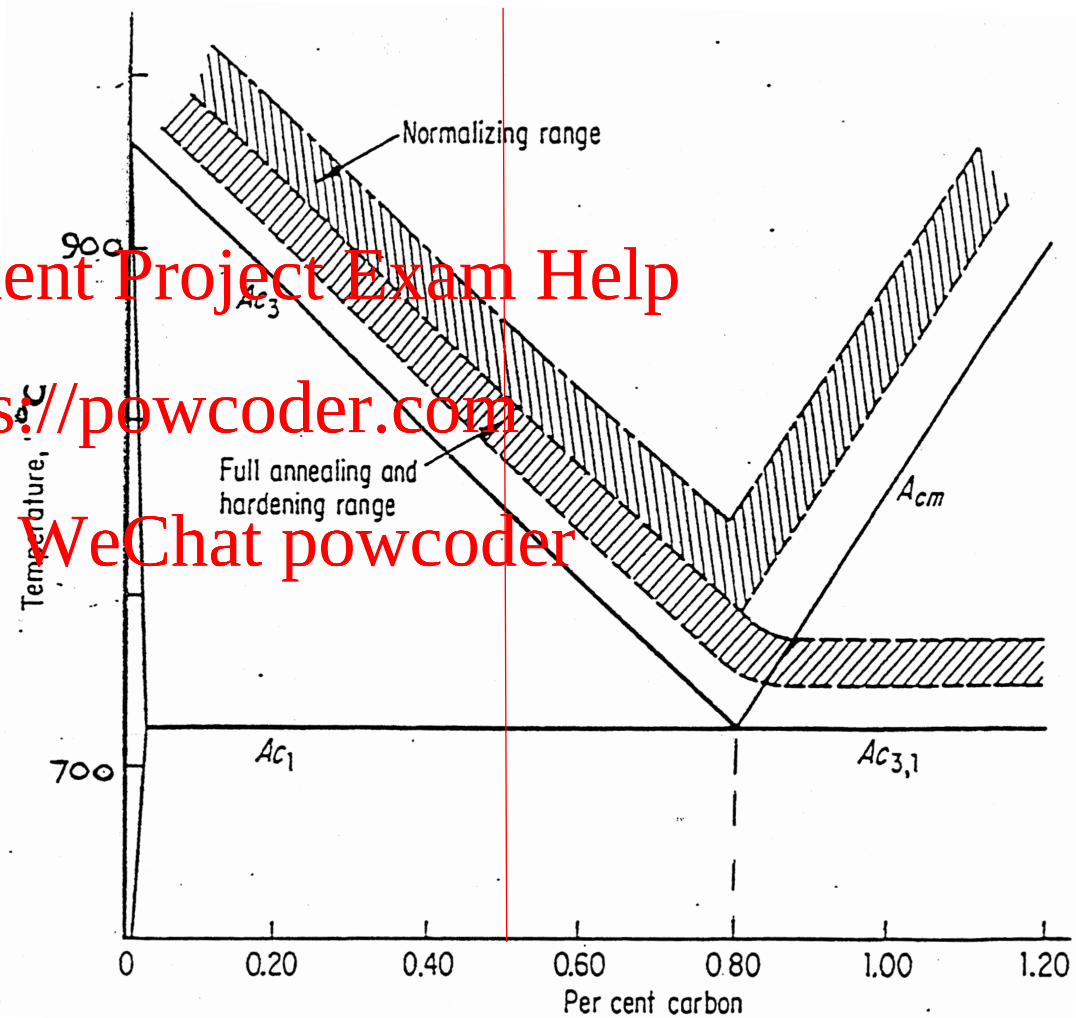
Full Annealing
Heat to the austenitic range (~900°C) and allow a very slow cooling rate

Process Annealing
Heat to below the austenitic range (~650°C) and allow a very slow cooling rate

Normalising
Heat to the austenitic range (~900°C) and allow an intermediate cooling rate (cool in air)

Hardening
Heat to the austenitic range (~900°C) and allow a rapid cooling rate (quench in water)
Forming very hard metastable phase - Martensite

Tempering
After the hardening treatment above, re-heat to between discrete temperature between 250° - 600°C for controlled period of time

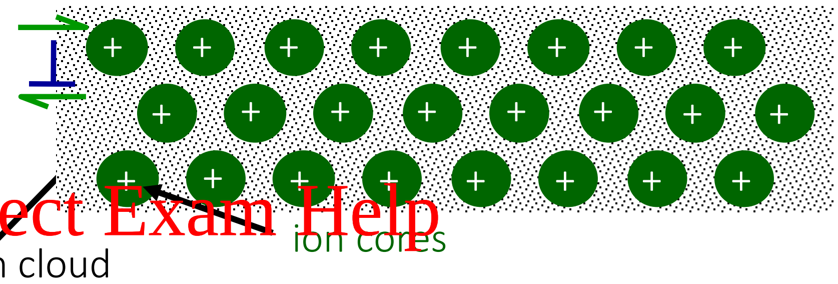


Learning Outcome Check 3

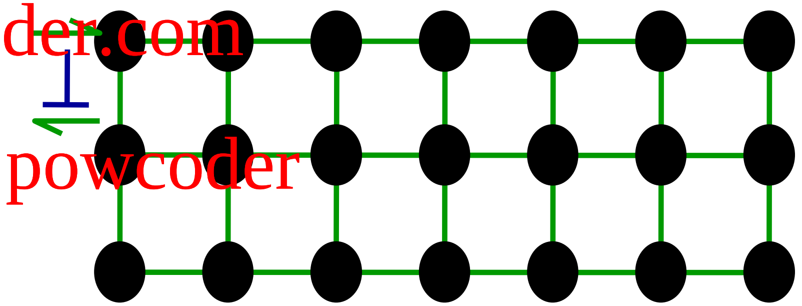
- Iron is an allotropic element. What does this mean?
- What is the difference between ferrite and austenite?
- What is
  - *a eutectic?*
  - *a eutectoid?*
  - *the eutectoid phase in the iron-carbon system called?*
- Describe the basic heat treatment required to create martensite.

