2

Ferrous materials

Introduction

The materials generally used in metalwork include ferrous materials, non-ferrous materials and plastics. Their selection and uses depend largely on their properties. The next chapter discusses non-ferrous materials and plastics. This chapter examines the manufacturing processes, identification, properties, uses and heat treatment of ferrous materials.

The importance of metals to man cannot be overemphasised. The most important metals are those of the ferrous group: that is, those that contain iron (*ferrum* is the Latin word for iron). The principal raw material for producing ferrous metals is iron ore. When a blast furnace is used to produce pig iron, which is the main substance used for manufacturing steel, the charge used consists of iron ore, coke and limestone.

Iron ores

Iron ores are minerals from which iron can be extracted. Much of the world's iron is extracted in Russia, Kazakhstan and the Ukraine. Other important producers are the USA, Australia, France, Brazil and Canada. The more important iron ores are magnetite, hematite, limonite and siderite.

Magnetite (Fe_3O_4) is one of the richest iron ores, which contains about 65 per cent iron. It is widely distributed. It is very hard and black, in the form of a stone. It has strong magnetic properties. **Hematite** (Fe_2O_3), which is red in colour, contains 50–60 per cent of iron. It is found in large quantities in the USA and Spain. **Limonite** ($2Fe_2O_3 3H_2O$) is mostly iron oxyhydroxide, but is usually found mixed with hematite and other iron oxides. It is yellowish brown and contains 30 per cent of iron. It is found in Sweden, France and Germany. **Siderite** ($FeCO_3$) or **chalybite** is a low-grade ore, which contains about 30 per cent of iron. It is mined in the East Coast areas of the UK.

Limestone acts as a flux in the production of pig iron from iron ore. It combines with most of the impurities such as sulfur, silicon and manganese to form **slag**, which is drained off. When slag solidifies it serves as a useful by-product for road building and cement manufacture.

The smelting of pig iron is made possible by the use of **coke**, which serves as the fuel for burning. Coke is produced by heating coal in the absence of air to drive off coal gas (a mixture of gases, including hydrogen, methane and carbon monoxide). Used in the blast furnace, the coke acts as a reducing agent.

Iron production

Pig iron, which is produced from iron ore, is the raw material for manufacturing other ferrous metals, such as wrought iron, cast iron, mild steel, alloy and carbon steels (Figure 2.1).

Pig iron smelting

The furnace for the manufacture of pig iron is called a **blast furnace** (Figure 2.2). It is a tall steel structure about 30 m high. The hearth is between 6 and 9 m in diameter. The furnace is lined on the inside with refractory fire bricks. Other parts include the stack, tuyere, hearth, iron and slag tap holes and the hopper.

Charging

The raw materials (the charge) are mechanically fed into the hopper. The small bell opens to allow them to flow

