Chemmat 121

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Contents

1   Deformation and structure of solids

1.1   Strength

How much force can a material withstand before it fails? That's a materials strength. A material can fail in several ways but the two most common are fracturing and permanent deformation.
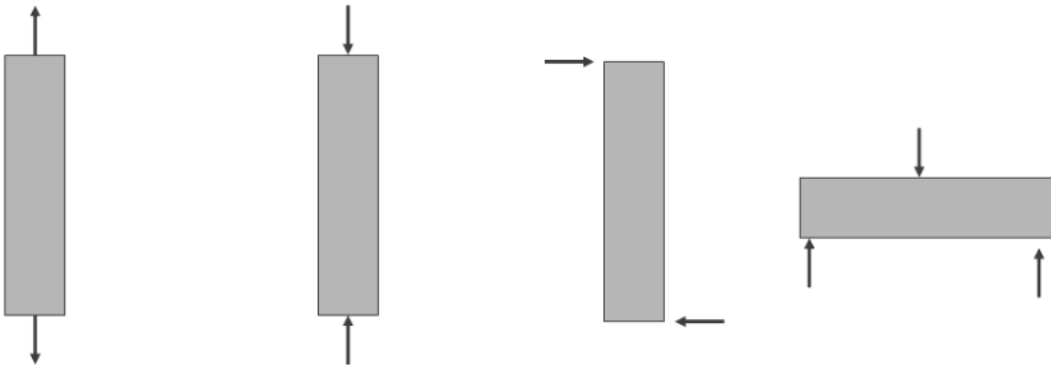
Some types of force that a material/object can undergo
From left: Tension, Compression, Shear and a Combination.

1.2   Stress

Engineers typically talk about stress instead of forces because stress is just a force proportional to its area. Stress is represented by the greek letter sigma (σ) and is given by the force (F) divided by the cross-sectional area (A).

$$\sigma = \frac{F}{A}$$

Cross-sectional area is the area that is perpendicular to the applied force

Example

Given: $m = 25\,\text{kg}, d = 10\,\text{mm}$

$$A = \pi r^2$$

$$A = \pi \times \frac{(0.01)^2}{2}$$

$$F = 25 \times 9.81$$

$$\sigma = \frac{F}{A}$$

$$\sigma = 3,120,000\,\text{Pa}$$

$$\sigma = 3.12\,\text{MPa}$$

1.3 Strain

Strain is how long something gets compared to its original size. Stress and strain are related very closely and the stress against strain graph is a very important thing to materials engineering. Strain is given by the change in length over the original length.

$$\epsilon = \frac{\Delta L}{L_o}$$

Strain is unitless but is commonly expressed as a percentage (%).

Example

$$\begin{aligned}
\epsilon &= \frac{\Delta L}{L_o} \\
&= \frac{100.32\,\text{mm} - 100\,\text{mm}}{100\,\text{mm}} \\
&= \frac{0.32\,\text{mm}}{100\,\text{mm}} \\
&= 0.0032 \\
&= 0.32\%
\end{aligned}$$

1.4 Stress-Strain Curve
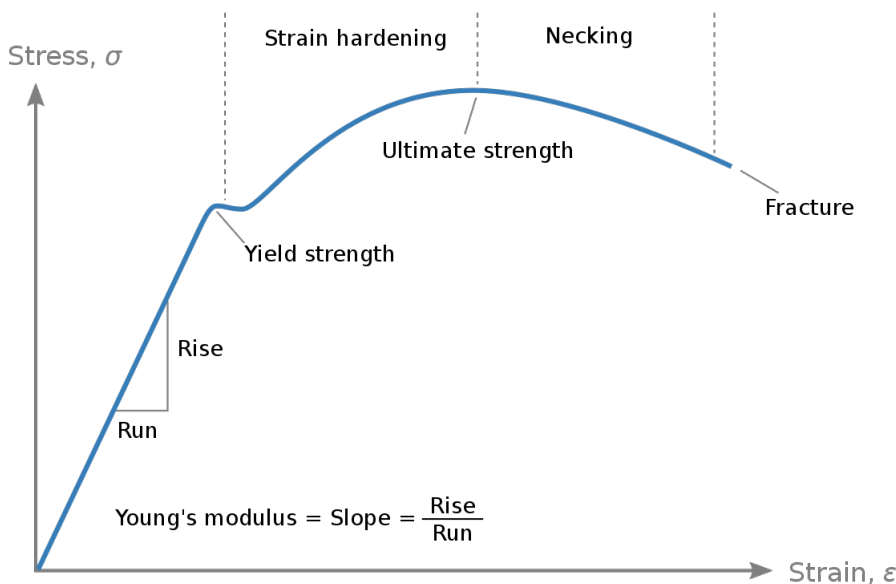
The area under the curve is $F \times d$ and gives the 'toughness' which is approximately the energy required.

Necking is a localised reduction in thickness, which reduces diameter, which reduces area, increasing stress. This causes it to fail.

