ENGINEERING COUNCIL

CERTIFICATE LEVEL

ENGINEERING MATERIALS C102

TUTORIAL 4 – MECHANICAL PROPERTIES OF MATERIALS

OUTCOMES

On successful completion of the unit the candidate will be able to:

1. Recognise the structures of metals, polymers and ceramic materials.
2. Assess the mechanical and physical properties of engineering materials
3. Understand the relationships between the structure of a material and its properties.
4. Select materials for specific engineering applications.

CONTENTS

1. INTRODUCTION

Engineering components and structures are made from materials carefully selected for their properties and cost. The properties we look for in materials are many. The following lists and explains the important properties.

2. MECHANICAL PROPERTIES

DENSITY

Density is a very important concept. It is a figure that tells us how many kg of a uniform substance is contained in a volume of 1 m^3. The value for pure water is one of the best-known figures since from the old definition that 1 kg was the mass of 1 dm^3 of water then since there are 1000 dm^3 in a the density must be 1000 kg per m^3. This is written in engineering as 1000 kg/m^3

In general density is defined as the ratio of mass to volume and is given the symbol ρ (Greek letter rho). **$\rho = M/V$**

RELATIVE DENSITY

Often the density of substances is compared to that of water and this is the relative density. For example Lead has a mass 11.34 larger than the mass of the same volume of water so the relative density is 11.34. The symbol used is d.

Relative density = d = Mass of a substance ÷ Mass of the same volume of water

If we take 1 m^3 as our volume then d = Mass of 1 m^3 of the substance ÷ 1000

d = Density of the substance ÷1000

SELF ASSESSMENT EXERCISE No.1

1. Lead has a density of 11340 kg/m^3. Calculate the volume of 12 kg.
2. Aluminium has a density of 2710 kg/m^3. Calculate the relative density.
3. Seawater has a relative density of 1.036. Calculate the density of sea water.

TABLE OF DENSITIES FOR MATERIALS

Material	Density kg/m^3	Material	Density kg/m^3
Air 20 °C, 1 atm, dry	1.21	Lead	11300
Aluminium	2700	Mercury	13600
Balsa wood	120	Nickel	8800
Brick	2000	Oil (olive)	920
Copper	8900	Oxygen (0 °C, 1 atm)	1.43
Cork	250	Platinum	21500
Diamond	3300	Silver	10500
Glass	2500	Styrofoam	100
Gold	19300	Tungsten	19300
Helium (0 °C, 1 atm)	0.178	Uranium	18700
Hydrogen (0°C, 1 atm)	0.090	Water 20 °C, 1 atm	998
Ice	917	20 °C, 50 atm	1000
Iron	7900	seawater 20 °C, 1 atm	1024

DUCTILITY

This is the ability to be drawn out into wire. Copper can be pulled out into a long thin wire because it has a large degree of ductility. Cast iron cannot be pulled out in this way and has virtually no ductility. This property is largely defined by the % elongation and% area reduction found in the tensile test.

MALLEABILITY

This is the ability of a material to be beaten into thin sheet by hammering. Lead is especially malleable and opposite to glass that has no malleability at all.

STRENGTH

This is the force at which the material will fail. Strength is normally given as the force per unit area or STRESS. There are various ways that a material may fail.

TENSILE STRENGTH

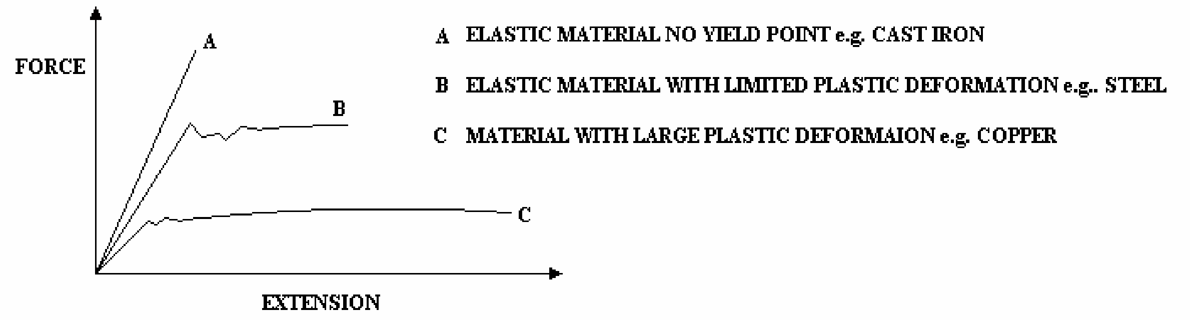
A material may fail when it is stretched in which case it is a tensile failure. The stress at which a material fails is found in a ***TENSILE TEST*** covered in tutorial 3.

