THE MAKING
OF
IRON AND STEEL

1 Overview

Before undertaking a detailed study of the processes involved in steelmaking, it is helpful to have an overview of the whole operation, so that the inter-relation of the various steps can be seen in perspective.

1.1 Location

The nature and location of steelworks depend on many factors:

- the availability of raw material;
- supply;
- transport (particularly deep-water port facilities);
- human resources and services availability;
- markets; and often
- government factors.

In early times when coal was consumed in far greater proportions in steel production, the trend was to site integrated plants either near the coal source, or near low-grade, but cheap ore. However, with the improvements in bulk transport and the relatively greater cost of handling finished products, the trend is towards locating integrated plants on deep water ports, perhaps thousands of kilometres from ore and/ or coal but close to markets and services. They *may* supply semi-finished products to more specialised finishing mills still closer to the market. The other major steelmaking method involves the melting and refining of steel scrap in an Electric Arc Furnace. Pig iron and refined iron ore pellets (briquetted iron) can also be used, and because this method is economic at lower volumes these operations are called mini mills. Plants that use Electric Arc Furnaces can be sited closer to the market.

Where market size permits, some degree of product specialisation is practised.

1.2 Raw Materials

The basic raw materials of large-scale steelmaking are:

- iron ore, treated in some way after it comes from the mine;
- coal, which must be converted to coke;
- limestone;
- steel scrap - important both to the integrated steelworks as secondary feed to the steelmaking furnace, and to the smaller scale "mini-mill" operator and special
- steel producer;
- fluxing materials;
- refractory materials; and
- alloys, which are elements added to steel to give it special properties for a variety of uses.

The output, or capacity, of a steelworks is generally expressed in terms of tonnes per annum of raw steel (the gross output from steelmaking furnaces). However, the marketed tonnage is only about 90% of the raw steel because of process losses and recycled scrap arising from rejects and trimming to size. Nowadays integrated steelworks are rarely viable at less than 3 million tonnes p.a. Whereas mini mills operate successfully at 100,000 tonnes p.a. and upwards to 1.5 to 2.0 million tonnes p.a.

1.3 The Steelmaking Process

Integrated steelmaking operations fall into three main phases:

Reduction: lronmaking

Iron ore, as mined, is a combination of iron with oxygen and various other unwanted substances, generally known as "gangue". The first metallurgical step is to reduce iron ore to metallic iron, a process which is mostly carried out in a blast furnace, using coke as both a fuel and reducing agent. The metallic iron produced by such a furnace contains a relatively high proportion of carbon (4%) and is passed to the steelmaking process as a liquid at approximately 1450C, called "hot metal".

Refining: Steelmaking

The refining of iron to make steel is where the carbon content of hot metal is lowered, usually to less than 1 % by an oxidation process in a steelmaking furnace. At the same time, alloying materials are added to the furnace to achieve the required chemical composition of the final product. The chemical content is controlled very closely during this stage. Originally most steel was produced by the "Bessemer" and "open hearth" processes but these have been replaced by the more modern "basic oxygen steelmaking" (BOS) and "electric arc furnace" (EAF) processes.

The BOS process uses pure oxygen, injected by a lance, for refining the relatively impure hot metal (and scrap is used for temperature control).

The electric arc furnace uses primarily electrical energy to supply heat to melt scrap steel, sponge iron, or mixtures of scrap and other iron units. Compared to the BOS process, the EAF requires less chemical reaction for refining.

Shaping & Coating

The liquid steel can then be cast or formed into a variety of solid shapes via the 'continuous casting' process. The cast steel can then be forged or rolled in successive steps to produce anyone of the many required shapes. Rolling is the most common method of shaping. The modern rolling mill is a huge installation, costing millions of dollars and incorporating highly complex electronic control systems. The amount of work to which the steel is subjected, and the schedule on which this work is carried out, have significant effects on its physical characteristics - it dictates whether the steel can be subsequently bent, machined, cut, or subjected to any other engineering operation, or formed into tubes, pipes or wire.

Once shaped, steel may be coated with other metals such as zinc or tin, or with organic coatings like paint or PVC.