Review of bond types

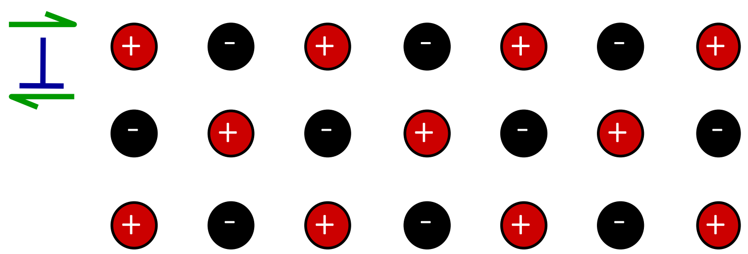
- Metals (Cu, Al):
  Dislocation motion easiest
  - non-directional bonding
  - close-packed directions
    for slip



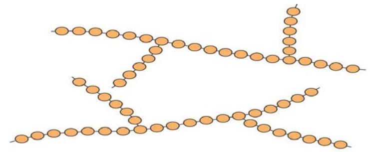
- Covalent Ceramics
  (Si, diamond): Motion difficult
  - directional (angular) bonding



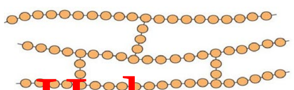
- Ionic Ceramics (NaCl):
  Motion difficult
  - need to avoid nearest
    neighbours of like sign (- and +)

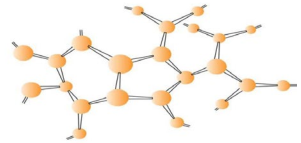


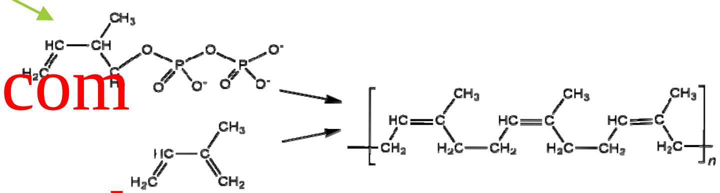
Polymers (Plastics)

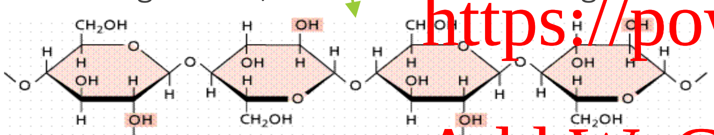


- Classification
  - Thermoplastic (Linear and non-crosslinked)
  - Thermosetting (‘Resins’) (crosslinked or networked)
  - Elastomers (Rubbers) (lightly crosslinked, coiled and amorphous)
  - Natural – e.g. starch/cellulose made of sugar molecules



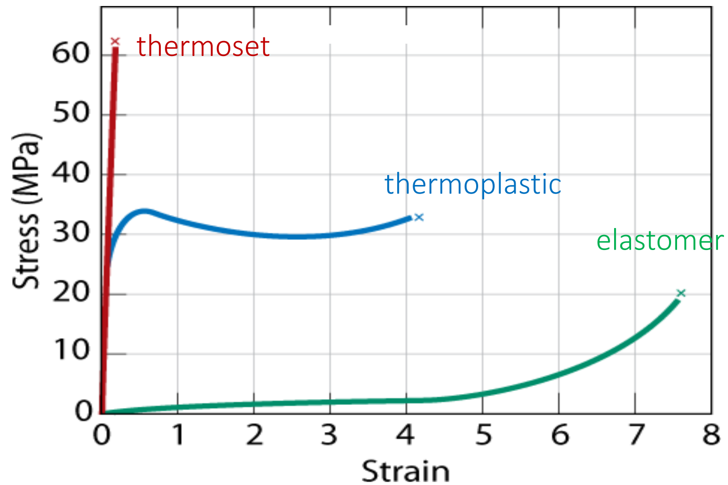






Mechanical properties

- Fracture strengths of polymers ~ 10% of those for metals
- Deformation strains for polymers > 1000%
- – for most metals, deformation strains < 10%
- Strain rate and temperature dependence
- Other environmental conditions:



Non Metals - Polymers

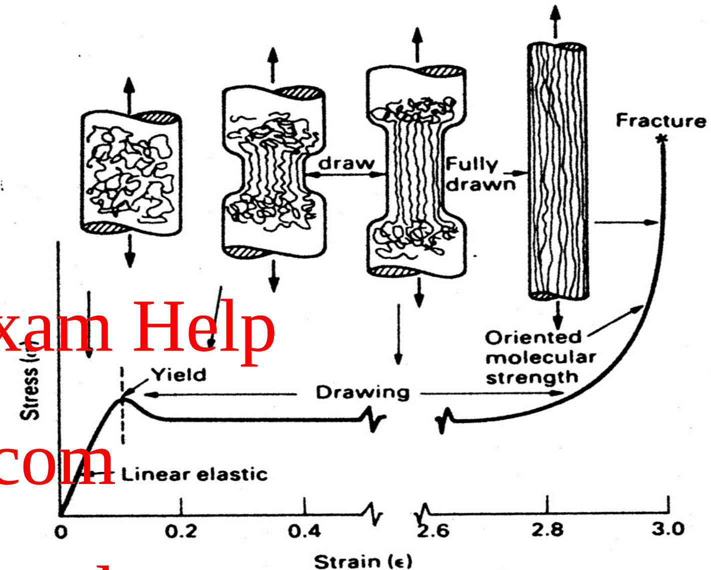
Factors affecting Mechanical Properties of Polymers