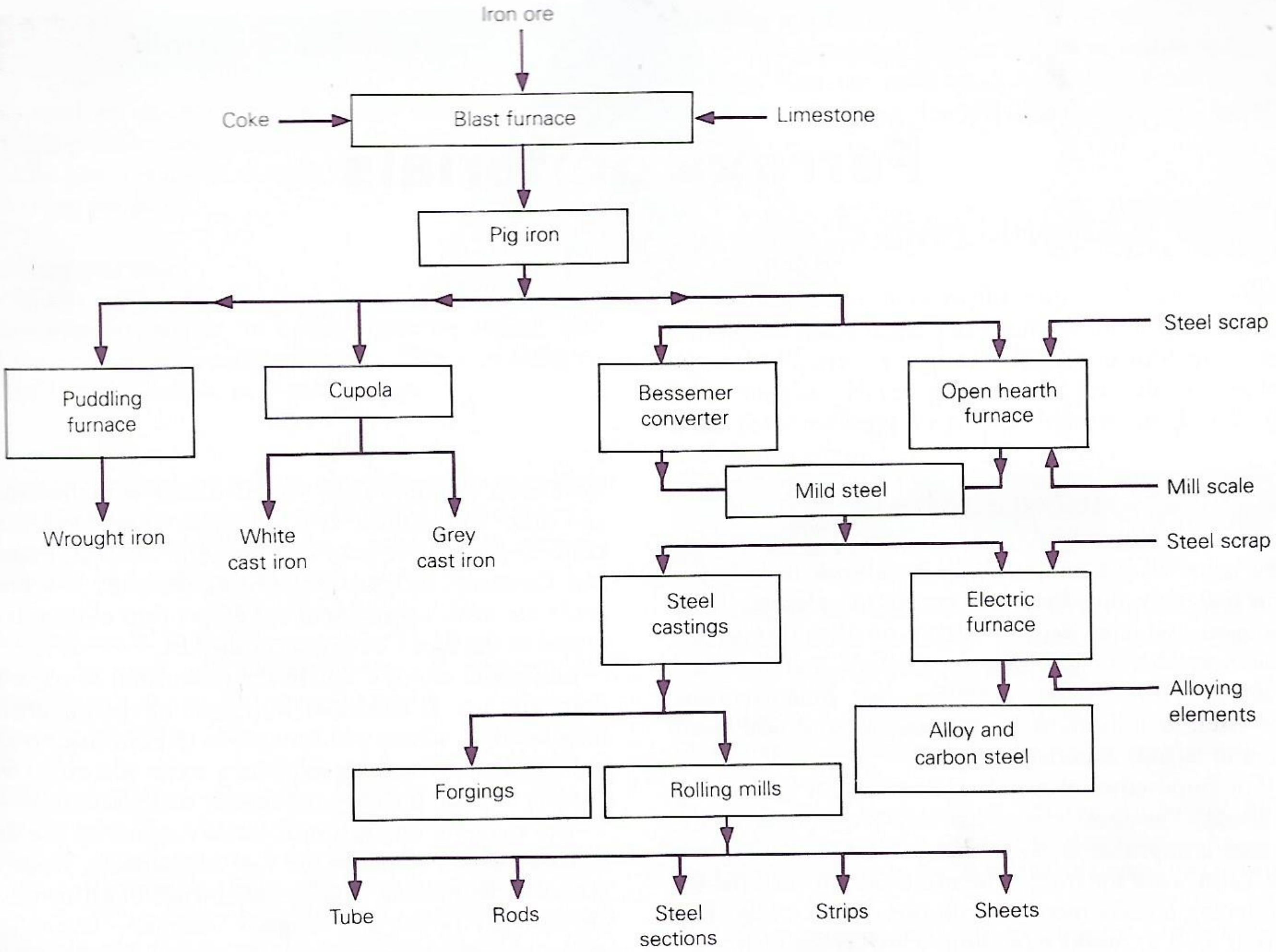


Figure 2.1 Flowchart of iron and steel production.

into the aperture, which is closed at the bottom by the large bell. When the charge has flowed into the aperture the small bell then closes and the large bell opens to allow it flow into the furnace. This arrangement prevents hot gas and air from escaping from the furnace.

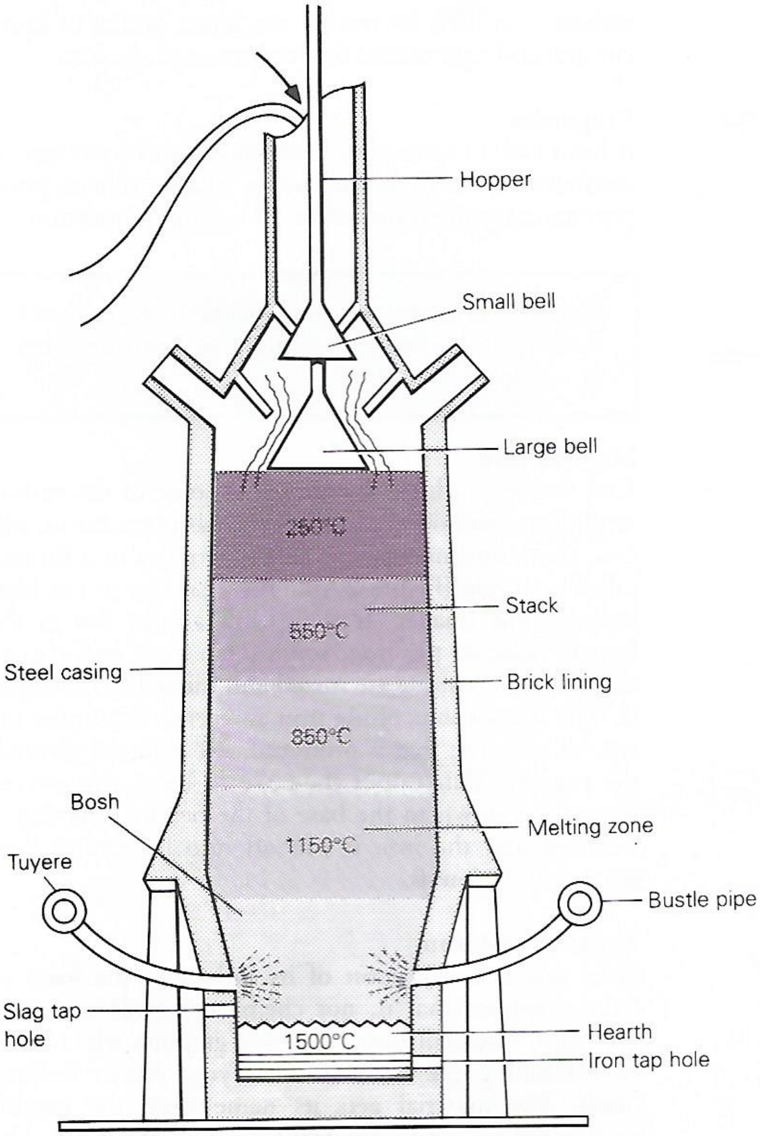
Smelting

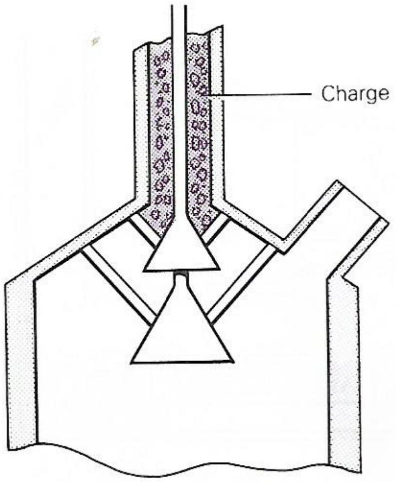
The limestone and the iron begin to form a spongy mass at the second heat zone (550 °C). This continues until the third heat zone (1150 °C), where the actual reduction of iron ore to iron takes place. Slag and molten iron are produced; as the iron is heavier than the slag, it settles at the bottom of the hearth, and the slag floats on top. The slag is tapped through the slag tap hole before the molten iron is cast into blocks in metal moulds called **pigs**, or taken direct to steelmaking furnaces.