1.5   Poisson's Ratio

Poisson's ratio is the relationship between deformation for a given material. It is a measure of the Poisson effect, that describes the expansion or contraction of a material in directions perpendicular to the direction of loading. It has no units and is represented by the greek character 'nu' (ν). For most materials $\nu \approx 0.3$.

$$\nu = \frac{-\epsilon_x}{\epsilon_z}$$

1.6   Young's Modulus

The Young's Modulus of a material is a measure of the 'stiffness'. It is the gradient of the elastic part of the stress-strain curve for a given material. It has units of Pascals (Pa) and is represented by the capital letter E.

$$E = \frac{\Delta\sigma}{\Delta\epsilon}$$

1.7   Steel

Steel has what is called a 'discontinuous yield'. This means at the yield strength there is a bit of 'noise' and it moves a little randomly before becoming nonlinear.

1.8   0.2% Proof Stress

The 0.2% Proof Stress of a material is a geometrical construct that is used when the yield stress of a material cannot be properly determined. It is a very slight overestimate (generally) that can be calculated by drawing a line parallel to the actual curve at a strain of 0.002 and finding the intersection with the original curve. This stress value is the approximation.

1.9   Safety Factor

The safety factor is a scalar value that demonstrates how much more stress a material can hold relative to the requirement. I.e. if, for example, $F \approx 1000\,\mathrm{N}$ the engineers might pretend $F = 2000N$. This would gie a safety factor of 2. When the conditions of the material are more uncertain, you would want a higher safety factor.

1.10   Engineering Stress vs Real Stress

In engineering, we draw a stress-strain graph as going 'down' after the ultimate tensile strength. In reality, because of the effect of necking, it goes up after this. As engineers, we use the model because it is easier to handle theoretically.

1.11 Ductility

Ductility is a measure of how much something can deform elastically (with 100% recovery / without permanent deformation). The stress-strain graph of a ductile material will have a longer elastic section while a more brittle material (less ductile) will have a shorter one. It is generally described by one of two equations:

$$\textbf{Percentage Elongation}$$
$$= \frac{\Delta L}{L_o} \times 100\%$$

$$\textbf{Percentage Reduction in Area}$$
$$= \frac{\Delta A}{A_o} \times 100\%$$

2 Microstructure and mechanical properties

2.1 Crystal Structure

If a material is crystalline, the atoms of a material have **LONG RANGE ORDER**. This means the material is made up of a crystal lattice made of repeating units called 'unit cells'.

There are 14 possible crystal arrangements but this course will only look at three. We describe arrangements by looking at the unit cell. The unit cell is a tessellating shape that has all the information to describe the entire lattice. The unit cell has 4 important properties:

- Number of atoms
- Co-ordination Number (The number of neighbours for the unit cell)
- Unit Cell Dimension (The length of each side of the cell written 'a')
- Atomic Packing Factor (Amount of space taken up by the atoms)

$$a = \text{ Atomic Packing Factor } = \frac{\text{volume of atoms}}{\text{volume of unit cell}}$$

2.1.1 Body Centered Cubic

Body Centered Cubic (BCC) has one atom at each corner of a cube and one right in the middle.

Callister, 8th Edition, Wiley & Sons, 2003, p35
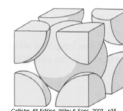
- Number of Atoms $= 2 = 1 + 8 \times \frac{1}{8}$
- Co-ordination Number $= 8$
- Unit cell dimension $= \frac{4R}{\sqrt{3}}$
- APF $= 0.68 = 0.68\%$

2.1.2 Face Centered Cubic

Face Centered Cubic (FCC) has one atom at each corner of a cube and one in the middle of each face of the cube.

- Number of Atoms = 4
- Co-ordination Number = 12
- unit cell dimension = $\frac{4R}{\sqrt{2}}$
- APF = 0.74 = 0.74%

2.1.3 Hexagonal Close Packed

Hexagonal Close Packed (HCP) is a prism shape with hexagonal arrangements of atoms layered up.

- Number of Atoms = 6
- Co-ordination Number = 12
- APF = 0.74 = 0.74%

2.2 Density

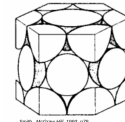Density is the degree of compactness of a substance. The amount of mass you get for a given volume. The density of a material is its mass divided by its volume.

$$\rho = \frac{n.A}{V_c.N_a}$$

Where n is the number of atoms per unit cell, A is the atomic mass of the material, V_c is the volume of the unit cell (a^3) and N_a is Avrogado's Number.

Example

Iron

$$a = 0.286\,\text{nm}, n = 2$$

$$\rho = \frac{2 \times 55.85}{(2.86 \times 10^{-8})^3 \times 6.023 \times 10^{23}}$$

$$\rho = 7.92\,\text{g.cm}^{-3}$$

The real density of iron is $7.87\,\text{g.cm}^{-3}$ so this is a good estimate.

2.3 Polymorphism

Materials that can exist in more than one crystal form (can have lattices made up of different unit cells) are called polymorphic. For example, Iron at room temperature has a BCC structure but at 912°C it has an FCC structure.

