

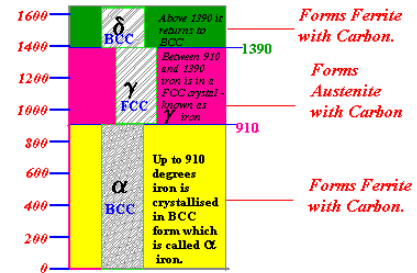
Iron Carbon Equilibrium Diagrams

Allotropic

Iron, when cooling from a high temperature, displays two special points known as arrest points or critical points. These change points occur at 1390°C and 910°C. Above 1390°C Iron exists with a BCC lattice but between 1390°C and 910°C it exists with a FCC lattice. Iron is said to be allotropic, which means that it can exist in two different forms depending on temperature.

The Allotropy of Iron

Iron changes its structure when heated. Iron has the ability to exist as BCC or FCC depending on the temperature. This ability is called the allotropy of iron



α =alpha γ = gamma δ = delta

Eutectic Point

- At this special change point, the liquid steel changes to the solid austenite + cementite phase without going through the pasty stage.
- This occurs at 1140°C for steel when 4.3% carbon is contained in the alloy.

Eutectoid Point

- At this special change point the solid austenite changes into solid pearlite.
- This occurs at 723°C for steel when 0.83 % carbon is contained in the alloy.
- Eutectoid **id** – Solid **id**

Ferrite

- This is almost pure iron but contains about 0.02% carbon.
- It has a BCC structure.

Cementite

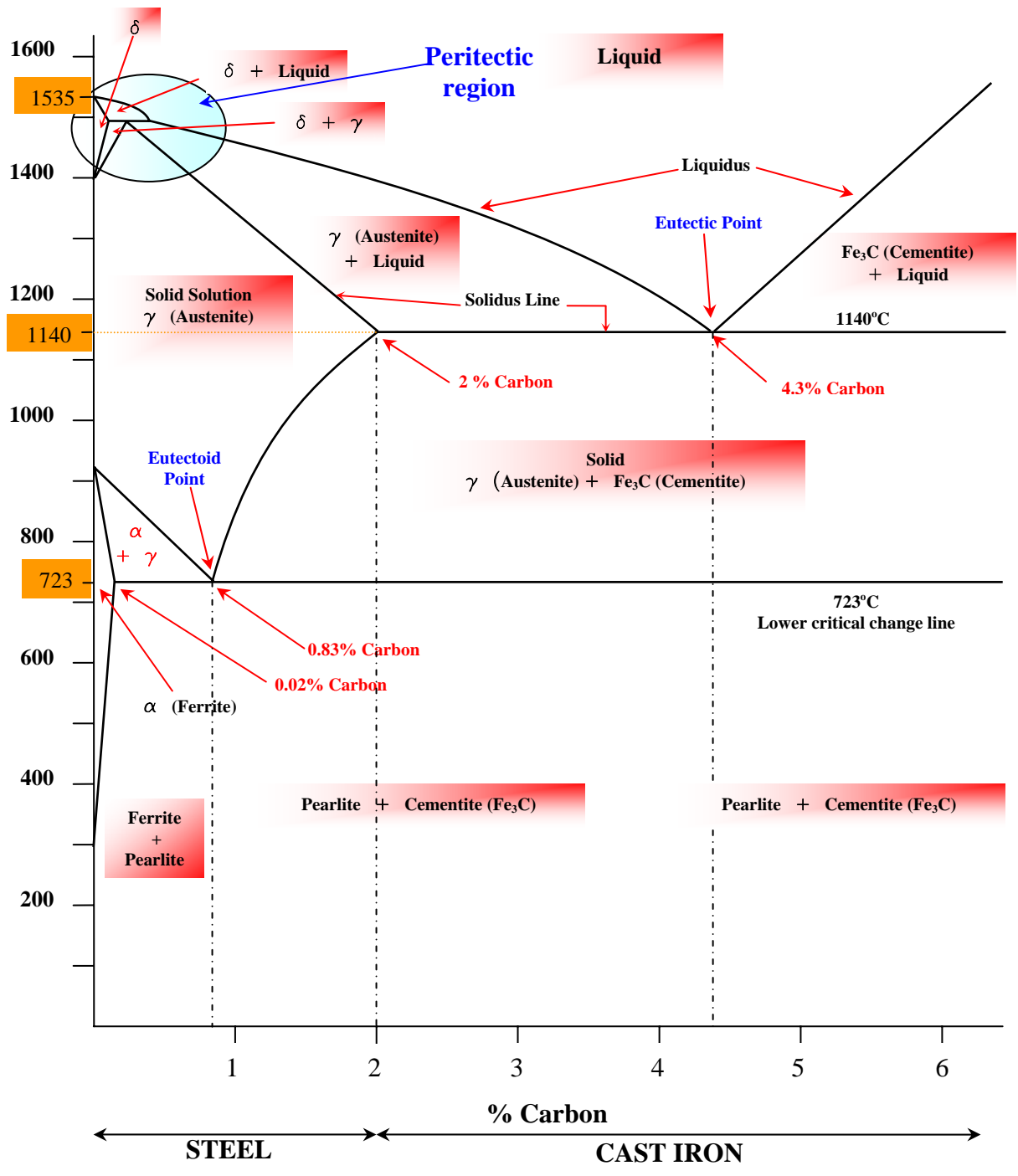
- This is a compound of iron and carbon.
- It is called Iron Carbide (Fe_3C). It is a hard, brittle material.
- This is what gives the hardness to high carbon steel.
- It has a higher melting point than either of its elements.

