METALS (2nd part)

Recap: Defects, dislocations, Poisson's ratio, unit cells

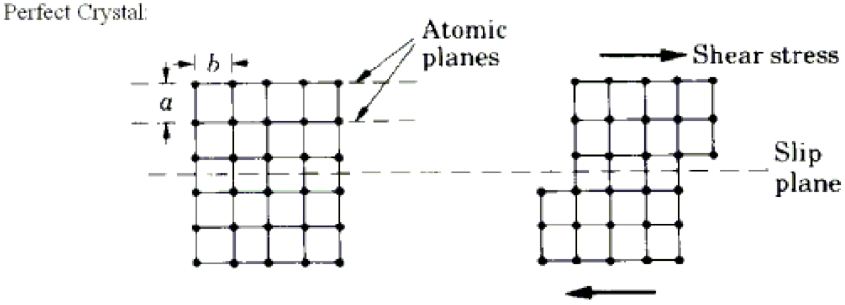
Summary

- Methods for metal reinforcement
- Effect of stiffening on stress-strain curves
- Hardness measurement
- Steel hardening: iron-carbon (Fe-C) state diagram
- Case studies: metal matrix composites and auxetic materials

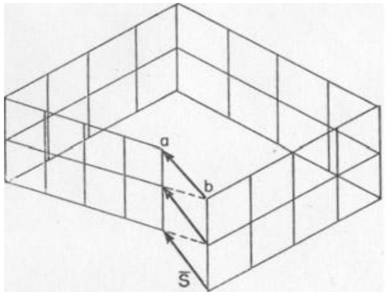
DISLOCATIONS AND DEFECTS

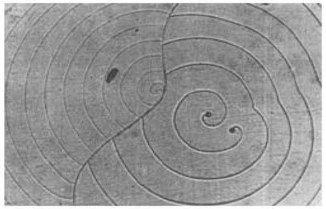
- Combining **edge** and **screw** dislocations metals lattice is able to slip through the presence of defects, producing plastic deformation.

Edge dislocation



Screw dislocation

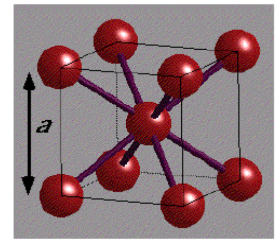




The occurrence of plastic deformation reduces brittleness in metals: however, it needs to be controlled to have sufficient stiffness and hardness

MAIN TYPES OF METAL UNIT CELLS

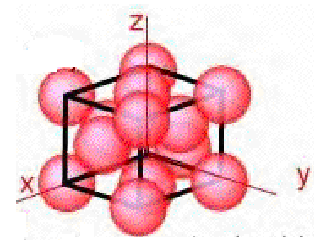
- **Body-centred cubic (b.c.c.)**
  (9 atoms: 8 on cube edges + 1 in cube centre): chromium, iron α (ferrite), tungsten, vanadium



Body-Centred Cubic

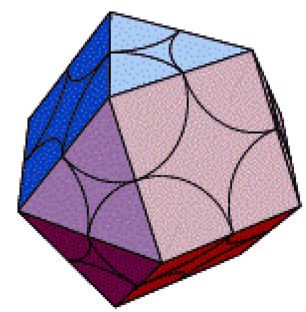
- **Face-centred cubic (f.c.c.)**

  (14 atoms per unit cell: 8 on the cube edges + 6 on the cube faces):
  aluminium, nickel, iron γ (austenite)



face centred cubic

- **Hexagonal close packed (h.cp.)**
  (17 atoms per unit cell: 12 on hexagons edges, 2 in the hexagons centres, 3 on three faces of the solid):
  magnesium, zinc, titanium α



F.c.c. and h.cp. give the maximum possible packing

HOW TO IMPROVE STIFFNESS IN METALS

- Plastic deformation needs to be **controlled** to improve stiffness
- Therefore **obstacles to the movement of dislocations** need to be created