If the material is ductile, we look for the point at which it starts to stretch like a piece of plasticine. This point is called the yield point and when it stretches in this manner, we call it ***PLASTIC DEFORMATION.***

If the material is not ductile, it will snap without becoming plastic. In this case, we look for the stress at which it snaps and this is called the ***ULTIMATE TENSILE STRENGTH***.

Most materials behave like a spring up to the yield point and this is called ***ELASTIC DEFORMATION*** and it will spring back to the same length when the load is removed.

The tensile test is carried out with a standard sized specimen and the force required to stretch it, is plotted against the extension. Typical graphs are shown below.



COMPRESSIVE STRENGTH

This is the strength of a material when it is squashed or compressed. Materials are normally very strong in compression because any cracks or faults in the structure will be closed and not pulled apart. Only soft materials like lead will fail easily because they are malleable and will spread out. Materials that are very weak in tension like cast iron and concrete are very strong in compression.

SHEAR STRENGTH

This governs how the material resists being cut in a guillotine or scissors and the ultimate shear stress is the stress at which the material is parted.

TORSIONAL STRENGTH

This governs the stress at which a material fails when it is twisted and a test similar to the tensile test is carried out, only twisting the specimen instead of stretching it. This is a form of shearing.

ELASTICITY

The elasticity of materials governs how much they deform under loads. The main properties are:

Modulus of Elasticity E defined as the ratio of tensile stress to strain and determined in a tensile test.
Modulus of Rigidity G defined as the ration of shear stress and strain and determined in a torsion test.
Bulk Modulus K defined as the ration of pressure and volumetric strain and found with specialised equipment for liquids.
Poisson's ratio ν defined as the ratio of two mutually perpendicular strains and governs how the dimensions of a material change such as reduction in diameter when a bar is stretched.

You should have studies these topics in other modules.

HARDNESS

This governs how a material resists being scratched and resists being worn away by rubbing. The hardness is found with a hardness tester and there are many of these. The main ones are the Brinell, the Vickers and the Rockwell test that basically consists of measuring how far a ball, cone or pyramid can be pressed into the surface. Hard materials are diamonds and glass. Soft materials are copper and lead. Hardness is measured by comparing it to the hardness of natural minerals and the list is called the Moh scale. The list runs from 1 to 10 with 1 being the softest ands 10 the hardest.

10	Diamond	5	Apatite
9	Corundum	4	Fluorite
8	Topaz	3	Calcite
7	Quartz	2	Gypsum
6	Feldspar	1	Talc

TOUGHNESS AND BRITTLENESS

Toughness is about how difficult it is to beak a material. Some materials are very strong but break easily. These are brittle like glass and cast iron. Other materials are not very strong but take a lot of energy and effort to part. Some polymers (plastics) are like this. Toughness is determined by measuring the energy needed to fracture a specimen. This is done in special test machines that use a swinging hammer to hit the specimen. The test also shows how susceptible the material is to cracking by putting a small notch in the specimen for the crack to start from.

3. THE AFFECT OF PROCESSING and MANIPULATION ON METALS

When a metal solidifies grains or crystals are formed. The grains may be small, large or long depending on how quickly the material cooled and what happened to it subsequently. Heat treatment and other processes carried out on the material will affect the grain size and orientation and so dramatically affect the mechanical properties. In general slow cooling allows large crystals to form but rapid cooling promotes small crystals. The grain size affects many mechanical properties such as hardness, strength and ductility.