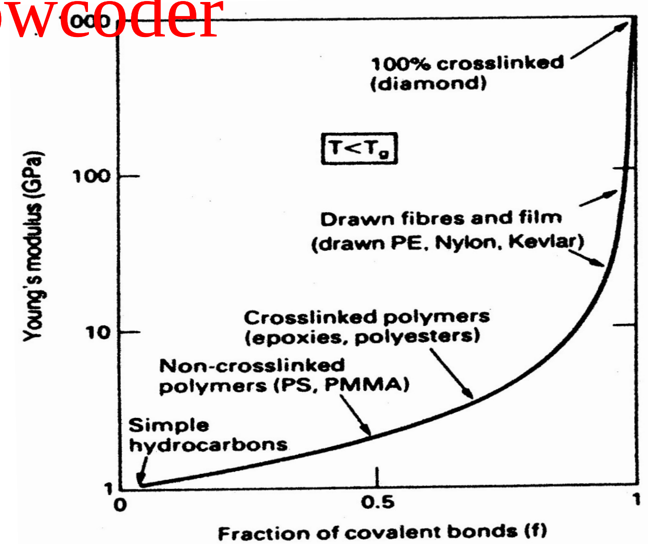
- Chemical compositions
- Molecular weight/length (degree of polymerisation)
- Structure
- Tacticity
- Polymer additives, such fillers, plasticisers…
- Temperature
- Strain rate
- Environments

Room-Temperature Mechanical Characteristics of Some of the More Common Polymers

Material	*Specific Gravity*	*Tensile Modulus [GPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Elongation at Break (%)*
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	13.8–15.2 (2.0–2.2)	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	25.0–69.0 (3.63–10.0)	1.2–2.5
Poly(methyl methacrylate)	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1 (400–600)	48.3–72.4 (7.0–10.5)	59.3 (8.6)	30–300
Polycarbonate	1.20	2.38 (345)	62.8–72.4 (9.1–10.5)	62.1 (9.0)	110–150

Source: *Modern Plastics Encyclopedia* '96. Copyright 1995, The McGraw-Hill Companies. Reprinted with permission.





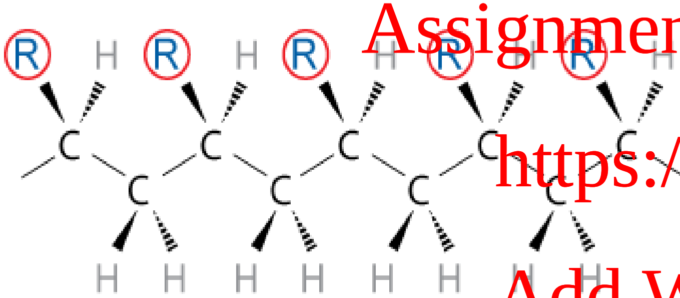
Callister Pg.314

Structure – Tacticity and Crystallinity

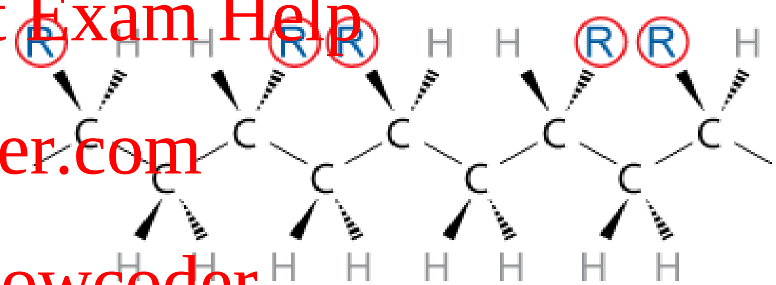
Stereoregularity or Spatial Arrangement of R Units Along Chain

Atactic – Random R group arrangement

Isotactic – all R groups on same side of chain



Syndiotactic – R groups on alternating sides



For same polymer, iso- and syndio-tactic are stronger than atactic – why? – **facilitates stacking, or crystallinity**

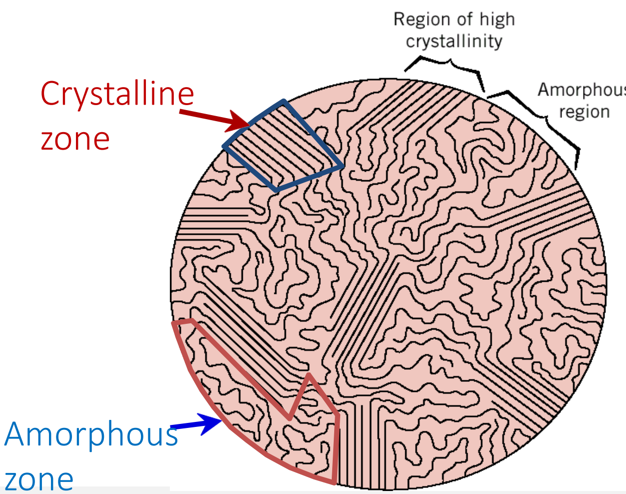
Crystallinity in Polymers

Increasing crystallinity in polymers can lead to improved strength, modulus, stiffness/brittle, lowering toughness.