2 Materials Used to make Steel

2.1 Iron Ore

Composition

Iron very rarely occurs in the earth's surface as a metal. It is widely distributed, combined with oxygen as iron oxides. In fact it is believed that iron makes up about 5% by weight of the earth's crust. Geologists recognise various types of iron ore, classified chiefly according to iron (Fe) content (see Table 1 below).

Table 1: Iron Ore Classification

Name	Classification	Theoretical maximum iron content (%)"
Haematite	Fe_2O_3	70.0
Magnetite	Fe_3O_4	72.4
Goethite	*FeO.OH*	62.8
Siderite	$FeCO_3$	48.3
Taconite	Wide variety of iron-bearing rocks, usually 20 to 40% (actual)	
Jaspilite	Contains magnetite or haematite.	

** Assuming no impurities present in the ore*

For example, Australia's main iron ore deposits are predominantly haematite (Fe2O3) but large quantities of goethite (FeO.OH) also occur. Some of Australia's deposits are among the richest in the world, with many showing well over 60% iron content, compared with a 30% iron content in many European and United States ores. Some typical analyses of Australian deposits are shown in Table 2, below.

Table 2: Typical Analysis of Iron Ores (%)

Iron Ore	Fe	SiO_2	Al_2O_3	Mn	P	S	H_2O(comb)
Mt.Newman High Grade LumpWA (H)	64.7	4.15	1.60	0.06	0.054	0.007	2.5
Mt.Newman High Grade Fines WA (H)	62.0	5.55	2.60	0.04	0.069	0.009	2.2
Yandi Fines WA (G)	58.5	4.9	1.3	0.03	0.043	0.005	9.6
Whyalla Pelletising Fines SA (H)	62.8	3.76	1.85	0.27	0.050	0.033	3.12

Ore Type: H = Haematite, G = Goethite

Australia's ores vary from strong hard types (lump ores) to loose powder (fine ores), and from purplish blues to reds. Goethite ores are usually softer, more porous and easier to crush than haematite.

Variations in chemical composition and physical state of the ore influence its usefulness, economic value, and the required **smelting** technique.

For a rich **lump ore**, crushing and sizing to between six and 35mm, and blending to overcome variations in chemical composition are the only pre-treatments needed before feeding into a blast furnace.

However, if fine ore were to be used as feed to a blast furnace its powdery nature would restrict the passage of the blast air up through the furnace, limiting its permeability. The problem of using the fines is overcome by agglomerating the ore into sinter or pellets.

Granular fines are more suited for sintering whereas very fine material of close size range is better for pelletising. Pellet plants are usually located at or near the ore source, because the hard round pellets can withstand bulk handling, and there are transport economies in the upgraded material. Sinter plants are usually located within the integrated steelworks, because sinter can break up with excessive handling, and because of the availability of coke breeze which supplies the heat required for the process.

As ironmaking technology has developed, and the efficiency demanded of modem plant has increased, the majority of flux required in the blast furnace is precalcined (burnt) in the agglomerated feed. Sinter is better suited to this practice than pellets.

Iron Ore Agglomeration

➢ Sinter Process

The sinter process was introduced around 1910 to treat flue dust extracted from blast furnace exhaust gases. It was quickly adapted to agglomerate fine ore and its use spread rapidly.

At the sinter plant, pre-blended fine ore is mixed with:

- coke breeze (small particles of coke from the screening plant);
- fine fluxes such as fine limestone, dolomite, quartzite, and serpentine;
- mill scale (small flakes of iron oxide from the rolling mills); and
- flue dust and precipitator dust (fine ore bearing particles) collected from the blast furnace and BOS furnace exhaust gases.

This moistened mixture is coarsened by a granulation process and is then spread as a layer up to 550 mm thick on a moving grate which travels like an endless belt. The grate carries the mixture through a furnace, in which gas burners ignite the coke. The coke burns in horizontal layers which proceed vertically downward as the air for combustion is continuously drawn down through the mixture as it travels along the moving grate.

Sinter

During this process the layers reach temperatures of approximately 1300°C, fusing the pre-blended fine ore mix together forming a solid clinker mass.