MANIPULATIVE PROCESSES

These are processes which shape the solid material by plastic deformation. If the process is carried out at temperatures above the crystallisation temperatures, then re-crystallisation occurs and the process is called HOT WORKING. Otherwise the process is called COLD WORKING. The mechanical properties and surface finish resulting are very different for the two methods.

HOT ROLLING

This is used to produce sheets, bars and sections. If the rollers are cylindrical, sheet metal is produced. The hot slab is forced between rollers and gradually reduced in thickness until a sheet of metal is obtained. The rollers may be made to produce rectangular bars, and various shaped beams such as I sections, U sections, angle sections and T sections. Steel wire is also produced this way. The steel starts as a round billet and passes along a line of rollers. At each stage the reduction speeds up the wire into the next roller. The wire comes of the last roller at very high speeds and is deflected into a circular drum so that it coils up. This product is then used for further drawing into rods or thin wire to be used for things like springs, screws, fencing and so on.

COLD ROLLING

The process is similar to hot rolling but the metal is cold. The result is that the crystals are elongated in the direction of rolling and the surface is clean and smooth. The surface is harder and the product is stronger but less ductile. Cold working is more difficult that hot working.

FORGING

In this process the metal is forced into shape by squeezing it between two halves of a die. The dies may be shaped so that the metal is simply stamped into the shape required (for example producing coins). The dies may be a hammer and anvil and the operator must manipulate the position of the billet to produce the rough shape for finishing (for example large gun barrels).

COLD WORKING

Cold working a metal by rolling, coining, cold forging or drawing leaves the surface clean and bright and accurate dimensions can be produced. If the metal is cold worked, the material within the crystal becomes stressed (internal stresses) and the crystals are deformed. For example cold drawing produces long crystals. In order to get rid of these stresses and produce "normal" size crystals, the metal can be heated up to a temperature where it will re-crystallise. That is, new crystals will form and large ones will reduce in size.

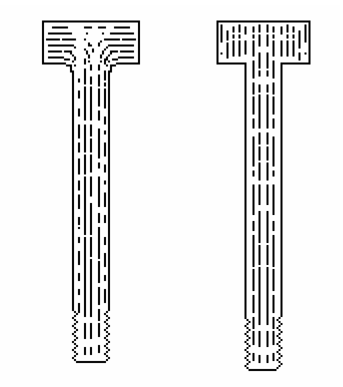
If the metal is maintained at a substantially higher temperature for a long period of time, the crystals will consume each other and fewer but larger crystals are obtained. This is called "grain growth".

Cold working of metals change the properties quite dramatically. For example, cold rolling or drawing of carbon steels makes the stronger and harder. This is a process called "work hardening".

HOT WORKING

Most metals (but not all) can be shaped more easily when hot. Hot rolling, forging, extrusion and drawing is easier when done hot than doing it cold. The process produces oxide skin and scale on the material and producing an accurate dimension is not possible.

Hot working, especially rolling, allows the metal to re-crystallise as it is it is produced. This means that expensive heat treatment after may not be needed. The material produced is tougher and more ductile.



Hot working aligns the grains in a particular direction giving it a fibrous property. This may be used to advantage. Forging in particular makes use of aligning the grains to give maximum strength in the required direction. The diagram illustrates how the head of a bolt is formed by forging to change the direction of the grain. The right hand diagram shows the result of machining the head leaving a weakness at the corner.

Engine crankshafts are forged to produce optimal grain flow in a similar manner.

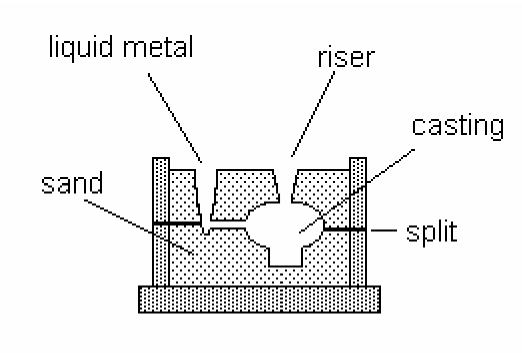
Many materials, especially metals, are suitable for casting by pouring the liquid metal into a mould and allowing it to solidify. The product has the shape of the mould and this may be the shape of a component which will need machining to complete it (for example an engine block) or an ingot for further processing such as rolling or drawing.