Wrought iron

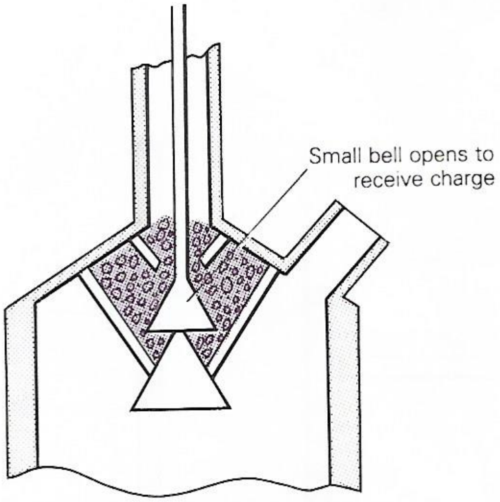
Wrought iron is the purest of all ferrous metals, containing about 99.9 per cent iron. Because of this it has special qualities, being strong, tough and easy to machine. It resists corrosion, and its ability to withstand shock makes it suitable for use as haulage gear, couplings and shackles.

The **puddling furnace** (Figure 2.3) is used in the production of wrought iron. Pig iron, which is the main charge of the furnace, is rid of most of its impurities (such as carbon) by stirring. Carbon is eliminated in the form of carbon monoxide gas, which escapes and burns on the surface. The pasty mass of iron – in the form of **balls** or **blooms** of about 30 kg in weight – is removed and hammered and rolled into bars or strips.

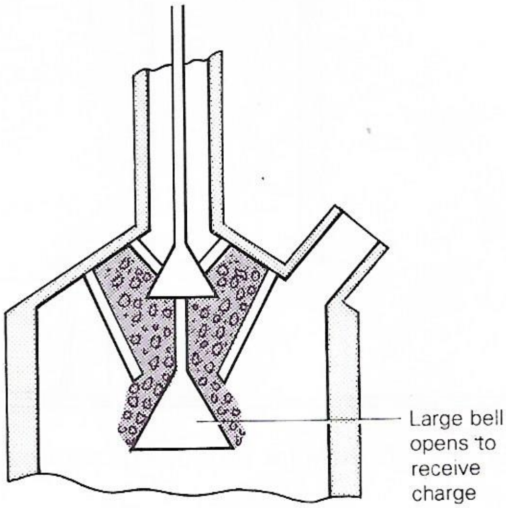




Filling the hopper



Function of small bell



Function of large bell

Figure 2.2 The blast furnace.

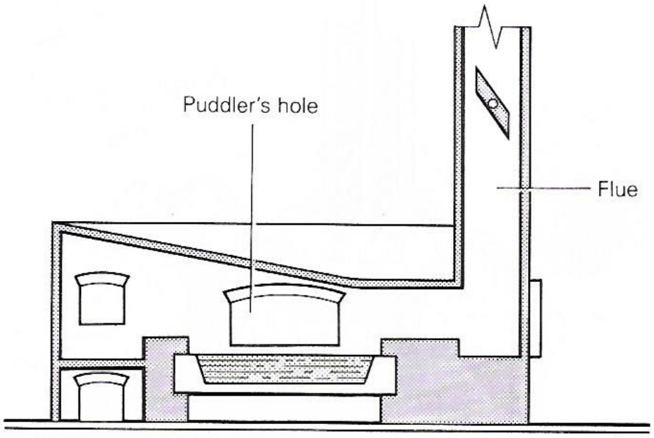


Figure 2.3 Puddling furnace for producing wrought iron.

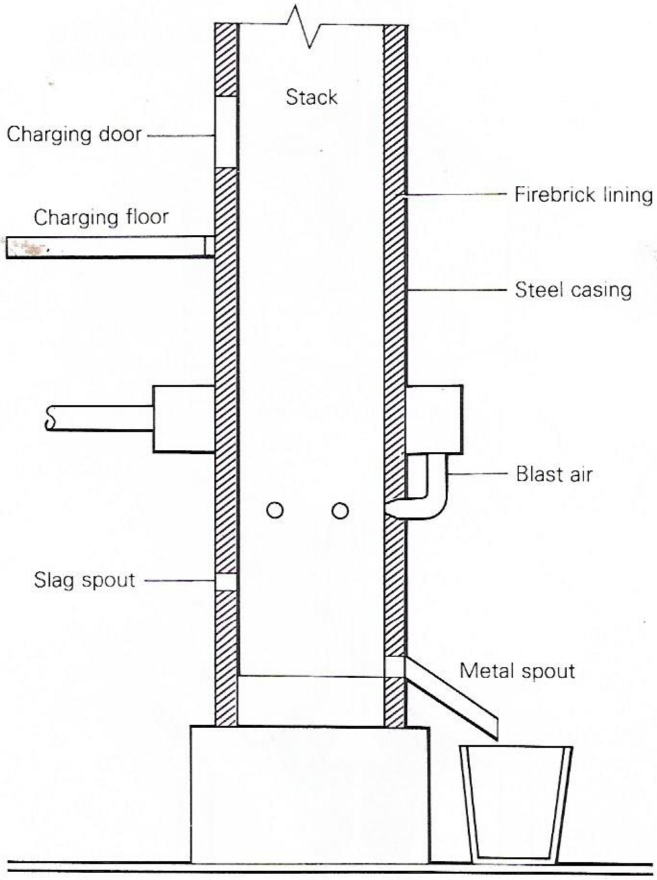


Figure 2.4 Cupola for producing cast iron.

Cast iron

Cast iron is a ferrous metal, and an alloy of iron and carbon. It is used for casting machines, bodies of horticultural and agricultural implements, and the like.