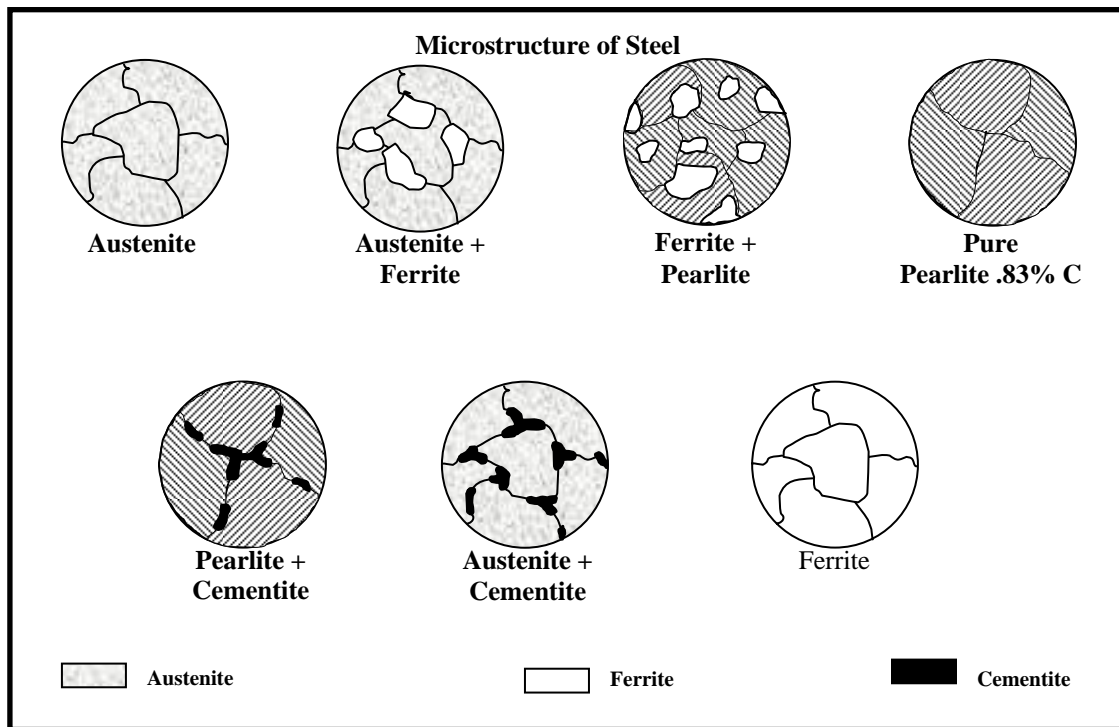
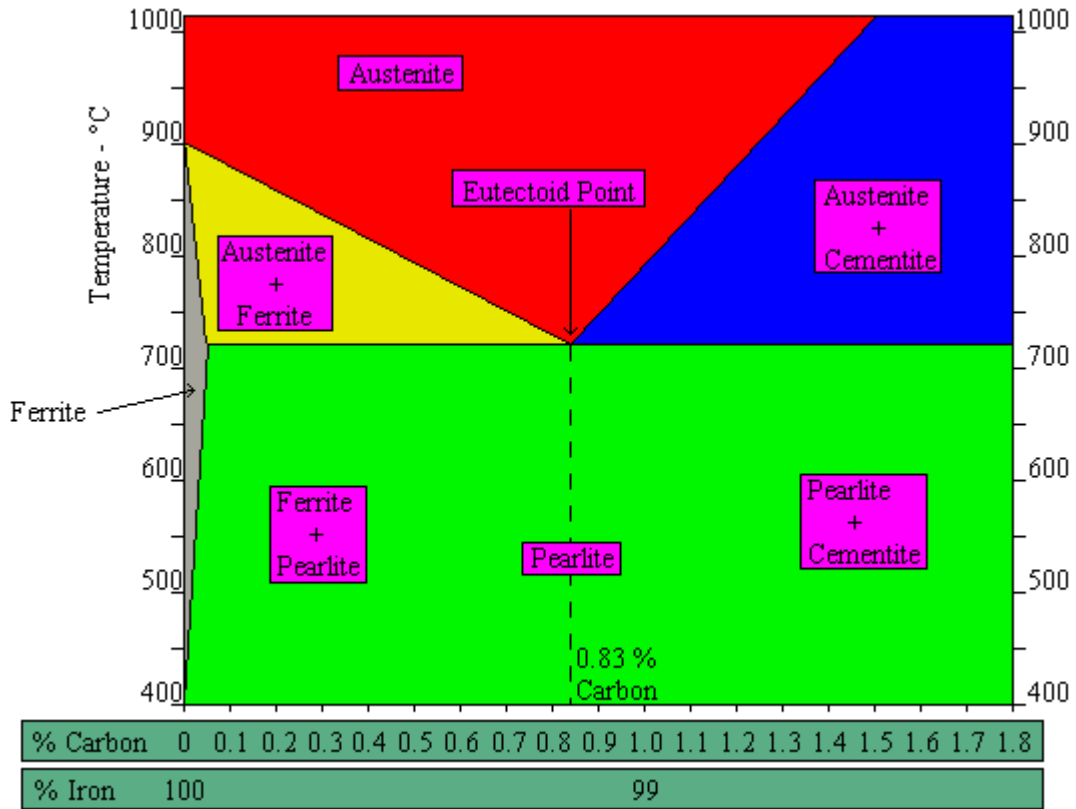
Pearlite