LIQUID CASTING AND MOULDING

When the metal cools it contracts and the final product is smaller than the mould. This must be taken into account in the design.

The mould produces rapid cooling at the surface and slower cooling in the core. This produces different grain structure and the casting may be very hard on the outside. Rapid cooling produces fine crystal grains. There are many different ways of casting.

SAND CASTING



A heavy component such as an engine block would be cast in a split mould with sand in it. The shape of the component is made in the sand with a wooden blank. Risers allow the gasses produced to escape and provide a head of metal to take up the shrinkage. Without this, the casting would contain holes and defects.

Sand casting is an expensive method and not ideally suited for large quantity production. Typical metals used are cast iron. Cast steel and aluminium alloy.

DIE CASTING

Die castings uses a metal mould. The molten metal may be fed in by gravity as with sand casting or forced in under pressure. If the shape is complex, the pressure injection is the best to ensure all the cavities are filled. Often several moulds are connected to one feed point. The moulds are expensive to produce but this is offset by the higher rate of production achieved. The rapid cooling produces a good surface finish with a pleasing appearance. Good size tolerance is obtained. The best metals are ones with a high degree of fluidity such as zinc. Copper, aluminium and magnesium with their alloys are also common.

CENTRIFUGAL CASTING

This is similar to die casting. Several moulds are connected to one feed point and the whole assembly is rotated so that the liquid metal is forced into the moulds. This method is especially useful for shapes such as rims or tubes. Gear blanks are often produced this way.

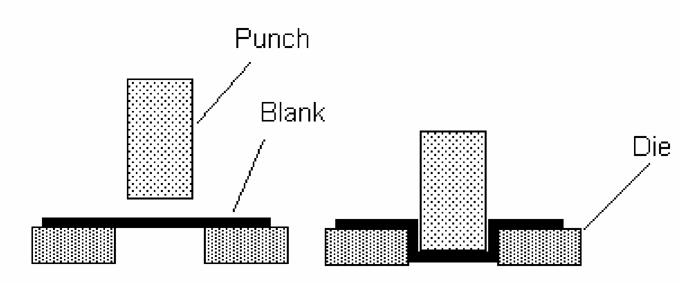
INVESTMENT CASTING

In this process, wax shapes are first made in a metal mould. The shape is then coated with a ceramic material. The wax is melted leaving a ceramic mould. After the metal is poured, the mould is broken to release the casting. The advantage of this is that metals with a very high melting temperature may be cast (e.g. turbine blades). These metals would destroy ordinary die casting moulds very quickly. Excellent dimensional tolerance is produced.

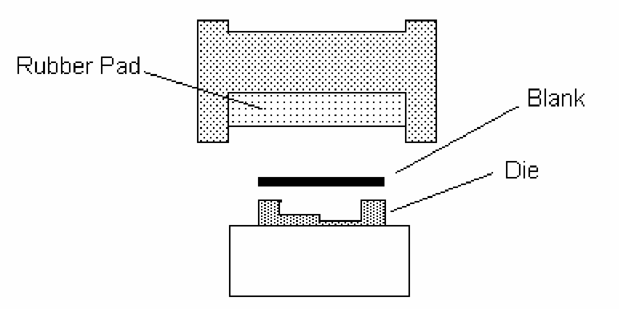
DRAWING

In this process, a metal billet is pulled through a die. The hole in the die has the shape of the finished section. This process is used to produce copper wire, seamless steel or copper tubing and so on. Hot rolled steel wire may also be used for further drawing as described earlier. Cold drawing produces work hardening and it may be necessary to anneal the metal at some stage.