OBSTACLES

Further dislocations → Cold-working

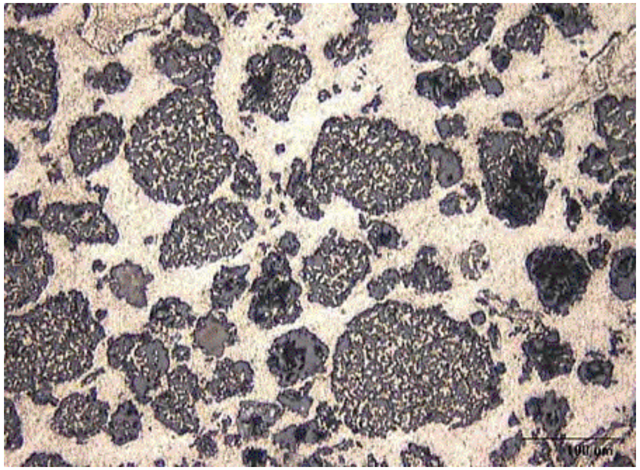
More grain boundaries → Grain size reduction

Atoms of another metal → Alloying

Impurities → Particles insertion

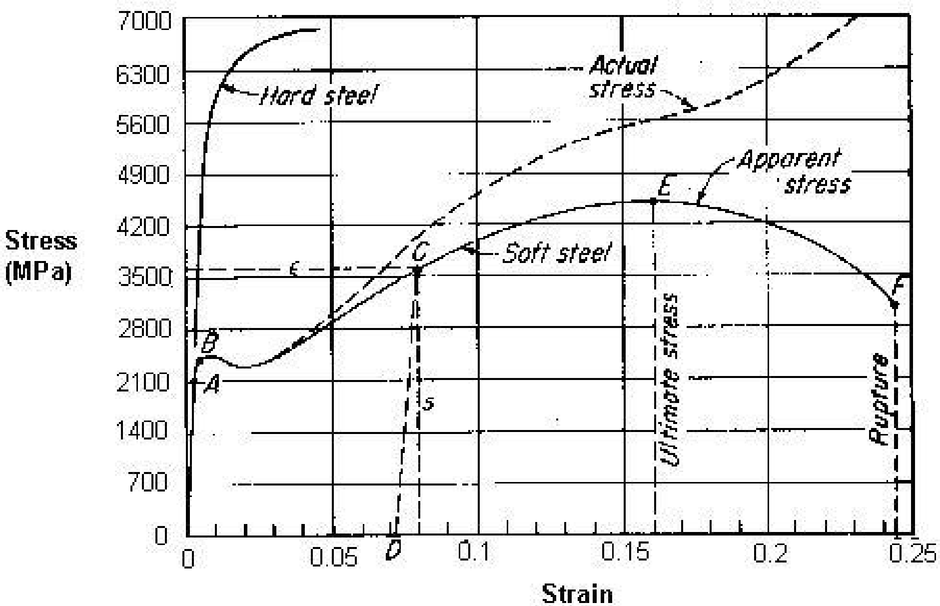
CASE STUDY:
METAL MATRIX COMPOSITES

- To reinforce aluminium alloys, particles or short fibres of ceramics, such as alumina (Al_2O_3) are often used to improve stiffness and reduce expansion with heating.
- However, processing and machining is not easy (the particles tend to be randomly dispersed): as a consequence, costs involved are higher than alloying for example with copper.



Micrograph of an aluminium alloy with alumina (Al_2O_3) particles used for anti-wear (brakes) applications

EFFECT OF REINFORCEMENT ON STRESS-STRAIN CURVES



Reinforcement increases stiffness,
increases resistance (ultimate tensile stress:UTS),
reduces plastic deformation (and possibly workability)

STIFFNESS, HARDNESS, TOUGHNESS

- **Stiffness:** Resistance to deformation. A stiff material has a low plastic deformation when a force is applied (e.g., it is pulled)
- **Hardness:** Resistance to penetration. A hard material does not easily allow another material to penetrate, when it is pressed against its surface.
- **Toughness:** Resistance to cracking. A tough material does not easily crack (or let a crack propagate) when a sudden impact is applied