- At the eutectoid point (0.83% carbon) solid austenite changes into two solid phases - ferrite and cementite.
- These two solids combine to form pearlite.
- Pearlite is a layered structure of ferrite and cementite.

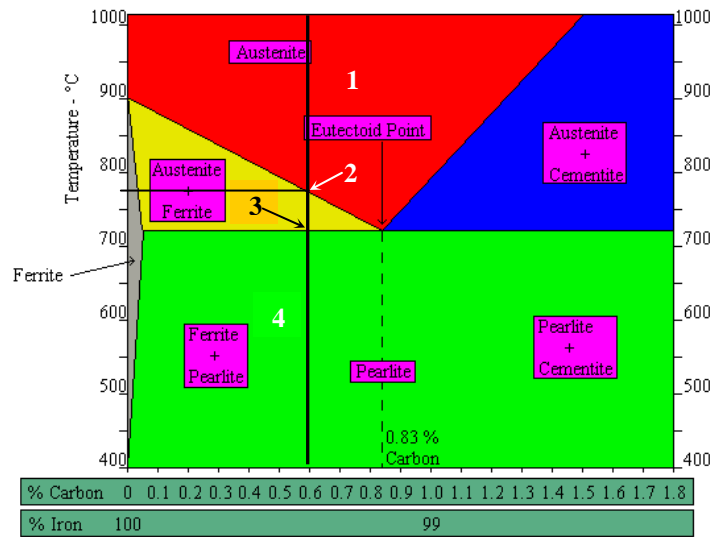
Austenite

- This is an FCC solid solution structure which can contain up to 2% carbon.
- It is a hard non-magnetic substance.





The Slow Cooling of 0.6 % Carbon Steel from a Temperature of 1000° C



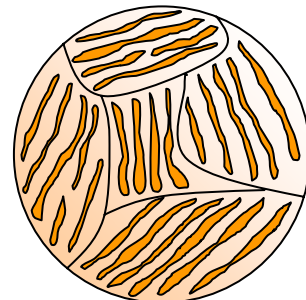
1. Here the carbon steel exists as Austenite. This is a solid solution of carbon dissolved in FCC Iron (γ)
2. Once the temperature reaches the upper critical temperature (approx. 775°C, from the graph) the austenite begins to form with ferrite.
3. At the lower critical temperature (723°C) all of the ferrite has been formed. Austenite and ferrite exist in this zone containing all of the dissolved carbon.
4. Below the lower critical temperature the austenite is transformed into pearlite. In this zone ferrite and pearlite exist.

Quenching (rapid cooling) of Carbon Steel from 1000°C

If rapid cooling of carbon steel occurs the steel takes a new and different form. The carbon in the iron gets trapped and is not allowed to form as separate crystals of carbide. This results in considerable distortion of the structure which in turn makes slip impossible. This is displayed as a hard, brittle material. Its microscopic structure shows a needle-like grain composition. This is called Martensite. Martensite is a BCT (Body Centred Tetragonal) Structure. Steels existing as Martensite are useless and need to be put through a heat treatment process called Tempering.