2.4 Planes, Directions and Positions

Navigation around our crystal structures is based on a typical x,y,z orthogonal axis. We can denote the postition of an atom using a typical three dimensional vector. By convention, positions are denoted with round brackets.
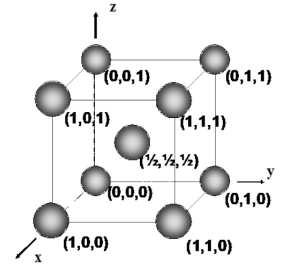
2.4.1 Directions

Directions in the lattice are defined with square brackets $[u, v, w]$.
1. Draw a vector from the origin for the direction
2. Project the length of the vector onto the unit cell axes
3. Put this in terms of the coefficients
4. Convert to integers (multiply by a constant)
5. Put in square brackets

Example

Projecting the length of the vector onto axes: $1a\ 0b\ \frac{1}{2}c$
Put this in terms of co-efficients: $1\ 0\ \frac{1}{2}$
Convert to integers (multiply by two): 2 0 1
Put in square brackets: [201]

Note: Negative directions will have a bar over them (read 'bar').

$$[1\bar{1}0]$$

2.4.2 Planes

Planes in the lattice are defined by **Miller Indices** (h, k, l).
1. Ensure the origin is not on the plane
2. Determine distance to to intercept plane, by travelling along each axis from the origin (intercepts)
3. Take reciprocals of the intercepts
4. Convert to integers (multiply by a constant)
5. Put in round brackets (parenthesis)

Example

Intercepts: $1\ -1\ \infty$
Reciprocals: $1\ -1\ 0$
Integers: $1\ -1\ 0$
Round Brackets: $(1\bar{1}0)$

2.4.3 Families

You can denote the 'family' of a plane (all of the planes made up with these values). Families of planes are denoted with curly brackets e.g. Cube Faces {100}. Families of directions are denoted with angle brackets e.g. $< 100 >$.

2.5 Slip, Theoretical Strength and Defects

Recall that there are two types of deformation: Elastic and Plastic (In-elastic). Elastic Deformation springs back (recovers), Plastic Deformation does not.

At the atomic level, Elastic Deformation is merely stretching the atomic bonds. Any further deformation is permanent (plastic, past the yield point) and results from a process called **slip**. In plastic deformation, atomic bonds are broken (and remade).

2.5.1 Theoretical Strength

We can can calculate the *theoretical* strength of a material by evaluating the amount of energy needed to break and remake the atomic bonds. This is not a very good approximation. For example, the theoretical shear strength of pure iron is 10,000MPa but the measured shear strength of pure iron is 20MPa... Why is this? Imperfections.

2.6 Imperfections

There are a number of a different imperfections that DO happen within a lattice containing millions of atoms. This is what causes our theoretical strength and theoretical density to be off. It is EXTREMELY difficult to get 'pure' anything so this is true for any sample.

- Point Defects
  - Vacancy
  - Substitution
  - Interstitial Atom
- Planar Defects (Dislocations, $\perp$)
  - Edge Dislocation
  - Screw Dislocation

A vacancy is simply a missing atom in the lattice. A substitution is when a different atom is in the place of the atom that should be there. Interstitial atoms are atoms that occupy a normally unoccupied site in a crystal lattice.

2.7 Slip
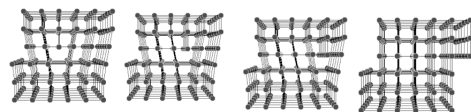
Explaining how Slip works is a common exam question. Draw these!

The model of slip we will use is the movement of dislocations. The movement of dislocations means that slip can occur more easily than in a perfect arrangement of atoms. Easy slip means that a material is easily plastic deformed, this means it is *ductile*.

2.7.1 Slip Systems

Slip (dislocation movement) occurs most easily on closepack planes and in closepacked directions. Not all systems have closepacked planes so slip happens on the *closest* packed plane

A slip system is a combination of planes and directions. For FCC, the closepacked planes are $\{111\}$[1]. The closepacked directions on these planes are $< 110 >$[2].

Hence, the main slip system for FCC is: $\{111\} < 110 >$

The main slip system for BCC is: $\{110\} < 111 >$

HCP structures have closepacked planes but they are all parallel. Slip is very difficult so HCP metals are often brittle.

[1] *A family of planes*
[2] *A family of directions*

2.8 Microstructure

Engineering components are very rarely single crystals, this means they are polycrystalline (many crystals). Most metals have at some point been molten and as they solidify they form many crystals.

Solidification:
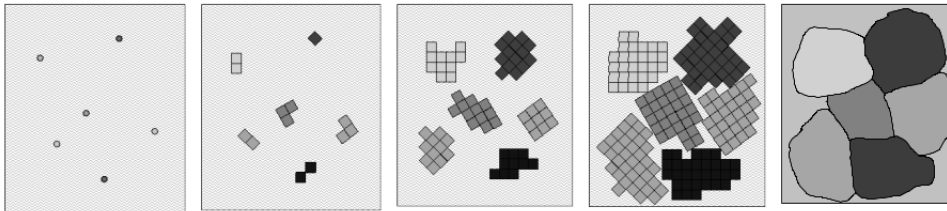
The name for the individual pieces is nucleus. If they have lost enough energy (cooling down) they might form nuclei when they bump together. This happens in the 2nd panel, you can call them "Baby Crystals".