This fused mix is broken down into lumps, cooled and screened, forming a sinter product with a mean size of 23-26 mm which is sent to the blast furnace on conveyors.

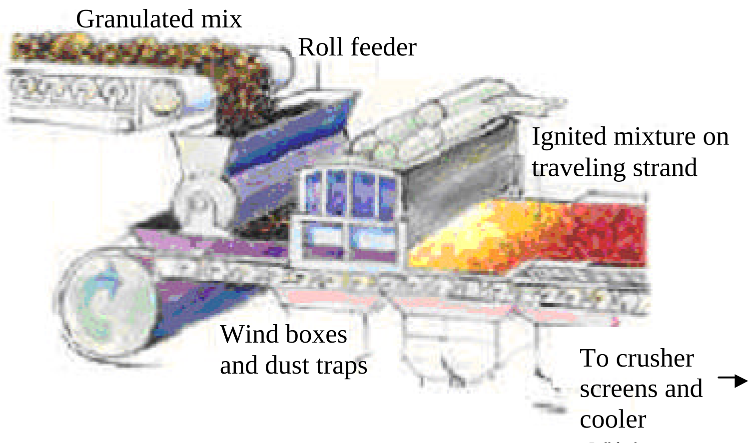


Figure 1 The Sinter Process

In modern practice, the combined iron plus coke burden is self **fluxing** and virtually no limestone is required at the blast furnace. When the flux is added at the sinter plant, the limestone is precalcined, the sinter strength and chemical reactivity are improved and the sinter can be prepared at a lower temperature. Consequently the fuel rates (consumptions) and productivities of both processes improve.

- **Pelletising techniques**

Pelletising was first developed in Sweden. Since the late 1950's it has been extensively applied to the very large deposits of iron bearing rock called "taconite" which underlie much of the Mesabi Range in Minnesota (USA).

Low grade run-of-mine ore is crushed and ground to a very fine powder so that the iron may be separated magnetically from the silica and other unwanted material. A binding clay such as bentonite is added, also some fluxes, (if required), and the mixture is then moistened and rolled into 14mm diameter balls in cylindrical balling drums. Initially the "green" pellets are relatively weak, being cemented together only by the added water. They are then baked at about 1315C in a shaft furnace, rotary kiln or grate system similar to a sinter strand. Because of their regular size and shape, and their hard, dense nature, pellets were considered an ideal feed material for blast furnace operations.

Table 3: Typical Analyses of Australian Coking Coals (%)

Colliery	Ash	Volatile Matter	S	P	Vitrinite		H_20
Appin (NSW)	8.8	23.3	0.37	0.053	53	8.3	
Cordeaux (NSW)	9.5	22.2	0.36	0.040	47	8.8	
Elouera (NSW)	9.5	24.6	0.58	0.008	78	13.5	
NorwichPark QLD)	9.9	17.2	0.65	0.040	75	10.0	
Sarap (QLD)	9.7	19	0.62	0.025	72	10.0	
Peak Downs QLD)	9.7	21	0.60	0.045	72	9.5	
Riverside (QLD)	9.8	23.8	0.58	0.007	60	9.5	
Goonyella (QLD)	8.9	24.2	0.55	0.025	63	10.0	

Blackwater QLD)	8.2	26.5	0.50	0.060	56	10.0
Gregory (QLD)	6.5	33.5	0.65	0.025	76	8.0

However, with changing conditions, sinter is increasingly regarded as the preferred agglomerated feed: the sinter strength advantages on fluxing have been described, and the fuels commonly used in the pellet roasting (heavy fuel or natural gas) are becoming increasingly expensive.

Pellets

Pelletising is usually associated with the chemical upgrading of an ore, but it may be used to produce a useable feed from the fines of a high grade ore.

2.2 Coal

Composition

The modem integrated steelworks depends on coal both as a source of carbon and as a primary source of energy. Various marketable by-products become available from the processes involved and a sharing of the fuel by-products between the major processes make a significant contribution to reducing the cost of steel.

The industry's need is for bituminous grades of coal suitable for coke-making. Australian coking coals are obtained chiefly from the Northern and Southern fields in New South Wales and from the Bowen Basin in Queensland.