Properties

It has a carbon content of between 2.5 and 4 per cent in combination with other elements, such as silicon, phosphorus, manganese and sulfur, in varying proportion.

> Cast iron is harder and more brittle than steel, and these qualities make it difficult to bend or forge into shape.

Manufacture

Cast iron is produced by removing some of the carbon in pig iron, and other elements such as phosphorus, silicon, sulfur and manganese, in the foundry in a furnace called a **cupola** (Figure 2.4). This is similar to the blast furnace, but smaller. It is lit with a coke fire in the hearth. Selected pig iron, some scrap iron, and a small amount of limestone are mixed and melted in the cupola. The proportions of pig iron and scrap determine the type of cast iron that is produced. Air is forced through the **tuyeres.** This causes the coke to burn; the molten iron settles down to the base of the hearth. The slag is removed and the iron is run off into ladles and then poured into moulds.

Types of cast iron

Grey cast iron has most of its carbon in the form of **flake graphite** (that is, not chemically combined with the iron). You will notice the free graphite when filing or machining grey cast iron, as your hands become black. The material gets its name from the greyish appearance caused by the graphite when fractured. The main constituents of this type of cast iron are iron and carbon. It is sometimes alloyed with silicon, sulfur, manganese and phosphorus. Silicon helps in the formation of the free graphite, which serves as a 'softener'. Sulfur and manganese can cause the iron to harden. Phosphorus encourages fluidity.

Grey cast iron has a low melting temperature: 1150–1250 °C. This, coupled with its fluidity when molten, makes it a suitable material for casting such things as machine tools, bodies and engine cylinder blocks. It is not able to withstand tensile forces, but it is good in compression. It is brittle, and machines well: it is machined dry because of the free graphite, which acts as a **lubricant.** Other uses of grey cast iron include the manufacture of bases of surface gauges, surface plates, and vices.

and, after passing over the charge, heat the other set until it becomes hot enough. The direction of flow changes approximately every 20 minutes. The periodic change in the flow of the heated gas and air is known as the **regenerative principle**.

The main processes involved when using the open hearth furnace are as follows. The charge consists of pig iron, scrap, millscale and lime to mix with other impurities to form slag. The mixture of air and gas is passed over the charge and burns over the hearth, directing the flame onto the charge. The metal is maintained at a very high temperature. Samples are taken from time to time for chemical analysis until the required composition is attained. A deoxidiser, such as ferro-silicon or ferro-manganese, is added to remove air and to bring the carbon to the required content. The molten steel is finally poured into ladles and then into ingot moulds, or is continuously cast.

The basic oxygen converter

> The oxygen furnace is one of the two major steel-making processes used in the United Kingdom (the other being the electric arc furnace).

The furnace produces up to 350 tonnes of steel in about 450 minutes or less. It is similar to the Bessemer converter (Figure 2.7), but uses oxygen instead of air to produce steel.

The converter is tilted and charged with scrap, molten iron (about 75 per cent of total charge). A water-cooled lance is lowered into the furnace, and oxygen blown at a very high pressure combines with carbon and other unwanted elements to remove impurities. The carbon leaves as carbon monoxide. Lime is added during the 'blow' to combine with the impurities to form slag. Alloy additions are added to the molten steel before **tapping** into ladles. The converter is finally turned upside down to pour the slag into ladles.

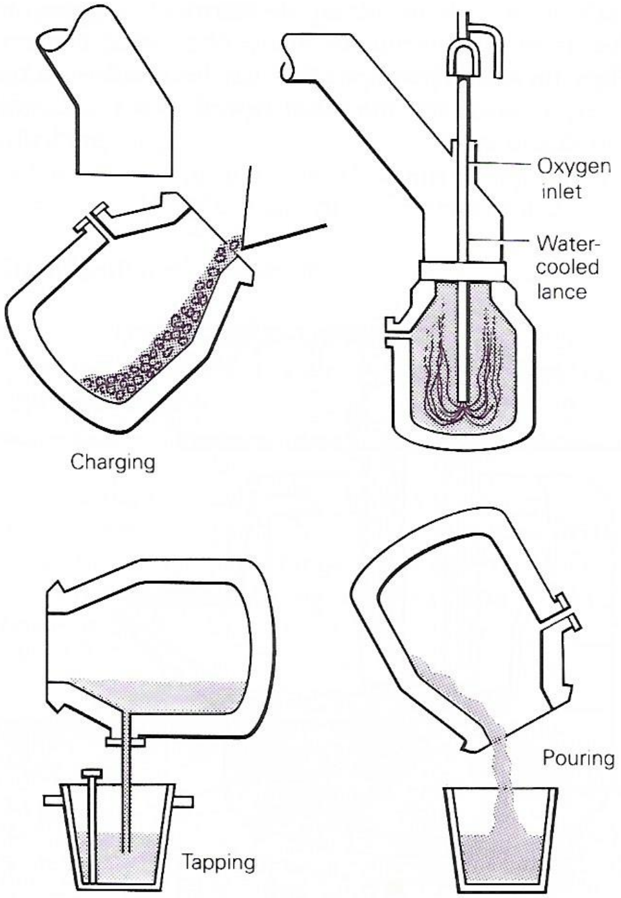


Figure 2.7 Oxygen converter.

Electric furnaces

The introduction of electric furnaces eliminated the effects of oxides formed by burning either coke or gases in the open hearth furnace and Bessemer converter. A very high-quality carbon and alloy tool steel is produced. The two types generally used are the **electric arc furnace** and the **high-frequency induction furnace**.