The separate sections are 'perfect crystals' (but they still contain defects) and in the 4th panel they are **equiaxed**. This means they are roughly equal in each axis and of the same size (roughly spherical/of the same size). Each one of these crystals is called a 'grain'. We can then talk about **Grain Structures** within a metal and **Grain Boundaries**.

When one grain meets another, the atoms are not perfectly aligned. This means there is a little extra energy due to the atomic bonds being incomplete or out-of-equilibrium. This makes the grain boundary a 'high energy region'.

2.8.1 Nucleation

When the grains form from a molten state it is called **nucleation**. This can occur on another solid material or in solution. It is quite rare to occur in solution on its own but it is called **Homogeneous Nucleation**. When it forms on a surface e.g. the side of a mould it is called **Heterogeneous Nucleation**.

2.9   Casting

2.9.1   Sand Casting

Sand Casting is an ancient method of casting. You use something (foam etc) to make a hole in the sand and then fill your 'runner' (input) with molten metal until it burns away all the filler. This will then set in the sand you can take off the 'cope' or 'drag' (bottom or top) and access your new sword or cannon or frypan!
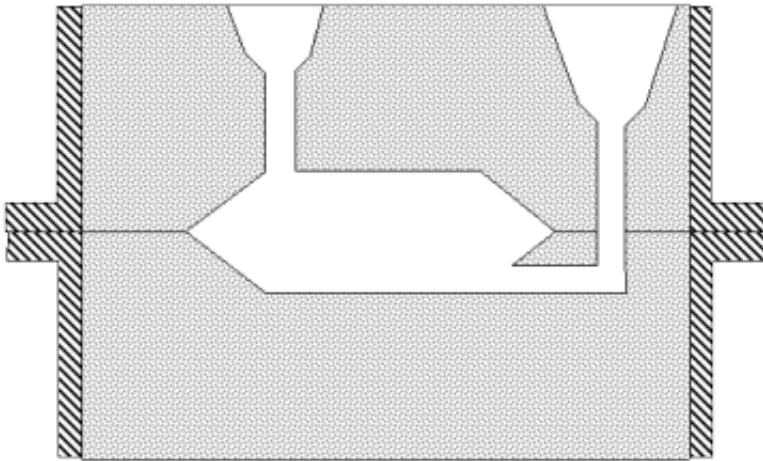
2.9.2   Die Casting

Die casting is a much more expensive modern method of casting. In die casting, a permanent mould is created using machining tools out of another metal. These moulds can be hundreds of thousands of dollars. All forms of casting are prone to porosity however, weakening the part.

2.10   Grain Structure Development

Grains will mostly nucleate on the sides (walls) of the mould. The first grains you will get are equiaxed grains. Columnar grains will form in 'columns' and stretch across the mould, possible touching the grains on the other side. Sometimes columnar grains will form branches, these are called dendrite formations.

Frost will also form dendrites when it goes from gas to solid.

2.11   Metallography

Metallography is the study of the structure of metals. We use a reflective-light microscope (instead of a transmission microscope) because the metal is far too opaque to use a transmission scope. Before we can use a microscope however you must prepare the surface. This is to make the rough, cut surface smooth and reflective.

To allow us to see the grain boundaries, we 'etch' the metal with an acid or alkali that selectively 'attacks' the boundaries. This means the boundaries will scatter light instead of reflecting it so they appear dark under the microscope. The general preparation process is

1. Grinding
2. Polishing (using finer and finer abrasives)
3. Etching
4. Cleaning (with hair-dryer, water, etc)

2.12 Grain Boundaries and dislocation movement

More grains strengthen the metal because the grain boundaries stop dislocation movement (slip). There is hence a relationship between the grain diameter and yield stress. This relationship is described by the *Hall-Petch Equation*.

$$\sigma_y = \sigma_o + kd^{-\frac{1}{2}}$$

From high school maths, you can see that this equation is linear (of the form $y = mx + c$). On the graph $d^{-\frac{1}{2}}$ is (typically) on the x-axis so grain size is decreasing as you move right.

2.13 Grain deformation

Plastically deforming grains results in work hardening. People do this using rollers and it is called 'rolling'. Rolling gives a rolling texture (grains are stretched out/thinner).
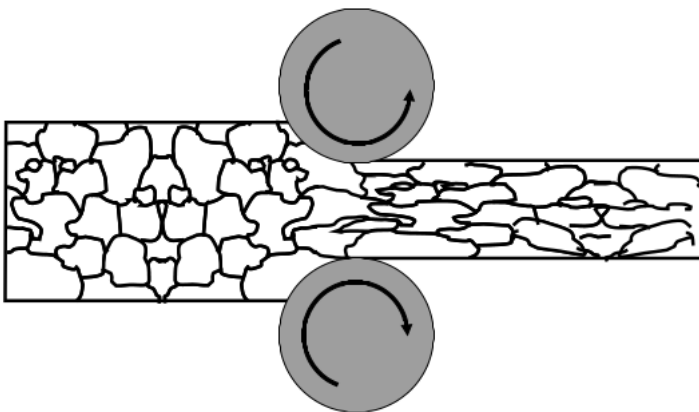
Figure 1. Rolling (note the thinner grains)
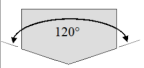
2.14   Work Hardening

As seen previously, work hardening occurs when a material is plastically deformed and released before it inevitably fractures. Plastic deformation introduce many new dislocations. Dislocations stop dislocations moving (and create new dislocations when moving). The more dislocations there are, the harder it will be for them to move. This is, very scientifically, called a 'traffic jam' and is what causes the strengthening due to work hardening.