Defination:

When steel is cooled rapidly a structure known as Martensite is formed. In steels, Martensite is very hard and brittle.



Microstructure of Martensite

Rapid cooling (quenching) of 0.6 % Carbon Steel

- This can be referred to as 'the hardening of steel'.
- The steel must be heated well above the upper critical temperature (775°C for 0.6 % Carbon Steel). Usually 1000°C plus.
- During the fast cooling the FCC structure tries to change to BCC but fails to do so.
- A different structure is produced called Martensite, which is hard and brittle.

Quenching Media In Heat Treatment

- Caustic Soda Solution
- Brine (water & salt solution)
- Cold Water
- Warm Water
- Oil (less severe and helps to prevent distortion and cracking).
- Air
- Soaking (leaving the component in the furnace, switching off the furnace and allowing it to cool naturally)



Descending order of
quenching speeds.
Fast - Slow

Heat Treatment Process

The basic steps in a heat treatment process are:

1. Heating the component to a particular temperature
2. Soaking or keeping the component at this temperature for a period of time.
3. Cooling the component in a particular way.

Heat Treatment Processes

- Annealing
- Normalising
- Stress Relieving
- Hardening
- Tempering

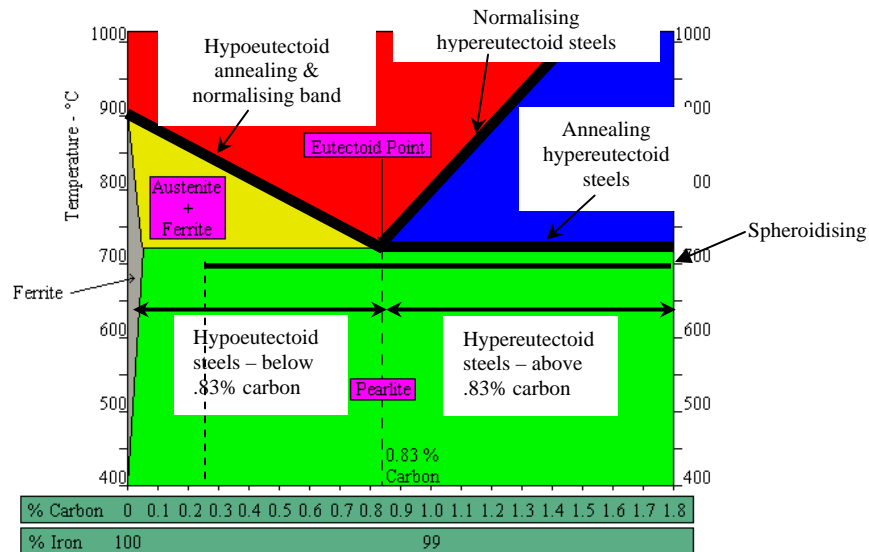
Specialised Heat Treatments

- Case Hardening
- Induction Hardening
- Flame Hardening
- Age Hardening

Annealing

Full annealing, which is carried out in order to make the metal as soft as possible, also improves ductility, refines the grain size and removes internal stresses. Internal stresses, or residual stresses, result from cold working (when the material is bent into shape) or from rapid heating and cooling. Internal stresses or residual stresses may speed up corrosion or encourage fatigue. During cold working of a material or a component the

grains of the metal are deformed. As annealing is carried out, a whole new set of grains appear, which replace the old grains or crystals. This is known as recrystallisation. Once the desired temperature is reached during annealing, the steel is *soaked* to ensure uniform heating. Cooling is controlled by reducing the temperature of the furnace gradually; this is often done by switching off the furnace and allowing it to cool naturally.



Process annealing is used when components made from up to .25% carbon steel are going through a manufacturing process which involves cold working. Process annealing is not as costly as full annealing because the temperatures required are not as high. To process anneal carbon steel containing up to .25% carbon it is heated to a temperature of about 80°C to 180°C below the lower critical temperature. It is allowed to soak for a time, and then normally cooled in air. Recrystallisation takes place in a similar manner to that in full annealing but because the temperature is lower, the new grains are much smaller.

Spheroidising

Higher carbon steels are heated to 30°C below the lower critical temperature, and put through a process annealing procedure. This is known as *spheroidising*. This improves the machinability of the steels because the hard cementite is gathered into spheres.