Electric arc furnace

The electric arc furnace was originally used to make special high-quality steels. However, today it is employed in producing alloy and stainless grades and carbon and other low-alloy steels. The process is costly because of the greater power consumption, but it makes it possible to monitor the final composition closely. Today's electric arc furnaces can produce up to 150 tonnes of metal in less than 90 minutes.

The furnace (Figure 2.8) consists of a circular bath with a movable top. It has a steel casing with the inside lined. There are three carbon/graphite electrodes, which generate the heat by a spark that passes between them. The whole furnace sits on a tilting mechanism, which allows charging and discharging to be carried out.

The charge consists of either scrap metal or good-quality open-hearth steel (when producing tool steel). The furnace is returned to the upright position after charging and the top is swung back into position. The electrodes, which are automatically controlled, are then lowered and the arc is struck as they get near the charge. The heat generated melts the scrap. Lime and fluorspar are then added to act as fluxes, and oxygen is blown into the melt. Impurities combine to form a liquid slag, which is run off by tilting the furnace. Samples are taken from time to time to analyse the carbon content. When the correct composition has been achieved the furnace is tilted and the metal tapped into a ladle and **teemed** into ingots.

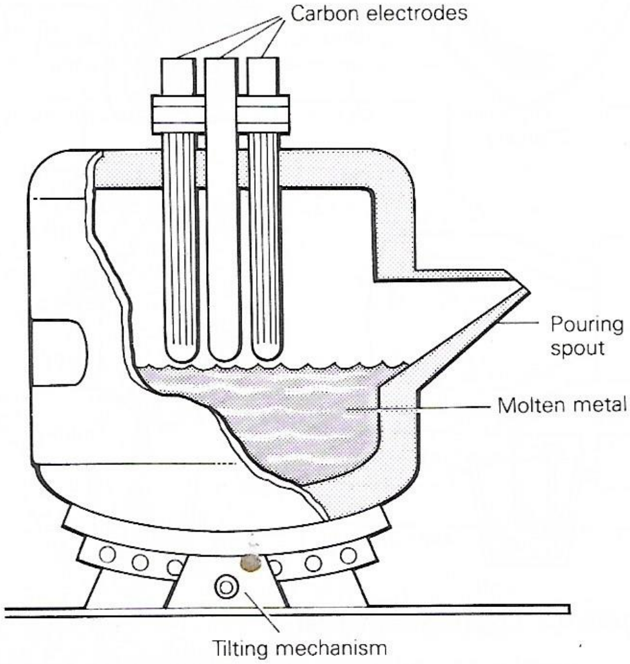


Figure 2.8 Electric arc furnace.

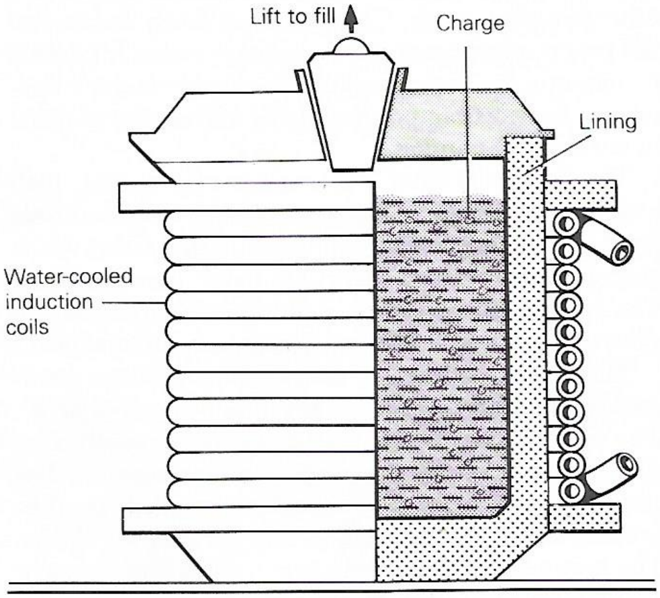


Figure 2.9 High-frequency induction furnace.

High-frequency induction furnace

This process produces high-carbon steel, stainless steel, high-speed steel and other alloy steels. The furnace (Figure 2.9) is smaller than the electric arc furnace, and only holds up to about 1 tonne. The furnace consists of a **crucible** with a **refractory lining** surrounded by a water-cooled copper coil through which an alternating current passes.

The charge consists of carefully weighed steel scrap and special alloy elements when producing alloy steels. An alternating current is caused to flow in the coil. The strong magnetic field surrounding the coil induces powerful **eddy currents** in the charge, which offers a resistance to the current, generating sufficient heat to melt the charge. The eddy currents cause the molten metal to circulate in the furnace, thus ensuring complete deoxidation and a sound product. When analysis of samples shows that the carbon content has reached the desired level, the metal is poured and teemed into ladles and ingot moulds respectively.

Properties of metals

It is essential to understand the properties of metals, because the selection and uses of metals largely depend on such characteristics. Table 2.1 shows the principal classification of the properties of metals.

The properties include:

Colour: This helps in identifying metals, and enhances their appearance when polished. It is useful in beaten metalwork and jewellery.
Fusibility: This is the characteristic of becoming liquid when a metal is heated. It is important when considering metals for casting.
Conductivity: This is the ease with which a metal allow heat or electricity to flow through it. Copper and aluminium are good conductors.