Cold work is a name for the process of work hardening without heat i.e. rolling. This causes a reduction in area as the material is because it is lengthening. Percentage cold work is hence the change in area over the original area.

$$\frac{\Delta A}{A} \times 100$$

2.15   Hardness

Hardness is a resistance to a localised deformation. Hardness can be measured in many different ways, one popular one is the Rockwell Hardness Scales. Geologists use Moh's which is basically "rate my rock 1-10" where 10 is diamond and 1 is Talc.

The scales go from R_a to R_e, where the different scales measure different levels of hardness. Hardness has no units but you must state the scale you used i.e. $60R_c$

You can test hardness with an indenter. Where you make a plastic deformation with a known force behind it.

2.16   Electrical Properties of Metals

Electrical properties depend on atomic and crystal structures just as much as mechanical ones. Resistivity depends on resistance (R), area (A) and length (L). Resistance changes with temperature and so there is a second equation that has ρ_0 (the resistivity at room temperature), α (thermal co-efficient, given for each material) and T (temperature).

$$\rho = \frac{RA}{L}$$

$$\rho_{\text{temp}} = \rho_0(1 + \alpha T)$$

Remember that resistivity will increase with cold work. This is because conduction in metals is due to electron drift and the velocity of that drift. Because work hardening causes increased dislocation density, electron movement is impeded.

Conductivity can be expressed as the product of n (the number of electrons), $|e|$ (the size of the charge on an electron and μ which is the 'mobility of electrons'.

$$\sigma = n \times |e| \times \mu$$

2.17 Annealing

Annealing is a heat treatment that allows you to recover the ductility of a material (while sacrificing yield strength). Annealing has three stages: Recovery, Recrystallisation and Grain Growth. We will discuss each.
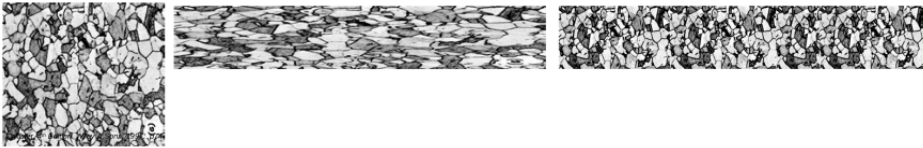
Figure 2. From left to right: untreated, rolled, rolled and annealed

2.17.1 Recovery

In this stage, the material recovers from the work-hardening. The dislocation density does not change but rearranges to a lower energy configuration.

2.17.2 Recrystallisation

In the second stage, the metal is strain free. New 'baby grains' nucleate at the grain boundaries. The driving force is the stored strain in the dislocations. These new grains expand until they are equiaxed with low dislocation density. Total recrystallisation occurs when just fully equiaxed.

2.17.3 Grain Growth

You can leave them to continue to grow for maximum ductility but this step is optional. You can choose to make the metal more ductile with larger grains or leave it to be stronger.

2.18 Recrystallisation Temperature

The rate of recrystallisation is proportional to temperature. There exists a 'recrystallisation temperature' at which: a 50% cold worked metal will just

fully recrystallise in one hour. Cold work less than 50% will take longer.
CW=50% but lower temp will take longer. Some examples are:

Metal	Melting temperature ($°C$)	Recrystallisation temperature ($°C$)
Lead	327	-4
Aluminium	660	80
Copper	1085	120
Iron	1538	370

2.18.1 Hot Work

Hot work (i.e. forging) is work done to a metal above the recrystallisation temperature. At this point, plastic deformation and recrystallisation happen at the same time. This means it won't be work hardened or it will be but it will be done at the same time.

2.18.2 Diffusivity

Diffusion is the movement of atoms through the lattice. Lattice atoms (or substitutes) move via vacancy diffusion. Interstitials 'jump' positions by interstitial diffusion.

Diffusivity is a measure of how easily atoms can move. Diffusivity (D) behaves according the Arrhenius equation (just like recrystallisation).

$$D = D_0 e^{\frac{-Q}{RT}}$$

3 Phase diagrams and Alloying

3.1 Phases

A phase is a component within a system that has uniform physical characteristics. In high school (and before) you were introduced to the typical Gas, Liquid and Solid (and maybe Plasma and Bose-Einstein Condensate).