Crystallinity in polymers is determined by the polymer structure; complexity and order

It can be induced by deformation or during manufacturing.

Liquid crystal polymers – crystal formation promoted in liquid state ("self-reinforced" plastics), **high strength at high**



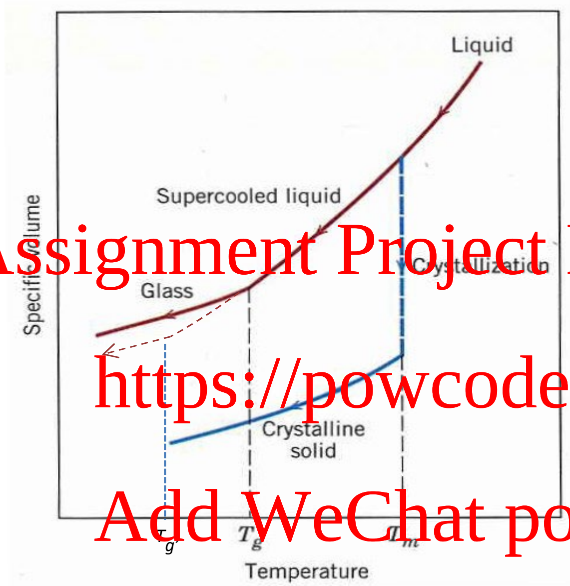
Temperature Effects

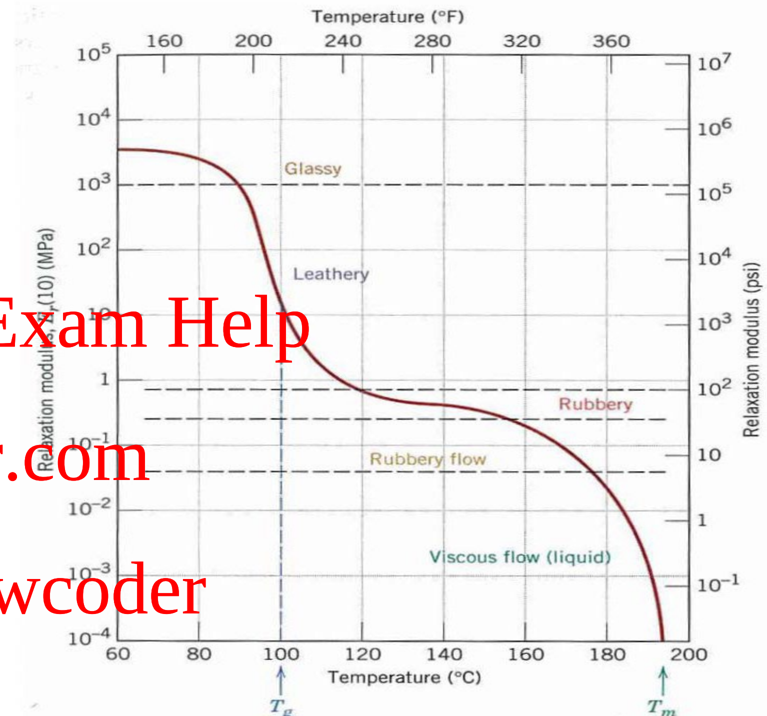
(Callister Pg. 462)

Melting temperature - T_m
Glass Transition Temperature – T_g

What factors affect T_m and T_g?
Both T_m and T_g increase with increasing chain stiffness
Chain stiffness increased by presence of
- Polar groups or side groups
- Bulky side groups
- Chain double bonds and aromatic chain groups

Regularity of repeat unit arrangements – affects T_m only





Modulus –Temperature Diagrams

Melting temperatures and approximate glass transition temperatures for several polymers	Polymer	T_g (°C)	T_m (°C)
	Polyethylene	−110	135
	Natural rubber	−70	28
	Polyvinyl chloride	80	180
	Polystyrene	100	230 (isotactic)

Temperature dependence of mechanical property is more "visible" due to low Tm/Tg of polymers compared to metals and ceramics, i.e., closer to ambient.
Temperature dependent modulus used to describe "engineering strength" (viability) at varying temperatures.
Descriptive terms on modulus diagrams
- glassy
- leathery (visco-elastic)
- rubbery (chain entanglements)
- viscous
- breakdown

Learning Outcome Check 4

- What is the difference between thermoplastics and thermosets?
- Describe *two* mechanisms by which a thermoplastic polymer can be made stronger.
- How can cross-linking be used to control the engineering properties of *elastomers*?
- What is the difference between glass transition temperature and melting temperature?

Non Metals - Ceramics and Glasses

Ceramics

Compounds of metallic and non-metallic elements, in which the **interatomic bonding** is **ionic (predominant) or covalent**. The atomic structure is **ordered or *crystalline.*** Ceramics encompass materials with highest hardness and melting point in nature – diamond.