Coal extracted by mechanical mining techniques inevitably carries with it a proportion of waste materials mined from the roof or floor of the coal seam as well as non-combustible material finely dispersed within the coal mass. The ash content, volatile matter and fixed carbon content vary from seam to seam. (Refer Table 3)

Preparation

Before coal is suitable for use in the blast furnace, it must be treated by crushing, washing and baking to form metallurgical coke.

- **Crushing & Washing**

The first step is to crush the run-of-mine material to a suitable size and process it through a coal preparation plant, or washery. Here, waste and low grade coal are separated, usually by a combination of various gravity separation and froth flotation processes. 'Middlings' (low grade coal) obtained from these processes is a valuable boiler fuel for the generation of either electricity or process steam. A typical coal washery in New South Wales (Australia) yields 70% or better of coking coal with the balance being energy coal and washery reject.

➢ Heating - Coke ovens

Metallurgical coke is made by heating crushed coal in large ovens in the absence of air. Each oven is rectangular and may be from 13 to 15 meters long, 4 to 7 meters high and 400 to 450 millimeters wide. As many as 100 ovens may be arranged side by side to form a battery. The oven linings are built almost entirely of silica brick and operate at temperatures around 1200°C.

Each oven is charged with coal from the top, through 3 or 4 holes and then sealed. After 17 to 20 hours of heating, the distillation of volatile compounds is complete and the coke so produced is pushed from the oven. It is then quenched with water and screened. Large coke, 25-80mm, is transferred by conveyor belt to the blast furnace feed bins. Small nut coke is also charged separately to the blast furnace whilst the smallest, coke breeze, is consumed at sinter plants.

The volatile compounds and gases distilled from the coal are piped to the gas processing or by-products plant where they are treated to yield coke oven gas, tar, BTX (a mixture of benzene, toluene and xylene) and sulphate of ammonia. After the extraction process, some coke oven gas is returned to the battery where it is mixed with blast furnace gas for use in heating the coking chambers and the remainder is available as a fuel around the steelworks.

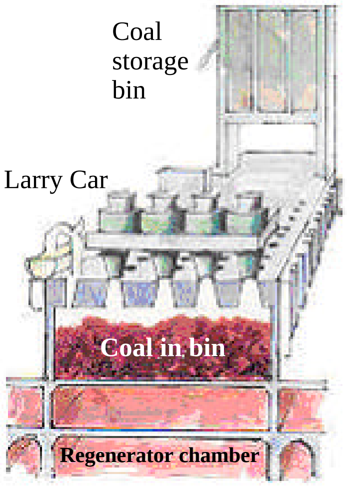


Figure 2 Coke Oven Batteries have up to 100 narrow ovens with heating chambers between each oven

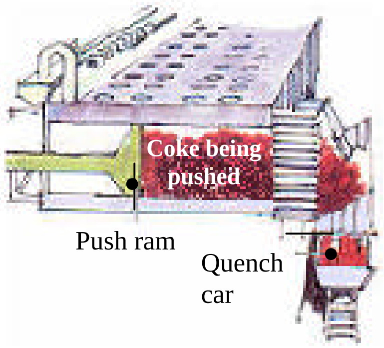


Figure 3 Heating for about 18 hours distils volatiles from coal to produce coke

Metallurgical coke must be hard and porous while still being physically strong. Its four main functions in a blast furnace are:

- as a fuel;
- to supply carbon for the reducing reactions which convert iron oxide to metallic iron;
- to provide a permeable support for the feed materials charged into the furnace so that the reducing gases derived from the 'air' blast can pass up the furnace; and
- to provide the carbon which is dissolved in **pig iron**.

Coke

2.3 Fluxes

Iron ore, coal and air are the main raw materials for iron and steelmaking but many other substances are used. Apart from energy sources, such as natural gas and electrical power, the majority of these supplementary materials can be broadly classified as fluxes, alloys and refractories. Some of the most common are listed together with their main functions and sources in Table 4, below.