3.2 Solid Solutions

There are two types of solid solution (in this course). Interstitial Solid Solutions and Substitutional solid solutions. These two types have a number of different properties:

Interstitial Solid Solutions
1. Solute atom must be small (relative to solvent atom)
2. Always have a solubility limit (limited interstitial spots)

Substitutional Solid Solutions
1. Similar Atomic Radius
2. Similar Crystal Structure (HCP, FCC etc.)
3. No Solid Solubility limit for some metals

3.3   Binary Isomorphous Phase Diagram

This is a two metal (binary) single shape (i.e. FCC, isomorphous) phase diagram. Here you can see the graph of temperature against weight percent Ni for a Cu solution. Clearly, when α is 100% copper it melts at the melting point of copper, 1085°C but when α is 100% nickel, it melts at the melting point of nickel 1453°C. For any other composition, α will melt at a range of temperatures. This is what we are graphing in a phase diagram.
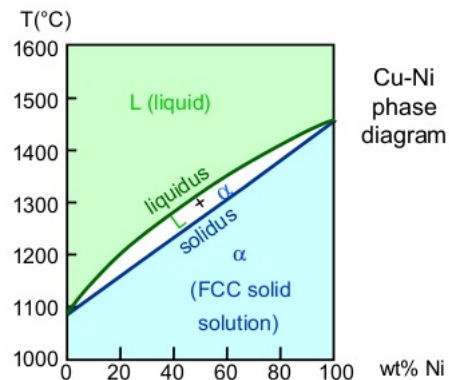
3.4   The Lever Rule

The lever rule lets you calculate percentage makeups of the alloys and their phases. To calculate the percentage of each phase at a given temperature:

1. Place Pivot (always at the overall alloy composition)

2. Draw the tie-line

3. Draw on the phase symbols

4. Calculate Lengths

3.4.1   What are the compositions of each phase?

Phases are oppposite, composition is on the 'right' side.

To calculate the amount of each alloy in each phase, look at where the tie-line intersects with the solidus, that will be the percentage amount of Ni (or whatever is on the x axis). You can then calculate the amount of the other metal by subtracting from 100.

The intersection with the liquidus will give you the percentage of Ni in the liquid state and so on. This is a useful tool for all phase diagrams but is especially easy to use in this case.

3.5   Binary Eutectic Phase Diagram
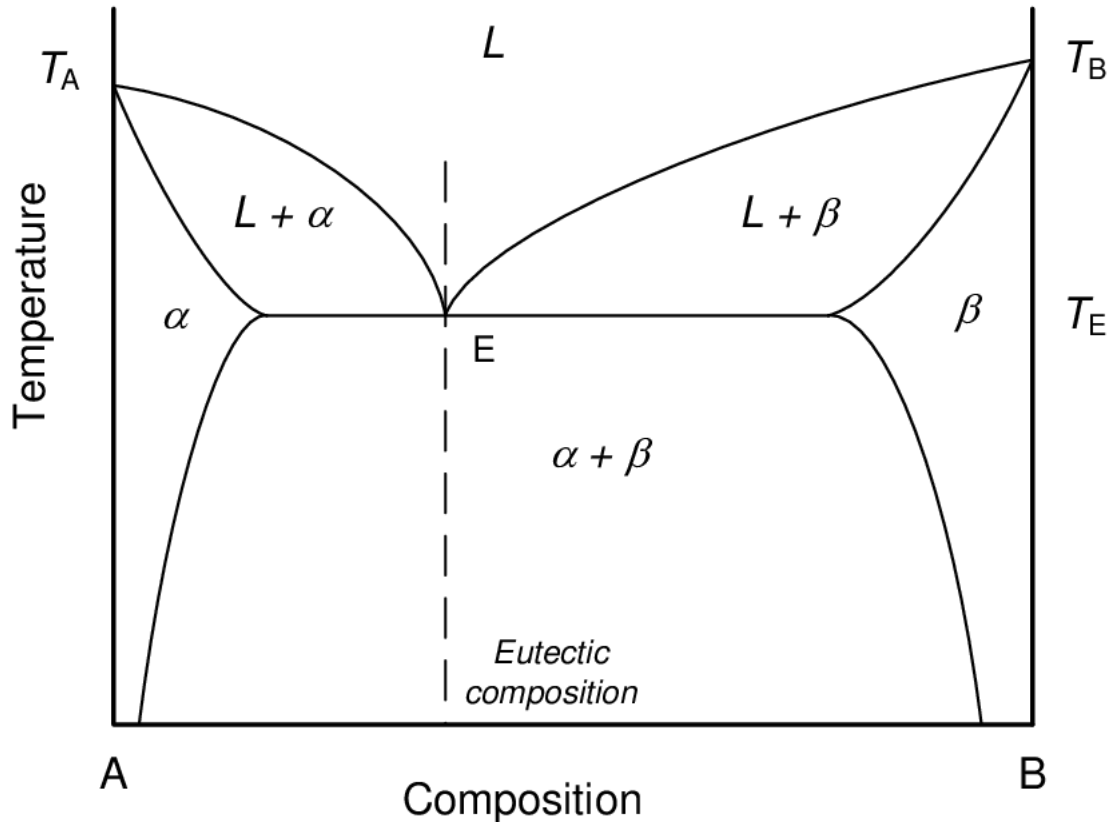
3.5.1   The Eutectic Point

The Eutectic Point is a point at which the alloy has its own freezing or melting point. This is clearly seen on the graph where the two lines meet with the α and β section. The Eutectic reaction is when a liquid phase transforms into two solid phases $(\alpha + \beta)$

$$L_{EUT} \underset{\text{heat}}{\overset{\text{cool}}{\rightleftharpoons}} \alpha + \beta$$
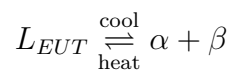
3.5.2   Microstructure Development

The microstructure of metals formed will vary greatly but noticably will form equiaxed grains of one element with grains of the other at the boundaries or layers of each metal. Metals that form large grains on grain boundaries are called proeutectic.