The term DEEP DRAWING is applied to the process of punching a sheet material into a cup shape as shown below. The metal is drawn into the die by the punch.

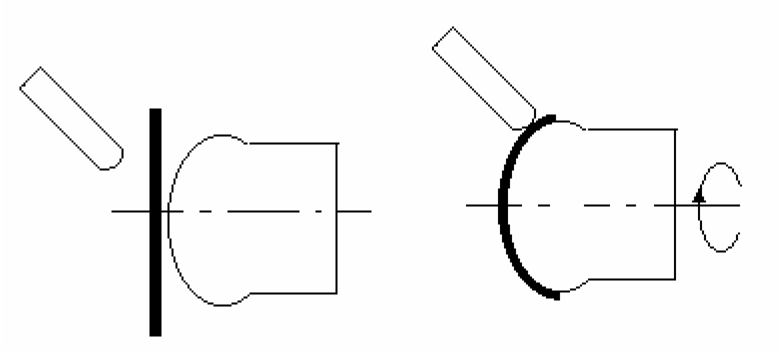


If the blank is clamped around the edge, the process becomes a PRESSING.



The blank is pressed into the shape, of the die by the rubber pad. This is used to produces car body panels and cooking pans.

SPINNING

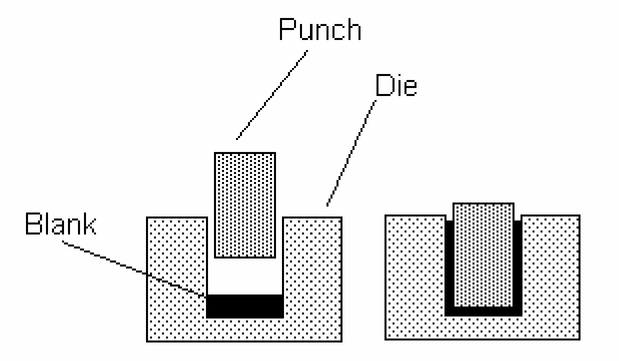


In this process the blank is held against the former and the whole assembly is spun. The blank is the forced into the shape of the former by forcing a forming tool against it. This method is used to produce aluminium satellite dishes, cooking pans and so on. The process is not best suited to large volume production.

EXTRUSION

Squeezing toothpaste from a tube is an example of extrusion. Under stress, ductile metal will flow and in industry a metal billet is forced through the die from behind by a powerful hydraulic ram. The die has the shape of the section required. This method is used to produce aluminium sections and quite complicated shapes may be produced this way.

IMPACT EXTRUSION



This process is similar to deep drawing but the blank is hit so fast with the punch that it flows plastically to mould itself into the shape formed between the die and punch. Drink cans and battery cases are made this way.

POWDER TECHNIQUES

In this process, metal powder is poured into the mould and pressed with a die into the required shape. The powder is heated and pressurised so that the particles fuse. The structure produced is porous because granules do not melt completely but become sintered leaving gaps between them. The end product may a course sinter or a fine sinter. Bronze bearing bushes which retain lubricants in the porous structure are produced this way. Steel components such as shaft couplings are made this way. Very hard materials such as tungsten carbide may be formed into cutting tool tips by this method.

MACHINING

Machining processes involve the removal of material from a bar, casting, plate or billet to form the finished shape. This involves turning, milling, drilling, grinding and so on. Machining processes are not covered in depth here. The advantage of machining is that is produces high dimensional tolerance and surface finish which cannot be obtained by other methods. It involves material wastage and high cost of tooling and setting.

NOTES ON NON - METALS

POLYMERS

Most of the shaping process described applies to metals but polymers may be moulded or machined depending upon their mechanical and thermal properties. You may recall that a thermoplastic may be re-melted over and over but a thermosetting plastic can only be melted once. Thermoplastics are shaped into bottles by BLOW MOULDING. They are easily moulded into buckets and other container shapes. They are also used to make tubing by being extruded hot through a die. They are also made into bags by forming the material into very thin sheets.
Thermosets are moulded into more durable components such as electrical plugs and appliance cases.