Table 2.1 Classification of properties of metals

Grouping	Description	Example
Physical	Concerning the body	Weight, fusibility
Chemical	Ability to withstand corrosion and alloying effects	
Mechanical	Effects of external forces on metals	Compression, tenacity

Hardness: This is the ability of a metal to resist scratching and wear. Centre punches and drills need this property.
Ductility: This is the ability of a metal to be stretched cold without breaking. It is an essential property for wire and tube drawing.
Brittleness: This is an undesirable property of snapping without warning. It is the opposite of toughness. Typical examples of brittle items include machine and bench vice bodies.
Toughness: This enables the material to be bent or twisted, and to resist shock without breaking.
Malleability: Materials that are malleable can be hammered, rolled or extruded without breaking. Gold and aluminium are examples of malleable metals.
Tenacity: This is the ultimate tensile strength of the material.
Elasticity: This is the ability of a metal to go back to its original shape or size after being stretched, compressed or deformed, as in a spring for example.
Magnetism: This is the property of acting as a magnet, to attract or repel iron.
Relative density: This is the ratio of the density of a material compared with the density of water; originally called specific gravity.
Expansion and contraction: Most metals expand when heat is applied to them and contract when cooled.

Classification of carbon steels

> Steel is composed of iron and carbon in varying proportions.

The carbon content ranges from a trace to about 1.5 per cent, providing soft, ductile and very hard steels at the lower and higher ranges respectively. Steels are therefore classified according to their carbon content, as shown in Table 2.2.

Table 2.2 Classification of carbon steels

Material	Carbon content (%)	Properties	Forms of supply	Uses
Low-carbon steel	0–0.18	Soft, ductile and malleable but not strong. Does not crack.	Available in rods, bars and sheets	Suitable for deep pressings. Stampings are used for car bodies.
Mild steel	0.25–0.3	Most common of all steels. Machines readily. It can be cast, forged and welded. It corrodes in the atmosphere.	Obtained in rod, bars, wires, sheets and various sections (e.g. 'T', angle)	For constructional purposes and general workshop use.
Medium-carbon steel	0.4–0.6	Machines readily. Can be forged and welded. When properly heat-treated, it is hard, ductile and strong.	Available in rods, bars, flats	Hammer heads, forged steel vice bodies, rivet sets, agricultural tools
High-carbon steel	0.7–1.4	Less ductile but combines hardness with high strength. Hard but can be heat-treated. Machines well. Can be welded. Those with carbon content 1.0% and above are the 'cast' or 'tool' steels.	Usually available in short lengths of rod in various sections (e.g. round, square, hexagon, octagon)	Suitable for all kinds of cutting tools as shown: 0.7% carbon – Cold chisels, punches 0.9% carbon – lathe tools, milling cutters, saw blades 1.0% carbon – drills, taps, dies 1.2% carbon – carpenter's chisels, plane blades 1.3% carbon – engineer's files, scrapers, ball-bearings

Marketing forms of iron and steel

After iron and steel have been produced they find their way onto the market to be put to various uses. This involves shaping or changing them into suitable forms and shapes so that they will be useful for making a wide range of articles. The forms include bars, rods, tubes, sheets, plates and strips.

In **forging**, the material is hammered or pressed into a diverse range of articles: car axles, for example. To produce **bars**, **rods**, or **tubes**, the molten metal or the red-hot ingot is first taken to the cogging mills, where it is reduced to **blooms** (typical size about 3600 mm). The blooms are changed into **billets** (about 100 mm) and then bars by squeezing them in shaped rollers. To produce **plates**, **sheets** and **strips** the billets are passed through cylindrical rollers at the slabbing mill until the desired sections are obtained. They are then cut to lengths (strips) or rolled into coils (sheets).

Hot metals that are rolled, pressed or forged have oxide scales, which on cooling leave the surface black: hence the name **black bars**. To produce **bright bars**, the black bars are **pickled** in dilute sulfuric acid, washed and oiled before passing through rollers.

Alloy steels

Alloying elements are added to plain carbon steels to improve their properties. The elements normally used are nickel, chromium, molybdenum, tungsten, vanadium, manganese and cobalt.

Nickel steels are plain carbon steels containing 0.4 per cent carbon with additions (in various quantities) of nickel. This increases the hardness and strength of the steel. It resists corrosion and is less liable to thermal expansion. Nickel steels are used for crankshafts and connecting rods, steam turbine blades, internal combustion engine valves and measuring instruments.

Chromium is added to plain carbon steels to improve their hardness. Chromium steels are used for ball and roller bearings, and cutlery. **Nickel–chromium** steels combine the properties of nickel and chromium, thereby improving their properties. They are used for high-tensile bolts and shafts.

Molybdenum increases strength, elasticity and machinability. Steel containing molybdenum is used in aero-engines. **Tungsten** increases hardness; tungsten steel is used for making tool bits, hacksaw blades, milling cutters and drills. **Vanadium** is added to steel t give general improvement in toughness and strength. Vanadium steel is wear resistant, and is used for crankshafts. **Manganese** increases strength and wear resistance. Manganese steel is used for conveyors, gears, and railway crossing points. **Cobalt** in steel increases toughness and strength, and helps it to retain magnetism. Steel containing cobalt can be used as cutting tools.

Heat treatment of plain carbon steel

Heat treatment of carbon steels involves heating the metal to a desired temperature and then cooling it at a suitable rate (Figure 2.10).

This process can help to:

1. make steel soft;
2. make steel hard;
3. relieve internal stresses in steel and make it tough;
4. give it a hard skin or **case**.

Tools, for example, need to be heat treated to give them the properties that they need. The tool or steel shoul be treated at specific temperature points, at whic changes occur when heating and cooling (Figure 2.11).