4   Strengthening mechanisms

In 121, when we say strength we are generally referring to yield strength. This is the stress at which a material will begin to plastically deform.

$$\text{strength} \approx \sigma_y$$

4.1 Work Hardening

Any plastic deformation increases strength. This is because for plastic deformation to occur, dislocations have to move. Plastic defomation increases dislocation density which causes a 'dislocation traffic jam' and the yield strength will increase.

4.2 Grain Size Reduction

Reducing the grain size will increase the yield stress of a material (by the Hall-Petch equation). We can do this by controlling the amount of cold work before recrystallisation, and then controlling the aount of grain growth after recrystallistion (see annealing).

4.3 Solid Solution Strengthening

Solid Solution Strengthening involves making an alloy with a bigger or smaller atom to distort the slip planes of the parent lattice. Distorting the parent lattice means it will be harder for dislocations to move so yield strength will increase. Hence, the maximum yield stress (and resistivity) will occur at the optimal combination of metals. (Remember, ductility is (sort of) the opposite of strength so the graphs will be opposite here)

4.4 Multiphase Strengthening

Any boundary can stop dislocation movement: a grain boundary or *a boundary between two phases*. Multiphase strengthening is choosing an alloy to maximise the number of boundaries. You can choose an alloy to maximise the number of boundaries most easily by increasing the amount of eutectic. This is because the layers of a eutectic solid are exactly what we are looking for.

A eutectic solid (a metal with the eutectic metal combination) cooled to solid will have the following properties: very high yield strength, lower ductility (In the CuAl example, still ductile). Pearlite like layers.

4.5 Strengthening Methods for Steel

4.5.1 Martensite

By quenching from the Austenite region we can form a phase called Martensite. No diffusion is required (because it is a displacive or shear transformation) so this transformation is almost instant.

- BCT $\implies$ No slip systems $\implies$ Hard and Brittle
- It is a super-saturated solid solution of C in Fe
- It is METASTABLE

4.5.2 Tempered Martensite

When you temper martensite, you get a very fine dispersion of Fe_3C particles in a ductile ferrite matrix. Tempered Martensite contains NO actual martensite. It has been heat treated (tempered) to 'push' the metastable phase into stable phases. Note that $Fe_3C+\alpha$ is **not** pearlite. Recall that we only get pearlite when cooling from the austenite region. This is hence a new compound that we call Tempered Martensite. Below 723°C, this reaction will happen:

$$M \to \alpha + Fe_3C$$
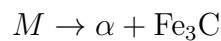
In this reaction, C diffuses out of the BCT structure of Martensite into Fe_3C, and the BCT structure relaxes into BCC Iron (α). Below is the resulting microstructure/s:
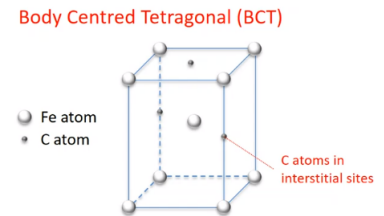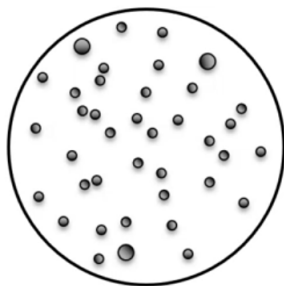
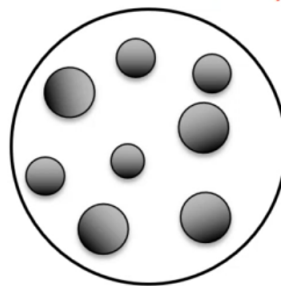Tempered Martensite Properties:
- Optimum Strength for a steel with sufficient ductility to still be tough

4.5.3 Spheroidising of Steels

The spheroidisation of Steel is a heat treatment that makes it more ductile. It only works for steels that contain pearlite i.e. have been slowcooled and have a hight amount of Carbon (0.5-1 %).

Heating to $700°C$ and holding for several hours transforms the layers of

$$Fe_3C \text{ into spheres.}$$

4.6 Time-Temperature-Transformation (TTT) Curves

A TTT curve tells us how fast is fast cooling. Generally, we do this to figure out what phases will form in a metal cooled from one temperature to another

in a given time. It graphs temperature against time (generally log time) It is useful but limited, it cannot tell you what happens in the bottom right (dotted point).