Most are element combinations with metals, non-metals or metalloids

- **Ionic ceramics** : Typically compounds of metal **with** non- metal e.g., MgO, Al_2O_3, ZrO_2.
- **Covalent ceramics** : Typically compounds of metalloid **or** non-metals e.g. SiO_2, SiC

Glasses

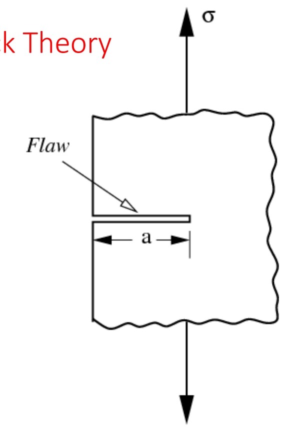
A combination of metallic and non-metallic elements, in which the interatomic bonding is **ionic or covalent**. The atomic structure is **random or *amorphous*** (usually silicate based).

Glass is a (inorganic*) product of fusion which has been cooled to a rigid condition without crystallising. Fused silica is SiO2 to which no impurities have been added
Other common glasses contain impurity ions such as Na^+, Ca^{2+}, Al^{3+}, and B^{3+}

(*Organic glasses do exist – e.g., Perspex (PMMA), polycarbonate.

Mechanical Properties

Griffith Crack Theory



High values of Young's Modulus

Diamond approximately 3 × Alumina and Alumina approximately 2 × steels

Low ductility, low or no tendency for plastic deformation due to the nature of the atomic bonding.

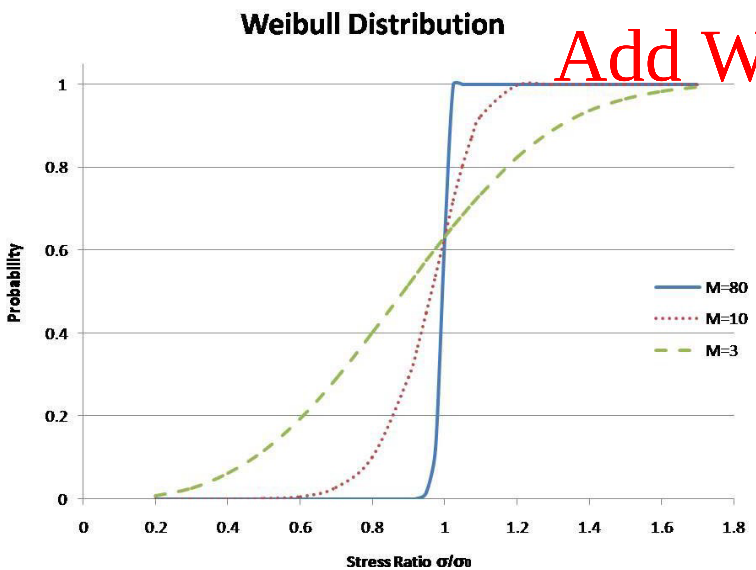
Brittle nature, related to the presence of flaws limits "engineering" strength.

The size and distribution of flaws significantly affect the strength of ceramics.

Flaws difficult to detect: **once fracture initiates it is catastrophic**.

The limitation is not on the average properties, but on the severity of the worst (i.e., largest) flaw.

Weibull Statistics (Ashby Pg. 214)



Material	σ_f (Nm^{-2})	Flaw Size (c/µm)
Al_2O_3 (crystalline)	7×10^8	0.8
Al_2O_3 (sintered), 5% porosity	2.8×10^8	5.0
SiC (sintered), 5% porosity	1.7×10^8	7.0
Silica Glass	1×10^8	6.5

Weibull Modulus (M)

M indicates how rapidly strength falls (confidence) approaching σ_0.

Low M – greater variability – low design strength.

High M – more stability, more confidence.

Vitreous ceramics: M ≈ 3-5

Engineering ceramics: M ≈ 10

Metals: M ≈ 100

Thermal Shock

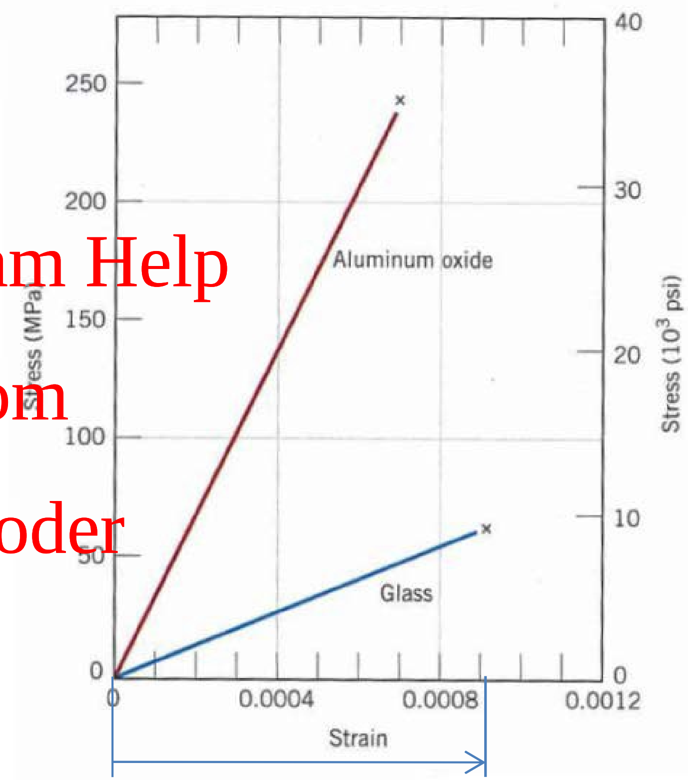
- When material passes through temperature range, fracture can occur.
- Due to stresses resulting from different shrinkage or expansion of surface layer and inner part on cooling or heating (poor conductivity).
- Parameters affecting thermal shock
  - ΔT (K)
  - Coefficient of thermal expansion [CoE] (α)

$\alpha(\Delta T)$ – strain in surface and S – elastic stress constant

$S\,\alpha\,(\Delta T) \geq \sigma_f$ -> fracture

For materials with lower α – better thermal shock resistance (TSR) – measured or expressed in °K

Material	CoE (µm/m°K)	TSR (K)
Diamond	1.2	1000
Soda Glass	8.5	80
Alumina	8.5	150
Sialon	3.2	500



How do we toughen these materials?