Normalising

When a material is formed by cold rolling, hot rolling, forging, etc., stresses are set up in the material. Normalising is very similar to full annealing and is a process that removes these internal stresses. For hypoeutectoid steels the metal is heated to the same temperature as for full annealing and allowed to soak until it is heated evenly throughout. Hypereutectoid steels are heated to their upper critical temperature, soaked and allowed to cool in air. The cooling rate is slightly faster than in annealing. This gives a fine grain structure which is free from internal stresses and has improved machinability. Normalised steel has higher strength and lower ductility than fully annealed steel.

Stress Relieving

This is a process in which the component is reheated, held at a slightly elevated temperature for a period of time and then cooled slowly. The temperature and period of time will vary depending on the component.

Hardening

Heating carbon steel until it is red hot, and then quenching it in water produces a significant change in the steel. It results in the steel becoming hard and brittle. The iron carbon diagram provides information about the various heat treatments for carbon steels. Martensite is formed during this hardening process. The extent to which steel can be hardened will depend on its composition. The carbon content is very influential, as is the rate at which the hot steel is cooled. The chromium or vanadium in some alloy steels will also affect the hardening process.

Tempering

Tempering involves re-heating the steel to a temperature below the lower critical temperature (723°C for Carbon Steel). The tempering temperature can range from 250°C to 500°C. Tempering relieves some of the internal stresses caused by rapid cooling and allows some of the Martensite to change into Ferrite + Pearlite (or Cementite + Pearlite). The tempering temperature depends on the properties required for a component. i.e. The balance between hardness and toughness.

Case Hardening Using Carbon

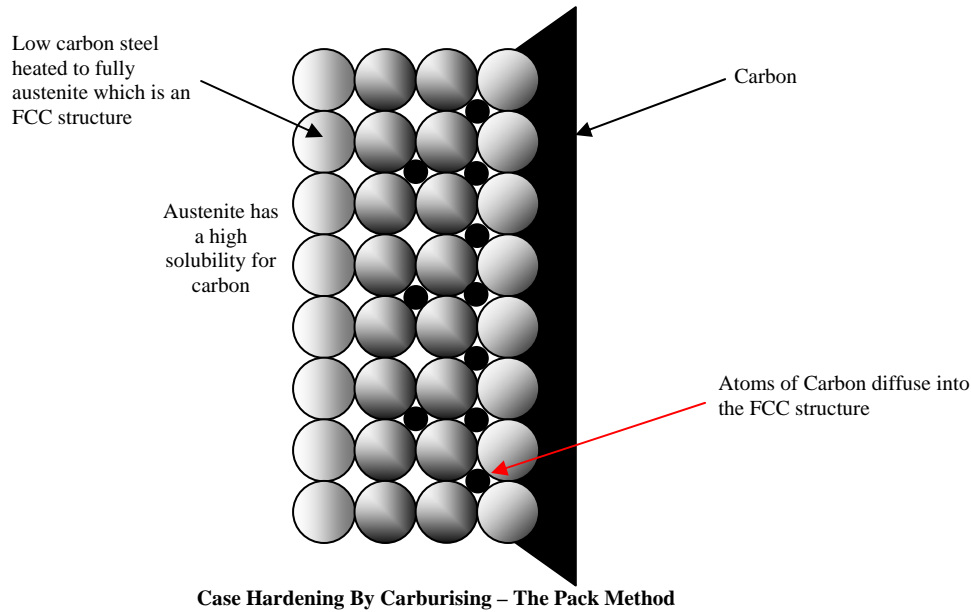
The hardening process that we have already discussed is based on the carbon content being greater than 0.3%. If a component does not contain enough carbon then the heating and rapid cooling process will have little effect. It is possible to add additional carbon to the outer surface of the steel component. This outer surface can be heat treated in the normal manner and is called the '*case*'. This process is known as case hardening and results in a component with a hard outer skin and a softer tough core.

The addition of carbon to the outer skin is known as carburising and can be carried out by;

- **The pack method (solid carburising)**
- **Salt bath carburising (liquid carburising)**
- **Gas carburising (gas carburising)**

The Pack Method

This is where the component is packed in a box surrounded by a carbon rich material and placed in a furnace at 920°C. This temperature is above the upper critical point, which allows the carbon to diffuse into the austenite. The high carbon case has a coarse crystalline structure which is prone to cracking. After cooling, the component is immersed in a bath of molten salt and kept at a temperature of 780°C.



Salt Bath Carburising

Case hardening without causing coarse structures is possible using salt bath carburising. The component is placed in the salt bath at 900°C for one hour. This gives a thin carbon case and not too much grain growth. It is then quenched in water to harden the surface.

Gas Carburising

This is carried out in a special sealed furnace. The carburising agent is a carbon rich gas circulating in the furnace chamber. This is a fast method of carburising and greater control over the process is possible.