The 'curvy' curve is the start and finish lines of the pearlite transformation from austenite (oft included is a '50%' complete line, which will be 50% Austenite and 50% Pearlite). Pearlite exists on a spectrum between 'coarse' and 'fine', above 'the nose' (farthest left point of the start line) will form coarse Pearlite and below that will form fine Pearlite. Below that, the microstructure formed will be Bainite (not important for 121). Below that is the Martensite Start Line, this will be where Martensite is formed.
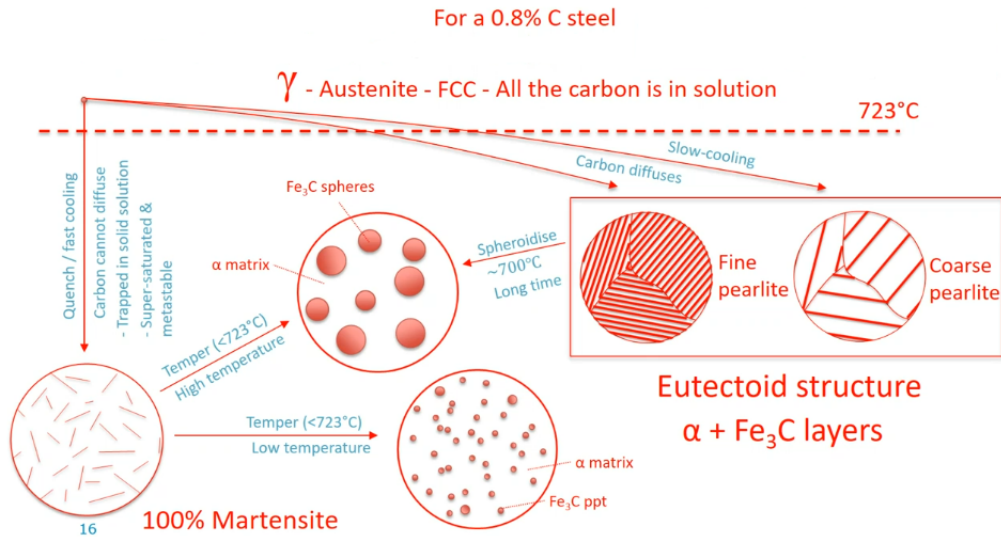
It's important to remember that these only really make sense with "Isothermal heat treatment". This means the line travels straight horizontally. This is an assumption that is rarely true in real life.

In 121, we only discuss a steel with a eutectoid composition (0.8% C).

For a steel of eutectoid composition (0.8% C),

4.6.1 Steel Summary

For a 0.8% C steel
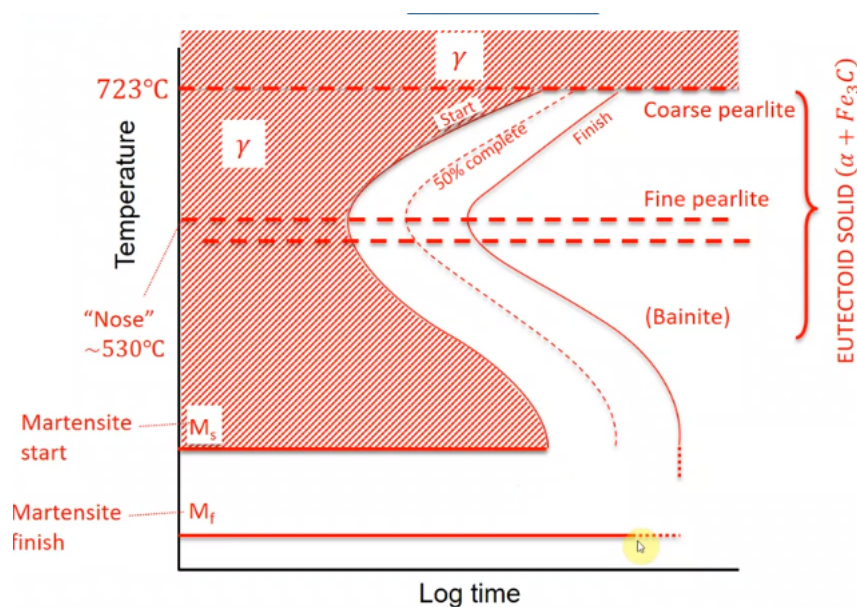
A steel is an alloy of Fe and C. Steels are widely used in engineering because they are cheap and effective. Steels are interstitial solids meaning each phase has a fixed solubility of Carbon.

Ferrite (α)
Ferrite has a BCC structure and exists on the far left of the phase diagram (maximum solubility of 0.02%). Ferrite is ductile, magnetic (ferrous) and exists between room temperature and $910°C$.

Austenite (γ)
Austenite has an FCC structure and a maximum solubility of 1.7%. It is also ductile but non-magnetic.

Cementite (Fe_3C)
Cementite is not a phase but a compound of fixed composition. It is very brittle and hard.

Pearlite (P)
Pearlite is the microconstituent of Steel that forms at the eutectoid composition (0.8%). It consists of layers of ductile ferrite (α) and brittle cementite (Fe_3C).

Martensite (G)
Martensite is a super-saturated solid solution of C in Fe that is BCT and hence hard and brittle. It is metastable and formed from quenching.

5 Engineering ceramics and glasses

5.1 Ceramic Materials

5.2 Ceramic Structures

5.3 Silicate Structures

5.4 Fracture toughness of ceramics

5.5 Processing Ceramics

5.6 Glass

5.7 Glass Processes

6 Polymers

7 Failure of materials

8 Corrosion of metals

9 Engineering composites