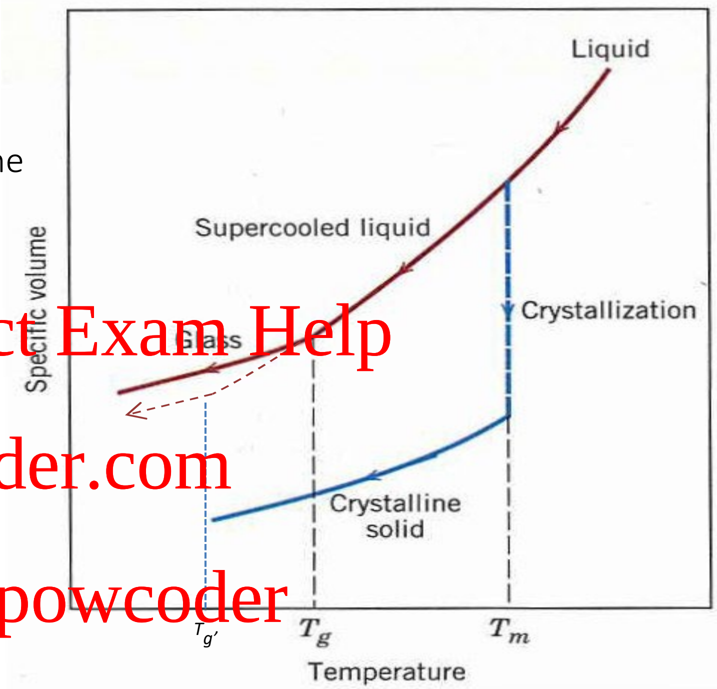
- ➢ Ceramics – make composites
- ➢ Glasses – make composites and also process treatments - Tempering

Non Metals - Glasses

Glass - actually a 'supercooled liquid' - not a solid

Tg – Glass Transition Temperature (when viscosity is so high, the glass can be considered solid)
Tg' – Lower GTT – can be achieved by slower cooling rate – stabilised glass.

Glass Formers	T_M (°C)	Viscosity (Poise)
SiO_2	1710	10^9
As_2O_3	309	10^6
B_2O_3	450	10^5
BeF_2	540	$>10^6$
GeO_2	1115	10^7
Compare to other materials		
H_2O	0	0.02
Na	98	0.01
Zn	420	0.03
Fe	1535	0.07



Most commercial glasses based on silicates – SiO_2

Soda-lime (window) – 75 SiO_2, 10 CaO, 15 Na_2O

Borosilicate (pyrex) – 80 SiO_2, 15 B_2O_3, 5 Na_2O

Glass forming capabilities relate to viscosity values at/around the melting point (softening point).

Non Metals - Thermal Toughening of Glass

Heat Treating Glass

Critical aspect :
Low thermal conductivity of glass

Annealing:
Removes internal stresses caused by uneven cooling

Tempering:
puts surface of glass part into compression
suppresses growth of cracks from surface scratches.

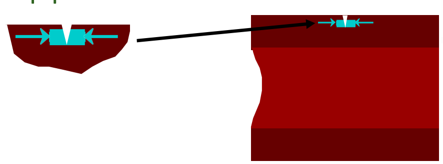
sequence:

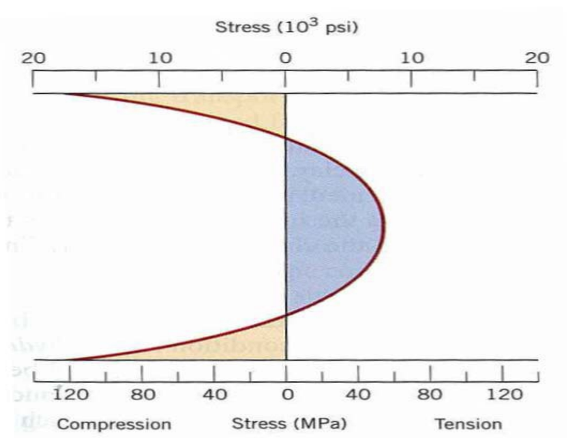
Surfaces of glass are in compression <u>but</u> subsurface in tension.

If compressive stress in surface penetrated glass fails catastrophically.

Compression is produced to finished size/shape prior to process.

Crack growth suppression





Learning Outcome Check 5

- What is the difference between ceramics and glasses?
- What is thermal shock?
- What parameter is modified to help control thermal shock resistance?
- How can heat treatment be used to control the engineering properties (toughness) of glass?

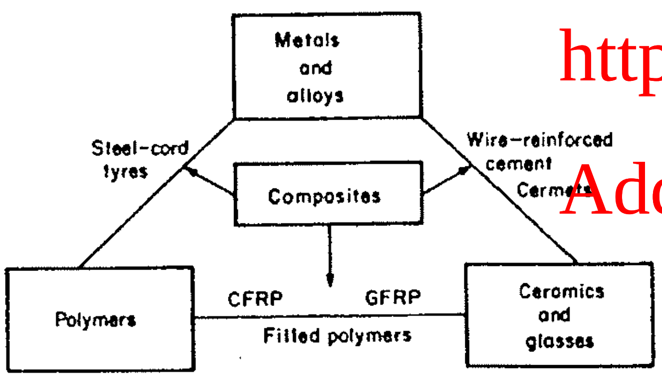
Non Metals - Toughening - by Producing Composite Materials

Composite Materials

Composite Materials effectively form the fourth classification of materials, and are essentially born of the first three classifications, namely metals and alloys, polymers and ceramics and glasses.