Case Hardening Using Nitrogen

Nitriding

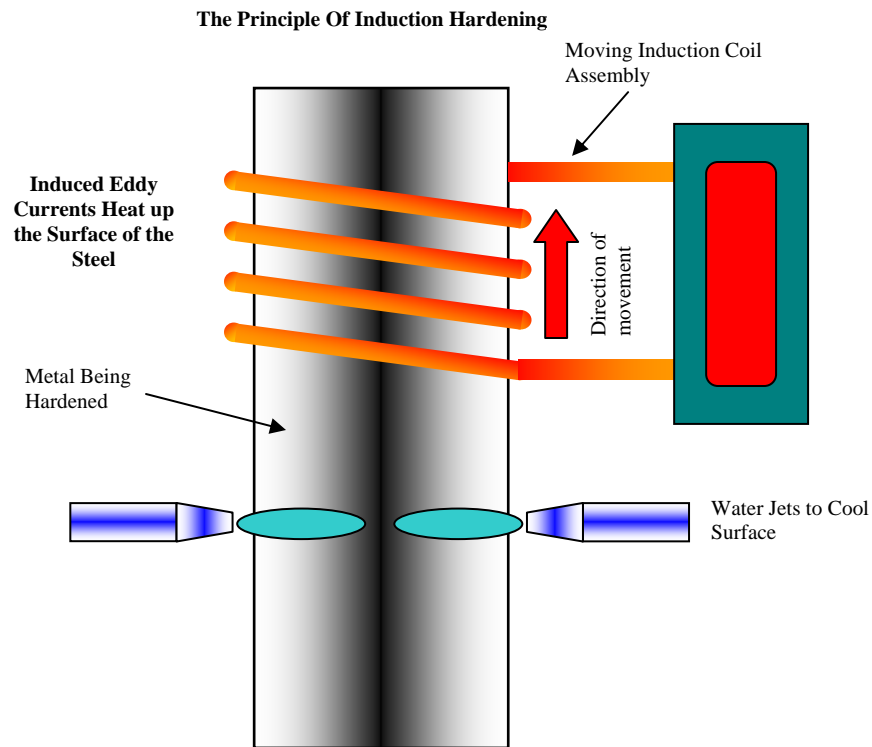
This is an expensive method of case hardening but is used where high quality is required. It is used for alloys which contain elements such as chromium, vanadium and aluminium. During heating, these elements form *nitrides* at the surface. A nitride is a binary compound of nitrogen – e.g. aluminium nitride. Nitrides are ultra-hard, so the cases formed, although thin, are extremely hard also. Nitriding is carried out in a furnace in which ammonia is circulated. Heating the ammonia produces nitrogen. The temperature of the furnace is 500°C and the process can take up to 100 hours. This process can be used to case harden parts which are finish machined. Because no quenching is necessary, no distortion of the component is likely.

Carbonitriding

This is carried out in a gas atmosphere in a special furnace. The gas is a mixture of ammonia and carbon monoxide. This atmosphere can produce carbon and nitrogen, and both of these elements diffuse into the steel. The iron carbides and iron nitrides produced are very hard at the surface of the component. The component is quenched during this process once the required case depth is achieved.

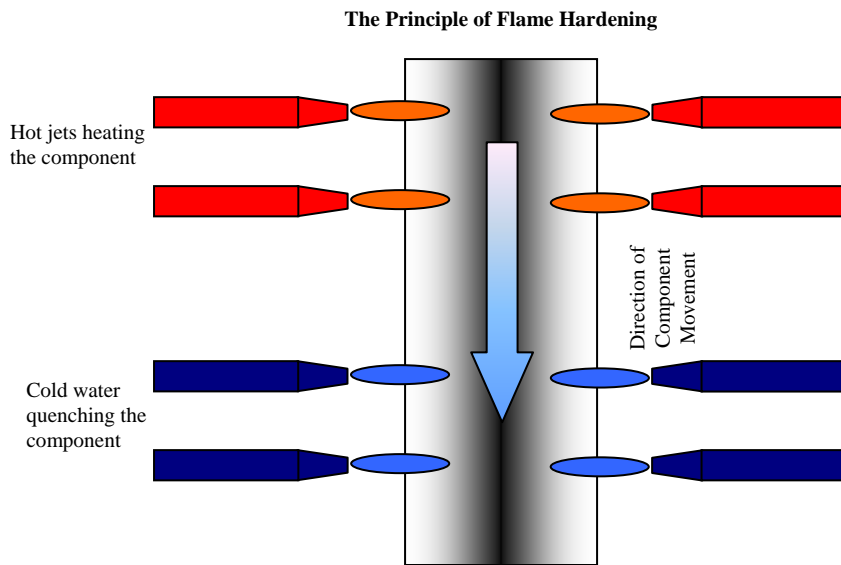
Induction Hardening

It is sometimes necessary to heat treat a component in such a way that it has a very hard outer surface and a softer inner core. An example of this would be the slideways of a lathe. The process of induction hardening involves the heating of the component very quickly in small areas using a high frequency electric current. This high frequency current passing through the coil produces eddy currents in the component. These cause a rapid rise in temperature in the outer surface. Water is then sprayed onto the surface by a number of jets, to quench the component.