Behaviour of steel when heated and cooled

Heating

When steel is heated, its structure is not changed unt the temperature has reached the lower critical poin (about 700 °C) (Figures 2.10 and 2.11). The rise i temperature is observed to be uniform. Steels containin up to 0.87 per cent carbon are made up of ferrite an pearlite; those above 0.87 per cent consist of cementi and pearlite.

Between the lower and upper critical points there is a change in structure, as the carbon in the steel begins t form a **solid solution** with the iron. Heat is required t bring about this change, and so there is a 'pulse' or discontinuity in the temperature–time curve (Figure 2.10 This is referred to as the point of **recalescence**, and i occurs at the lower critical point. At the upper critic point (about 900 °C), austenite is formed. This is a solid solution of carbon and iron, and is a hard, nonmagnetic substance.

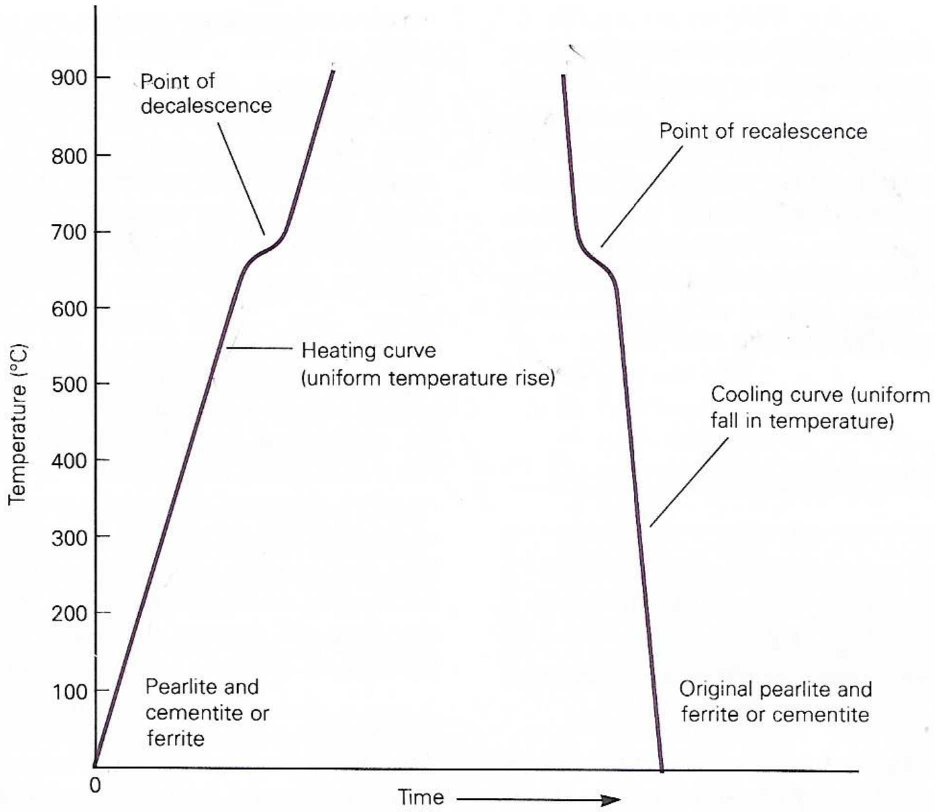


Figure 2.10 **Heating and cooling curves for steels.**

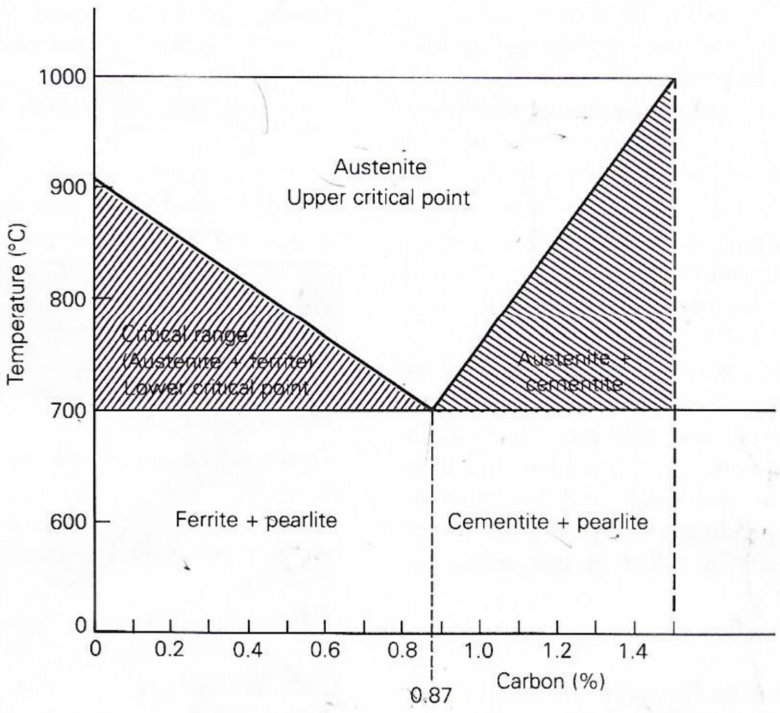


Figure 2.11 **Heat treatment ranges of carbon steel.**

Cooling
When the steel is slowly cooled down, the austenite is converted into pearlite and ferrite or cementite, depending upon the carbon content. The point of **recalescence**, which occurs at the lower critical point, is where the cooling is observed to pulse. The cooling can be speeded up by **quenching** in oil or water. When this happens, **martensite** (that is, austenite and large amounts of ferrite or cementite) is formed. Steels cooled this way are harder (depending on the amount of carbon content) than the slowly cooled type.