Fluxes are the materials used in metallurgical processing to react with impurities to form a liquid slag at the process temperature. This allows the metal to be easily separated from the impurities. The impurities are mainly oxides, either as they occur in the feed (gangue and ash) or generated in refining, so the fluxes are also generally oxides.

Table 4: Some supplementary raw materials for fluxes, refractories alloying

Material	Process Function
Limestone	Flux in ironrnaking and steelmaking
Dolomite	Flux in ironrnaking and steelmaking
Quartzite	Flux in ironrnaking
Serpentine	Flux in ironmaking
Fluorspar	Slag fluidity in steelmaking
Magnesite	Refractory brick linings
Manganese Ore	Ferromanganese, silicomanganese manufacture for alloying steel

Composition

Fluxes have 'acidic' or 'basic' properties. Silicon dioxide, SiO_2, forms an acid slag, while calcium oxide, CaO, forms a basic slag.

This is analogous to acids and bases in aqueous chemistry, such that acid and basic oxides tend to react together. Physically, this means that high melting point oxides can form lower melting point mixtures.

Chemically, if there is a surplus of one type of oxide, then the mixture will more strongly hold (dissolve) an oxide of the other type in the slag. Therefore a very basic slag (high in CaO, low in SiO_2) is more efficient for removing phosphorus during refining because phosphorus pentoxide P_2O_5 is an acid oxide. On the other hand, a basic slag will not dissolve basic oxides so readily, which enables high melting point oxides to be used as container materials for slags providing they are the same type as the slag. Thus "basic" oxygen steelmaking employs basic slags (high in CaO and often saturated in magnesium oxide MgO) in a vessel lined with high melting point basic oxide refactory bricks (mainly MgO), referred to as magnesia bricks.

Limestone, the most used flux, is a sedimentary rock, usually white, varying from hard and compact to soft and friable.

Limestone for use in a Bas furnace must be burnt (calcined) in kilns before charging. A fine grained lump limestone is needed to produce a sufficiently hard lime.

Dolomite is becoming increasingly important as a flux material. It is a combined calcium magnesium carbonate, geologically similar to limestone, reacting chemically in the same way. Lump material is calcined along with limestone as a BOS flux, and fines may be added to the sinter plant to modify the blast furnace slag composition.

2.4 Refractories

Refractories are the class of thermally and chemically resistant substances used as container materials in the various high temperature metallurgical processes. The steelmaking furnaces are lined with magnesia, and the slag composition is carefully combined to minimise attack by FeO, SiO_2l and other impurities. The impurities are removed from the liquid steel at temperatures which may be greater than 1650°C.

Carbon is used to line the blast furnace hearth, which contains liquid iron saturated with carbon from the coke.

Zirconia, magnesia and **high alumina** refractories are used in equipment like ladles, tundishes and torpedo cars for handling molten metal.

Silica is used in coke ovens and silica or high alumina fire bricks are used in blast furnace stoves.

Various grades of alumina fire clays and bricks are used in other high temperature and abrasive locations.

Water cooled metal shapes are also used to minimise erosion by cooling, often causing the formation of a protective covering of frozen slag. Uncommon refractories, such as silicon carbide and silicon nitride are required in critical applications such as in continuous casting.

2.5 Alloying Elements

Alloying elements are added to steel to give particular properties in the final product, such as hardness, toughness, corrosion resistance, ability to be hardened and machinability. They are also used to assist in refining, eg. for deoxidation and desulphurisation.

They include:

- Carbon (C)
- Manganese (Mn)
- Silicon (Si)
- Chromium (Cr)
- Nickel (Ni)
- Aluminium (Al)
- Boron (B)
- Calcium (Ca)
- Cobalt (Co)
- Molybdenum (Mo)
- Titanium (Ti)
- Tungsten (W)
- Nitrogen (N) and
- Phosphorus (P).

Many are added as ferroalloys, of which high carbon ferromanganese (approximately 76% Mn and 7% C, remainder Fe) is the most common. Ferrosilicon, (typically 75% Si,<l %C), and silicochrome, ferronickel and nickel oxide (which is readily reduced to the metal during steelmaking) are other major alloys. Many are produced in electric smelting furnaces, often by quite complicated processes, to serve the steelmaking and foundries industries.