COMPOSITE MATERIALS

Glass and carbon fibre structures are formed by the use of thermosetting polymers and fibres. The fibre is laid onto a mould and the thermoset is pasted or injected into it with a curing agent which makes it set. The strength of the structure results from the fibres but other properties result from the thermoset.

4. HEAT TREATMENT OF STEEL

The mechanical properties of materials can be changed by heat treatment. Let's first examine how this applies to carbon steels.

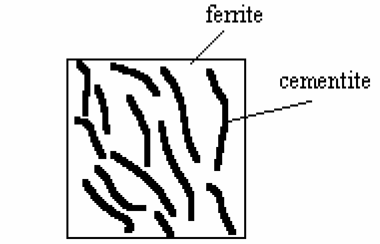
CARBON STEELS

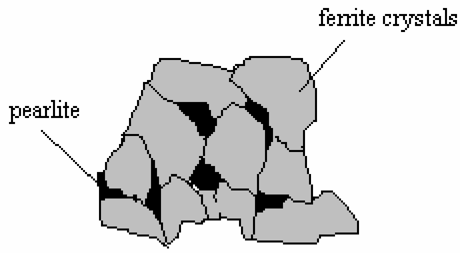
In order to understand how carbon steels are heat treated we need to re-examine the structure. Steels with carbon fall between the extremes of pure iron and cast iron and are classified as follows.

NAME	CARBON %	TYPICAL APPLICATION
Dead mild	0.1 – 0.15	pressed steel body panels
Mild steel	0.15 – 0.3	steel rods and bars
Medium carbon steel	0.5 – 0.7	forgings
High carbon steels	0.7 – 1.4	springs, drills, chisels
Cast iron	2.3 – 2.4	engine blocks

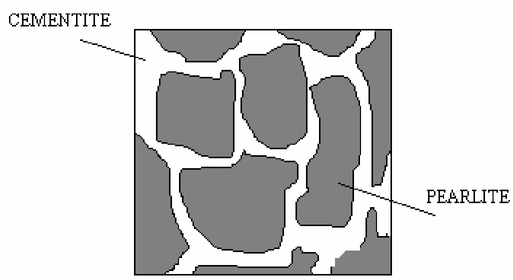
STRUCTURE

All metals form crystals when they cool down and change from liquid into a solid. In carbon steels, the material that forms the crystals is complex. Iron will chemically combine with carbon to form ***IRON CARBIDE*** (Fe_3C). This is also called ***CEMENTITE***. It is white, very hard and brittle. The more cementite the steel contains, the harder and more brittle it becomes. When it forms in steel, it forms a structure of 13% cementite and 87% iron (ferrite) as shown. This structure is called ***PEARLITE.*** Mild steel contains crystals of iron (ferrite) and pearlite as shown. As the % carbon is increased, more pearlite is formed and at 0.9% carbon, the entire structure is pearlite.



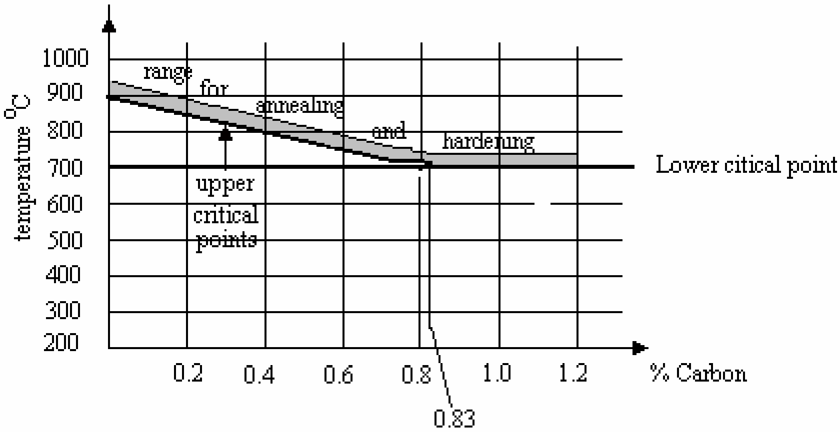


If the carbon is increased further, more cementite is formed and the structure becomes pearlite and cementite as shown.