Steel is stiff, diamond is hard, concrete is tough

HARDNESS MEASUREMENT: BRINELL TEST

- This is a common test to measure hardness on metals: a sphere of hard steel diameter D (mm) is pressed with a force P (N) against the metal to be tested for 10-15 seconds.
- This produces a penetration area with diameter d (mm).
- Brinell hardness (HB) is therefore determined by the formula:

$$HB = \frac{0.2 * P}{\pi D(D - \sqrt{D^2 - d^2})}$$

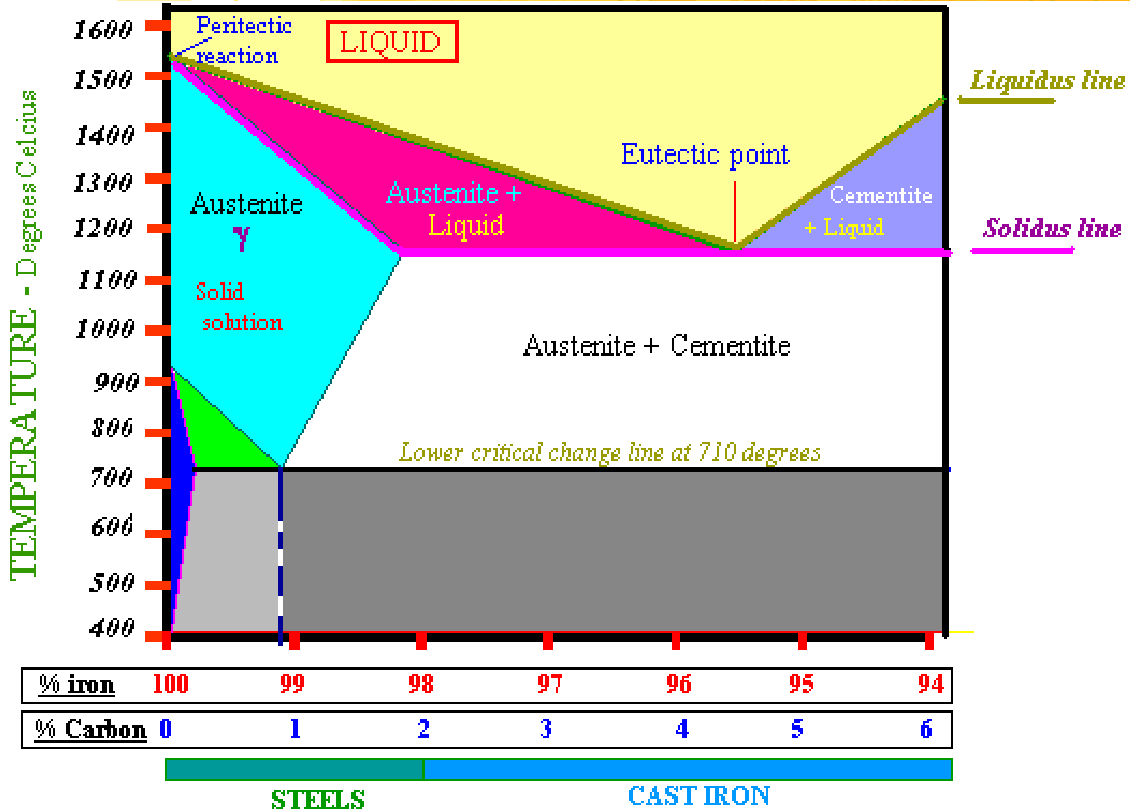
In steel, Brinell hardness is proportional to ultimate tensile stress via a coefficient h (dependant on the type of steel): UTS=h*HB

FERRITE AND AUSTENITE

- **Hardness** is a function of carbon content of the steel.
- **Hardening** of a steel requires a change in structure from the b.c.c structure (ferrite) found at room temperature to the f.c.c. structure (austenite).
- In this way more carbon atoms are introduced (higher packing)

- Hardening is composed in two phases:
  - Heating above the austenite temperature (around 900°C)
  - Controlled cooling at a different rate aiming to get a definite hardness

STATE DIAGRAM
IRON (Fe)- CARBON (C)



Most common steels have 0.8-1% carbon, whilst cast irons (softer and used to cast large components) have usually 2-3% carbon