A composite material can be made up of any combination(s) of the materials, within certain guidelines.

ENGINEERING MATERIALS



The classes of engineering materials from which articles are made.

Components - Matrix and Reinforcement ('fibre')
Continuous or discontinuous (oriented, random)

Geometries
Fibrous, Particulate, Structural and Natural

Guidelines

A composite material is a mixture of two or more distinct constituents or phases, whereby:

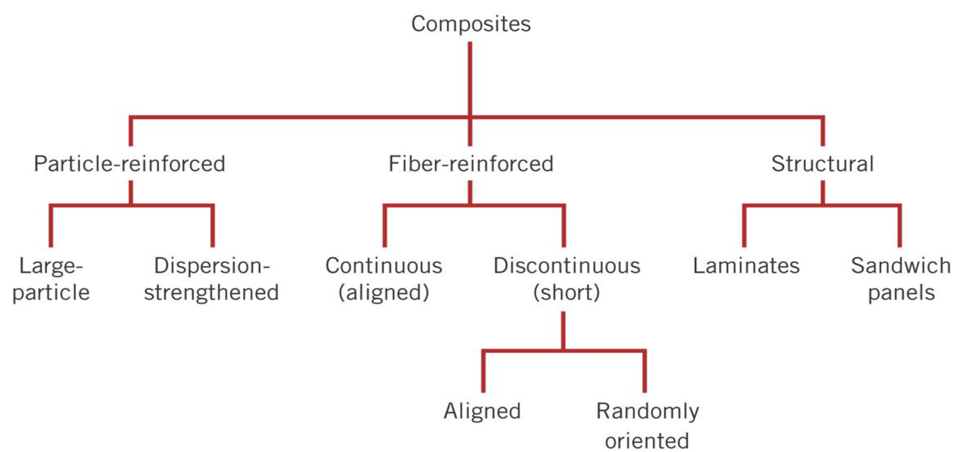
Both constituents are present in reasonable proportions e.g., >5%.

Constituent phases must have noticeably different properties.

In man-made composites, the composite material is produced by intimate mixing and consolidation of the constituents (not by the development of one constituent from another within the process eg phase nucleation in metals and alloys).

A viable composite material will have properties superior to those of the individual constituents (properties described by the **law of mixtures**).

Composite Classifications

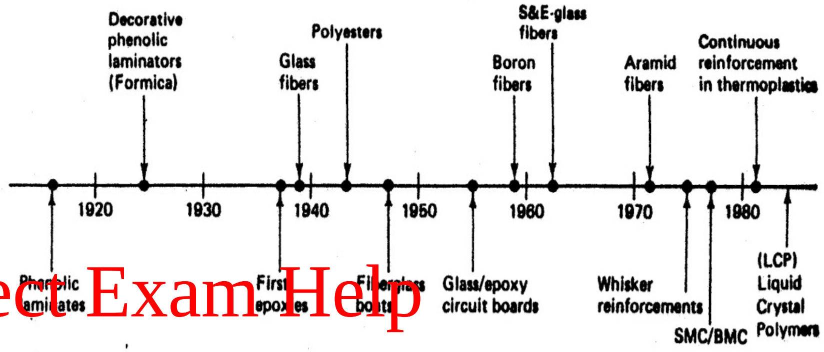


Non Metals - Composite Materials

History of Composites

- Biblical references – mud/straw constructions
- Natural composites – materials of construction – wood and bone.
- Man-made composites in “modern” materials (1900’s → present).

- Future – increased use of composite materials for
- **special & extraordinary functions** in all industries
- (aero, auto, medical, etc.).



Genealogy of polymer composites.

Man-Made Fibre Composites

Essentially, a composite material reinforced with randomly shaped and **oriented or randomly** dispersed **fibres**.

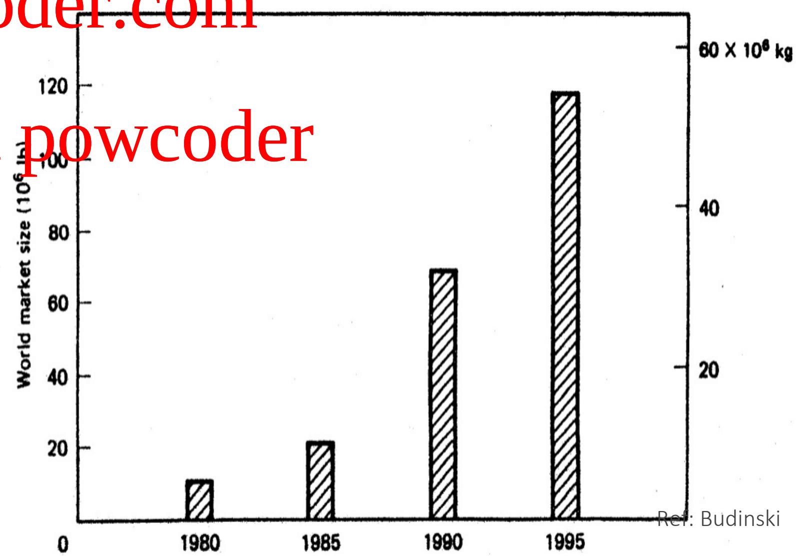
Most common examples - **GFRP (Fibre Glass) and CFRP (Carbon Fibre)**

Man-Made Particle Composites

Essentially, a composite material reinforced with **randomly shaped and randomly dispersed particles**.