HEAT TREATMENT of CARBON STEELS

Steels containing carbon can have their properties (hardness, strength, toughness etc) changed by heat treatment. Basically if it is heated up to red hot and then cooled very rapidly the steel becomes harder. Dead mild steel is not much affected by this but a medium or high carbon steel is.



When the steel is heated up to 700°C the carbon starts to dissolve in the iron like salt does in water. This produces a uniform structure called ***AUSTENITE***. As the temperature increases, the process continues until at some higher temperature the structure is all austenite. The temperatures at which this process starts and ends are called the lower and higher critical points. The upper critical point changes with %C as shown on the diagram. Notice that above 0.83%C the upper and lower points are the same. If the steel is cooled slowly, the reverse process occurs and cementite and pearlite forms. The following are all forms of heat treatment.

- Hardening
- Annealing
- Normalising
- Tempering

HARDENING

If steel just hotter than the upper critical point is plunged into oil or water (quenching) the steel cools very quickly. Instead of pearlite forming, a structure known as ***MARTENSITE*** is formed. This is a very hard substance and the resulting steel is hard. The degree of hardness depends on how fast it is cooled and water quenching is quicker than oil quenching. The graph shows the critical temperature plotted against %C. For example 0.3 % carbon steel should be heated to a temperature between 880 and 910^{o}C.

TABLE OF HARDNESS OF QUENCHED STEELS

Carbon %	0.1	0.3	0.5	0.7	0.9	1.2
Brinell Hardness	150	450	650	700	680	690

ANNEALING

The purpose of annealing is to soften hard steel. The steel is heated slowly to the upper critical point and held at this temperature for a time. It is then allowed to cool slowly. This process removes any stresses trapped in the material due to quenching, machining or mechanical working (such as rolling it).

TABLE OF ANNEALING TEMPERATURES RANGES FOR CARBON STEELS

Carbon %	0.12	0.12/0.25	0.3/0.5	0.5/0.9	0.9/1.3
Temperature ^{o}C	875/925	840/970	815/840	780/810	760/780

NORMALISING

This is similar to annealing. When the steel has been kept hot for a long time (e.g. for forging), the crystals become very large. When a cold steel has been mechanically worked, say by cold drawing it into a bar, the crystals are elongated in one direction. Normalising returns the crystal structure to normal and it is carried out by cooling the steel in air.

TEMPERING

The steel is heated up but not as high as the lower critical point. This allows some of the martensite to change into pearlite. This softens the steel but also makes it tougher.

TABLE OF TYPICAL TEMPERING TEMPERATURES

Component	Turning Tools	Drills Milling	Punches Twist Drill	Cold Chisels	Springs
Temperature ^{o}C	230	240	260	280	300

SELF ASSESSMENT EXERCISE No.2

1. Describe the method of carburising.
2. What process would you use to harden
   a) gear teeth
   b) machine tool slideway
3. Describe the process of full annealing.

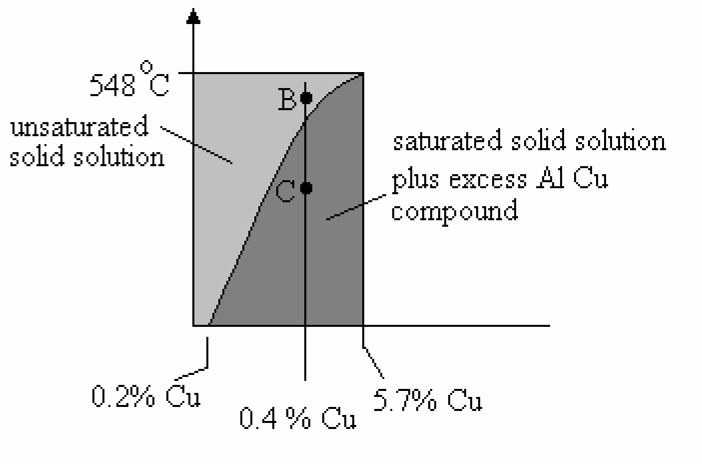
5. HEAT TREATMENT OF OTHER METALS

The heat treatment methods for other metals and alloys are numerous and would need a vast amount of study to cover them all. One important method worth studying is solution heat treatment and aging.