Flame Hardening

This process is similar to induction hardening. It uses a flame of hydrocarbon gas with oxygen. The flame is hot enough to raise the temperature of the outer surface above the upper critical temperature without allowing the core to become heated. The component is quenched with water jets similar to that used in the induction hardening process.



Age Hardening

Ferrous and non-ferrous alloys can be age hardened. The age hardening process involves quenching from high temperatures and allowed to remain at room temperature for a few days. In modern times, components are heated to a higher temperature than room temperature to speed up the age hardening process.

Measurement Of Furnace Temperature

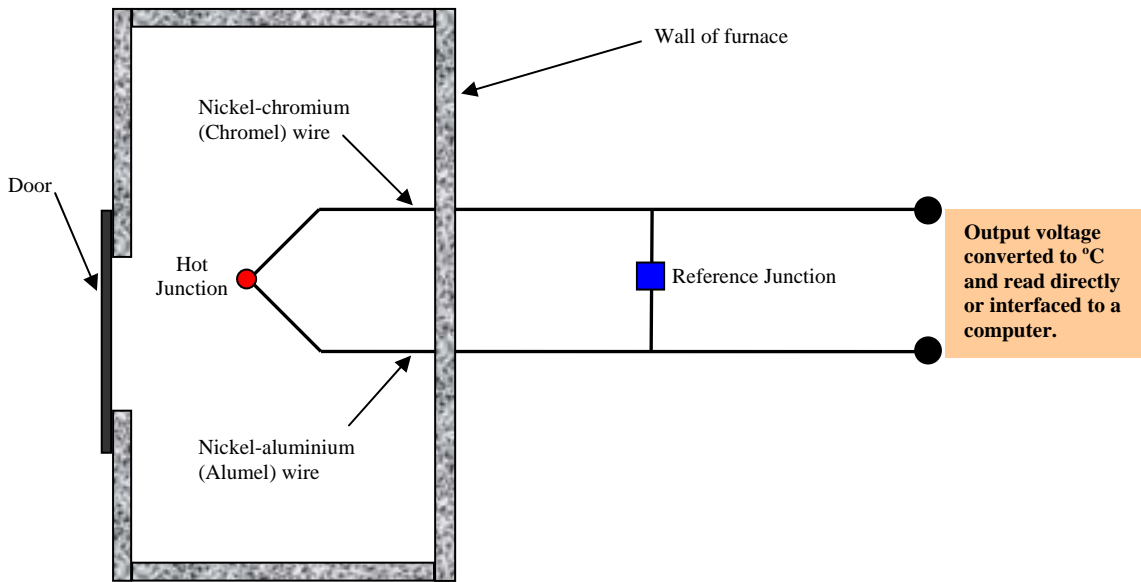
The measurement and control of the temperature in a heat treatment furnace is of extreme importance. Modern heat treatment furnaces use pyrometers to measure the temperatures. Ordinary thermometers are of no use due to the extremely high temperatures used, up to 1100°C.

Two common methods of temperature measurement used in modern times are;