Most common example – **Concrete.**

Reinforcements used in polymer composites.



Estimated expansion of the market for polymer composites

Ref: Budinski

Law of Mixtures

To describe and develop the properties of composite materials the law of mixtures is used.

In terms of modulus, when **two linear elastic solids** of a different moduli are combined, composite moduli (**in longitudinal direction**) given by:

$$E_C = V_f E_f + V_m E_m$$

- E_c – Modulus of composite
- E_f – Modulus of reinforcement (fibre)
- E_m – Modulus of matrix
- V_f – Volume fraction of reinforcement
- V_m – Volume fraction of matrix

Note: $V_f = 1 – V_m$

Adaptation of Law of Mixtures

Variations on above raw formula apply for **tensile strength**, **yield strength** and for variations of reinforcement orientation.

For tensile strength in a **continuous fibre** reinforced composite:

$$\sigma_C = V_f \sigma_f^F + V_M \sigma_M^Y$$

σ_f^F = Fracture stress of fibre

σ_M^Y = Yield stress of matrix

Approximations on **discontinuous and random orientations of fibres** reduce first term of relationship:

Case Study – Concrete

Concrete essentially comprises:

- **cement paste -** manufactured from **clay and limestone** (subjected to heat).
- **aggregate –** sand, pebbles, rocks
- **water**
- **pores**

How concrete is made: by mixing the above constituents in appropriate proportions

Concrete formation undergoes 2-stages:

- Plastic Stage – ease of deformation and forming into various shapes.

- Formation of <u>hard rigid</u> structure – can withstand many severe environments.

Cement paste allows the plastic stage and then forms the hard rigid phase.

The constituents of cement paste are:

SiO_2 + Al_2O_3 + $CaCO_3$ $\rightarrow$**heat**
calcium silicate + calcium aluminate

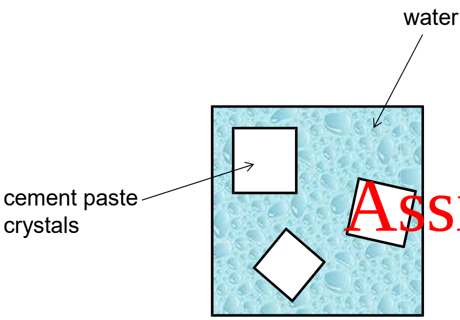
When water is added, hydration products form leading to setting and hardening.

Four stages of the "setting" of cement occur.

Case Study - Concrete

Cement Paste – Stage 1

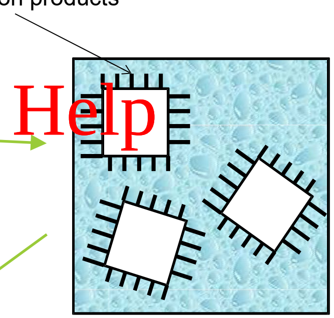
1. Paste suspended in water



Cement Paste – Stage 2

1. After a few minutes

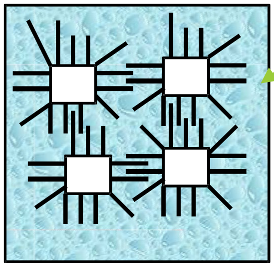
- Hydration products eat into the cement crystals
- Needle-like hydration products



Cement Paste – Stage 3

1. After a few hours

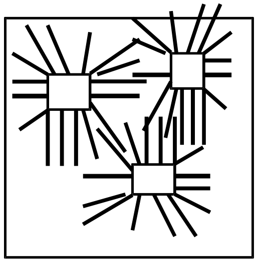
- Crystals now interlocking
- Joining together of cement paste crystals, hardening starts



Cement Paste – Stage 4

1. After a few days

- Further development of needle crystals
- Excess water in pores drains away.



Throughout process heat is generated and presence of water is essential

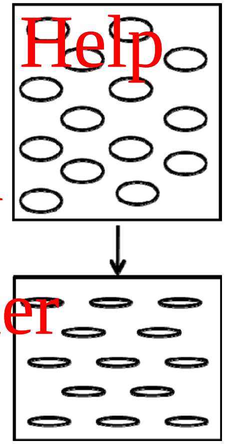
Case Study - Concrete

Concrete is very strong in compression, but has very limited strength in tension

Strength of Concrete

Porosity is the main reason for the lack of strength

a. Stress raisers source of cracks, hence material tends to be brittle (cemented paste is 50% stronger in compression than tension).



b. Pores allow <u>creep</u> to occur (high rate of creep, this can reduce crack propagation).

-causing non-elastic deformation under load

-The closure of pores (voids), allows the "squeezing out" of water from the voids.

To improve the tensile (including bending) response of concrete, for example, in the construction of bridges, the concrete has to be reinforced. There are three main methods - by the introduction of:

- Reinforcing steel bar (rebar)
- Prestressed rebar
- Fibre reinforcement

Learning Outcome Check 6

- What is the basic law used to describe the mechanical properties of composites?
- Give *two* functions of the matrix in a carbon fibre reinforced plastic (CFRP).
- What are *cements?* Name *one* example of such a material.
- What are the constituents of concrete?
- Give three methods of reinforcing concrete.