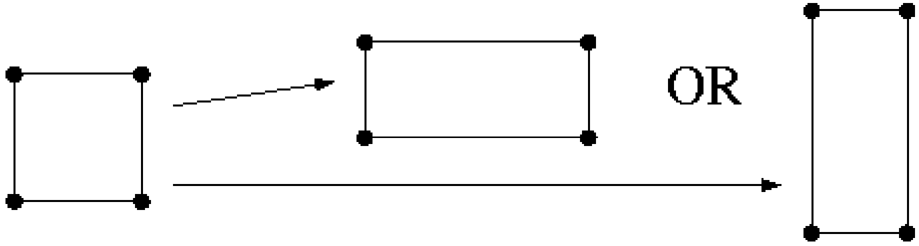
SLOW DIFFUSION: PEARLITE

- When slowly cooled (quenched) the steel structure will include **austenite** and **pearlite,** a partly hard and partly soft structure.
- When the cooling rate is extremely slow, then it would be mostly pearlite, which is extremely soft and made in lamellae
- This happens because time permits carbon atoms to fully diffuse throughout the structure, that is therefore prone to plastic deformation.

Lamellar pearlite: this is found e.g., in steel for rails which is naturally cooled and needs therefore further strengthening with manganese

FAST DIFFUSION: MARTENSITE

- Martensite is very strong and harder than ferrite and austenite, because it is formed by a **needle** structure
- This is due to the fact that many carbon atoms have not the time to diffuse throughout the lattice, and accumulate between iron atoms, producing an oblong, tetragonal structure



Cubic- tetragonal structure change due to trapping of carbon atoms in interstitial positions

EXERCISES 1

- Which is the expected shear stress of a mild steel specimen at 0.1% shear strain, if its Poisson’s ratio is 0.3 and its Young’s modulus is 210 GPa?

- Which is the depth of the penetration in a Brinell hardness test when HB is equal to 60, the diameter of the probe is 10 mm and the force P is 29400 N

- Some recently developed materials which are called auxetic, have a negative Poisson’s ratio. What happens in practice when a tensile force is applied on them?

- From aluminium (density 2.3) a honeycomb is made, by introducing a large quantity of voids. Which voids% is necessary to make the honeycomb float in water?

EXERCISES 2

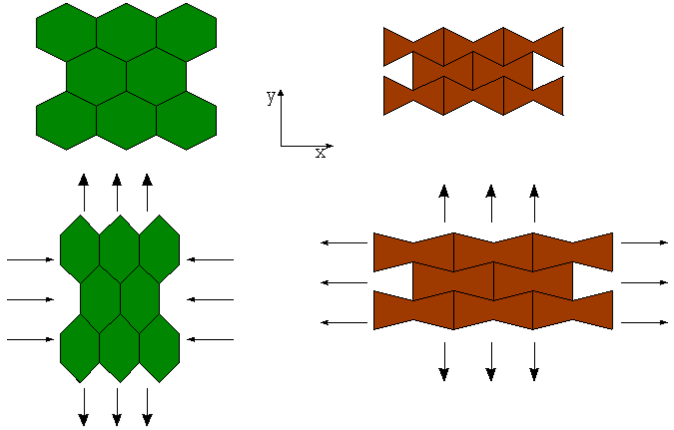
- A bullet of mass 10 g moving at 400 m/s strikes a tree trunk and penetrates to a depth of 25 mm. Determine the average force exerted on the bullet by the tree

- A bronze wire (length 1.5 m, diameter 2 mm) is joined end-to-end with a steel wire of identical size to form a wire 3 m long. Assuming that the proportional limit is not exceeded, calculate the resultant extension if a force of 300 N is applied (Young's moduli: bronze 100 GPa, steel 210 GPa)

- At a certain instant in time, there are 10^{11} atoms of an isotope with half-life of 15 hours (Half-life is the length of time required for half of a given number of initial number of atoms of that isotope to decay). Assuming the decay rate is constant, how long will it be before there are 10^{10} atoms left?

AUXETIC MATERIALS

- Auxetic materials, having a negative Poisson's ratio, swell when they are pulled, instead of shrinking. This happens, because they have a honeycomb structure with cells of particular (butterfly-like) geometry
- Very few exist naturally but recently more have been fabricated by modifying the microstructure of existing materials e.g. foams, polymers.
- Applications are as piezoelectric materials or biomedical devices



Conventional (left) vs. auxetic material (right)