Heat treatment processes

> Heat treatment of carbon steels is commonly carried out using annealing, normalising, hardening or tempering.

Annealing
To anneal steel is basically to make it soft. Low-carbon steels are normally annealed. Annealed steels are therefore easy to machine, as the stresses caused by cold working are reduced. The annealing process involves heating the metal above the upper critical range (Figure 2.11) and cooling it slowly in the furnace or in sand. The slow cooling enables the steel to retain its original qualities. It consists of pearlite mixed with cementite or ferrite, depending on the carbon content, giving the steel a coarse structure. The process is suitable for forged steel, and for tools that require machining after they have been worked hot.

Normalising
This process, like annealing, is used to soften metals. Low-carbon steels are allowed to return to their original conditions. The process is just the same as annealing, but the rate of cooling is faster. The heated metal (heated to a bright cherry red colour) is allowed to cool in still air. The carbon does not have enough time to spread widely in the metal, and this gives normalised steel a fine crystal structure. A normalised metal is slightly harder than annealed steel, and less ductile. Normalising is used to produce a uniform grain structure when internal stresses in rolled or cast metal are relieved.

Hardening
Steels of high carbon content (between 0.8 and 1.5 per cent) are heated to between 700 and 900 °C (that is, just above the lower critical point). The structure is transformed to austenite; when quenched, it changes to a hard and brittle substance known as **martensite**.

After heating, the metal is quenched in brine (10 per cent sodium chloride solution), oil or water. The quenchant takes away the heat quickly, so that the hardened steel has the desired properties. It has high strength, is brittle, can cut other metals, and resists wear. Hardened steels are used for tools and wear-resistant surfaces, such as surface plates, knurling tools and shafts.

Case hardening
Mild steel can be given a hard **skin** or **case** by adding carbon and then quenching it. The metals to be treated are arranged in a steel tray, and carbon-rich powder (such as Kasenit) is sprinkled onto them. Heat (at cherry red) is then applied, and the metals absorb the carbon to a depth that depends on the time for which they are kept at a suitable temperature. The process is suitable for treating articles that need to be wear resistant and that have soft cores so that they can withstand shocks: for example, spanners, vee blocks and tool holders.

Tempering
After hardening, tempering is employed to remove the brittleness caused and to increase toughness. In the workshop, the colour changes during heating can be used to serve as a guide. Hardened steel is polished so that the colour change can be observed. It is then heated to the required tempering colour and quenched in a quenchant. Tempering is used to reduce brittleness in chisels, hammer heads and drills, for example. Table 2.3 shows the tempering colours, and some tools and articles that can be treated.

Table 2.3 Tempering chart

Use	Tempering colour	Temperature (°C)
Scribers, lathe tools	Pale straw	230
Drills and reamers Milling cutters	Dark straw	240
Taps and dies Shear blades	Brown	250
Plane irons, wood chisels, cold chisels	Brownish purple	260
Flat drills, forging set, wood chisels	Purple	270
Spanners, springs, screwdrivers, knives	Blue	300

CHECK YOUR UNDERSTANDING

- The principal raw material for the production of pig iron, which is the main charge for manufacturing steel, is iron ore. Common types of iron ore include hematite, magnetite and limonite.
- The blast furnace is used in the production of pig iron. The following furnaces produce other materials: puddling furnace (wrought iron); cupola (cast iron); Bessemer converter/open hearth furnace (mild steel); electric furnaces (high-quality carbon and tool steel).
- The properties of metal include colour, fusibility, conductivity, hardness, ductility, brittleness, tenacity and malleability, which all have their advantages and disadvantages.
- Steels are generally classified by the amount of carbon they contain. Basically, steel with a low carbon content is soft, whereas very hard steels have a high carbon content.
- Before marketing iron and steel, they are changed into a variety of suitable shapes and forms.
- To improve the properties of plain carbon steels, other alloying elements (such as nickel, chromium and tungsten) are added.
- Metals can be made soft, hard or have internal stresses relieved if they are heat treated, which involves heating the metal to a desired temperature and then cooling it at a suitable rate. They can be annealed (made soft), normalised, hardened, or tempered (made less brittle).

REVISION EXERCISES AND QUESTIONS

1 What are ferrous and non-ferrous materials?
2 In the production of pig iron, what kind of furnace is used?
3 What is the principal raw material of ferrous metal?
4 List **four** common iron ores.
5 Why is limestone added to the charge of the blast furnace?
6 How is wrought iron produced?
7 i) Describe how mild steel is produced, using either the Bessemer converter or the open hearth furnace.
  ii) Sketch a cross-section of the furnace you have chosen.
8 Briefly describe the following types of cast iron:
  i) grey cast iron
  ii) white cast iron
  iii) malleable cast iron.
9 Describe the following properties of metals:
  i) hardness
  ii) ductility
  iii) brittleness
  iv) malleability
10 i) What are the main constituents of steel?
  ii) State the carbon content and uses of: low-carbon steel; mild steel; medium-carbon steel; high-carbon steel.
11 i) What is the main reason for shaping or changing iron and steel into suitable forms and shapes?
  ii) Distinguish between bars, plates, tubes, blooms and billets. Illustrate with sketches.
12 i) Why are alloying elements added to plain carbon steels?
  ii) Describe the effects of alloying with nickel, chromium and tungsten.
13 State **four** reasons for heat treating carbon steels.
14 Describe the behaviour of steel when heated above the lower critical point.
15 Given a piece of forged steel, list the operations involved in making it soft. Name the heat treatment used.