- **The Thermocouple Pyrometer** (Thermo-electric)
- **The Optical Pyrometer**

The Thermocouple Pyrometer

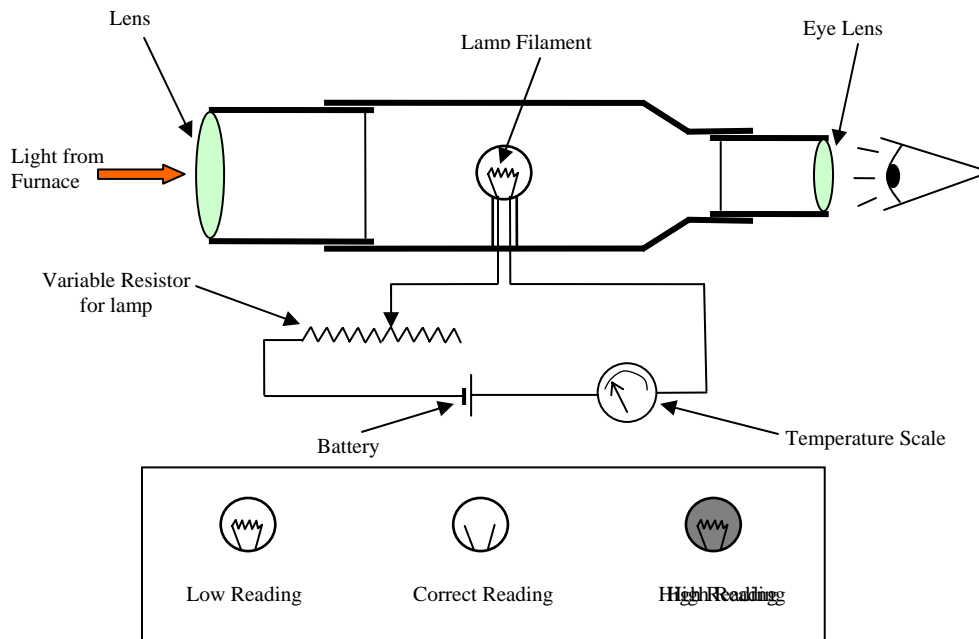
If one end of a thin wire is heated, heat will flow from the hot end to the cool end. This movement of electrons will produce a very small voltage in the wire. This is called a *thermo-electric effect*. If a couple of different types of wire (*Nickel-chromium & Nickel-aluminium*) of the same length are joined at each end a useful output can be obtained for measuring temperature. This can be referred to as the '*Seebeck effect*'. The hot junction, known as the thermocouple, is placed in the furnace. The other junction, known as the reference junction, is kept at a set temperature, this is commonly 0°C. The output is measured across the two wires. This output can be measured by a sensitive meter (Galvanometer) or amplified and interfaced to a computer.



The Optical Pyrometer

This pyrometer compares the intensity of the light coming from the furnace with the light coming from the filament of a lamp. The current flowing in the lamp is varied, until the light coming from the lamp matches that coming from the furnace. The variable resistance which is used to vary the current flowing in the lamp is graduated in $^{\circ}\text{C}$. The light from the lamp and the light from the furnace match when the filament of the lamp is no longer visible. Accuracy is good with this method but it requires a skilful eye and good judgement from the operator. The furnace doors must be transparent and clean otherwise they may have to be opened to get a reading. This will obviously lead to heat loss.

Optical Pyrometer



Properties of / Differences between, Grey Cast Iron & White Cast Iron

Grey Cast Iron

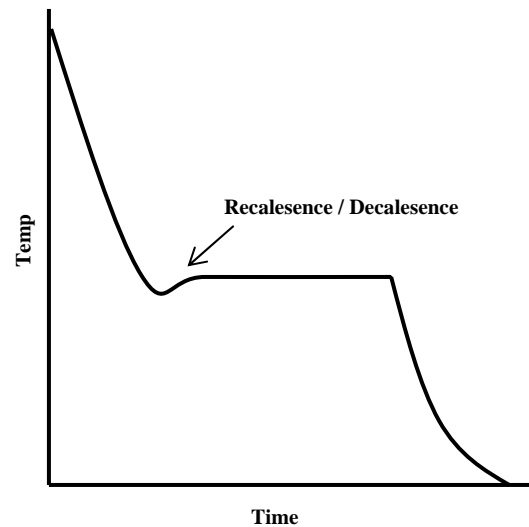
- Most common form of cast iron
- Least expensive of cast irons
- Carbon takes the form of graphite flakes
- When fractured, the freshly exposed surface has a grey appearance
- Alloy of iron, carbon, silicon and manganese
- Excellent compressive strength, machinability and wear resistance
- Weak in tension
- Self lubricating properties
- Outstanding vibration-damping characteristics
- Good corrosion resistance
- Great fluidity - desired for casting applications
- Formed under slow cooling conditions

White Cast Iron

- Receives its name from the white surface that appears when it is fractured – this whiteness is caused by the presence of cementite
- Carbon is present in the form of iron carbide
- Very hard and brittle
- Used where high abrasion resistance is required
- Formed under quick cooling conditions

Recalescence & Decalescence

When a piece of high carbon steel is heated to its critical point (723°C), the structure begins to change internally. The point at which the critical change begins is called *Decalescence*. When cooling high carbon steel these internal changes occur in reverse and the corresponding point is called *Recalescence*. At the points of decalescence and recalescence there should not be any temperature change but in fact there is.



Critical Range

The critical range starts at the point of Decalescence (723°C). During this period the material glows less brightly and contracts. A loss of magnetism is also experienced.