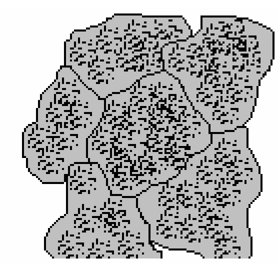
SOLUTION HEAT TREATMENT AND AGING

When salt is dissolved in water, the maximum amount of salt that can be dissolved depends upon the temperature. If the solution is saturated, then cooling causes the salt to precipitate out. Warming allows more salt to dissolve. The same principles apply to solid solutions but in this case the molecules precipitating out or being dissolved cannot move about freely so the changes are much slower.

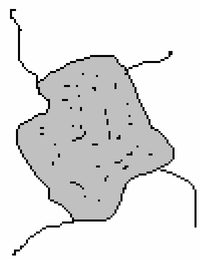
Consider the case of an aluminium-copper alloy. Part of the thermal equilibrium diagram is shown below. This shows that in going from 0 to 548°C the amount of copper that can be dissolved in aluminium increases from 0.2% to 5.7%



The light grey section contains an unsaturated solid solution. The dark grey portion contains the maximum dissolved copper possible (saturated solution) and any more copper than these forms the compound $CuAl_2$. Consider the alloy known as Duralumin widely used in making skins for aircraft and containers. This alloy contains 4% copper. Suppose the molten solution cools down very slowly. First it will pass through the unsaturated portion and will eventually end up as a saturated solution with excess copper.



At room temperature the structure will be as shown left with a background of solid saturated solution with 0.2% Cu and the rest are particles of compound containing the other 3.8% of the copper. The compound is a hard and brittle substance so duralumin in this form is brittle.



Suppose we know heat up the alloy to point C. The compound gradually dissolves into the solid solution (diffusion of atoms) as shown. At point B, just below the melting temperature, all the copper is dissolved into the solid solution with no compound at all. The alloy has to be kept at this temperature long enough for the transformation to be complete. If the alloy is now quenched in water for rapid cooling, the copper is trapped in the solid solution and the solid solution is supersaturated. The quenched structure is stronger and more ductile. This is known as ***SOLUTION TREATMENT***.

If the quenched duralumin is left at room temperature for a few days, the structure partially reverts to the equilibrium condition and the strength and hardness increases and the ductility reduces. This is called ***AGE HARDENING***. This process may be accelerated by heating the alloy to 160°C and this is called ***PRECIPITATION HARDENING***.

SELF ASSESSMENT EXERCISE No.3

1. Write out a brief definition of the following. Describe at least one component that is made from it.

   Wrought iron.
   Mild steel
   Medium carbon steel
   High carbon steel.
   Cast iron

2. Write out a short description of the following heat treatments used with carbon steels. Explain what must be done in order to produce the effect. Explain the result of conducting the treatment (on hardness, strength, toughness etc.)
   Hardening
   Annealing
   Normalising
   Tempering

3. Find out the temperature required for tempering the following.
   Knives
   Twist drills
   Cold chisel
   Springs

4. List the properties that may be found by conducting a tensile test.
   Define hardness. List the types of machines that are used to measure hardness.
   Define toughness and brittleness. List the types of machines used to toughness.

5. Explain why low carbon steel will not harden when quenched.
   Explain why tools such as chisels and files are made from high carbon steel.
   Explain the microstructure of quenched carbon steel with the aid of a suitable diagram.
   Explain the purpose of tempering and explain the changes that occur to the microstructure of carbon steel.

6. Explain the grain structure produced by hot forging components such as crank shafts and explain the benefits produced.

   Explain what annealing does and why metals that have been cold worked are often annealed.