Carbon may be added in the form of petroleum coke or as specially prepared high purity brown coal char.

Manganese is added as high, medium, or low carbon ferromanganese, electrolytic manganese or silicomanganese. They are produced in electric smelting furnaces from manganese ores and in manganese sinter plants for processing fines which are unsuitable for addition direct to the furnace. (See Section 6 for details on the effects of alloying elements on the properties of steel.)

2.6 Steel Scrap

Steel scrap is a major source of metallic iron for steelmaking. About half of the 700 million tones of crude steel now produced annually in the world will be recycled as scrap to the steelmaking furnaces sooner or later. (Every tonne of scrap consumed in steelmaking is estimated to conserve about three tonnes of natural resources.)

Scrap comes from two main sources:

- "home" (steel plant generated) scrap; and
- purchased scrap.

Home scrap (also known as circulating scrap) is the residue left from the steelmaking, rolling and finishing operations and includes croppings, offcuts and material rejected by quality inspection procedures. The home scrap usually accounts for about 10% of total crude steel production in an integrated steelworks.

In other words, from each 100 tonnes of crude steel produced in the steelmaking furnaces, 90 tonnes will be shipped from the plant as finished product; the remainder will be returned to the furnace as scrap feed.

Purchased scrap returns to the industry from various sources, partly as manufacturers' offcuts and defectives, and partly as obsolete and worn-out goods discarded at the end of their useful lives. Ship-breakers, for example, recover large tonnages. Increasing tonnages of steel cans are now recycled as steel scrap. In Australia, up to 75% of scrap is recycled annually.

There is a considerable international trade in scrap and prices are sensitive to the variable supply and demand conditions.

Scrap in the BOS process

The basic oxygen steelmaking process can consume up to 20% scrap in its metallic charge. As well as supplying ferrous feed units the scrap is used to control the temperature generated by the chemical reactions. The percentage of scrap used in the BOS can be influenced by such factors as blast furnace metal chemistry, use of cold iron and iron ore in the charge. Special pre-heating techniques can increase the scrap charged to the BOS to 30% of the charge but heat processing times are then normally extended. The BOS process depends on the oxidation of C, Si, P and other impurities (also some Fe to form the correct slag) to supply the heat needed to reach the final temperature (about 1650°C).

Scrap in the EAF process

The electric arc furnace process is often based entirely on scrap because the furnace is suited for heating, rather than extensive chemical reaction. In mini-mills, purchased scrap is generally used and this often has 'tramp' elements of Cu, Ni and Sn associated with it. These sometimes need to be lowered to meet the steel specification, so often a pure source of iron units such as **HBI** (Hot Briquetted direct reduced Iron) is added to the charge to dilute the residual tramp elements.

In 'special' or alloy steel plants (i.e. stainless steel), the scrap is a useful source of expensive alloying components containing Ni, Mo and Cr, so it must be carefully sorted and used according to the particular grade being made.

3 Iron making - the reduction of iron

3.1 Blast Furnace Method

Iron is present in most natural ferrous ores as an oxide, together with some impurities. Production of iron in the blast furnace is a thermochemical process, during which the metal is reduced from its oxides by a series of chemical reactions and carburised to reduce its melting temperature.
The majority of impurities present in the ore and fuel are removed as a separate liquid product called slag.

The modem coke-burning blast furnace is a massive structure, towering up to 100 metres high. The furnace shell consists of a truncated cone-shaped steel casing 30 to 40 metres high, lined with up to a metre of refractory brickwork. The furnace works continuously and usually operates for up to 15 years before new cooling staves and refractory lining are required.

Hearth dimensions of blast furnaces vary widely. The largest blast furnaces in the world, with diameters up to 16 metres, produce over 10,000 tonnes of hot metal per day.

Process

Raw materials are continuously fed into the furnace top, producing the iron and slag which are removed at the base periodically. A hot air blast, together with auxiliary fuels, is injected into the furnace through the tuyeres. It takes about eight hours for a piece of solid-feed material to pass through the furnace. Names of the various main parts of a blast furnace are shown in Figure 4.

➢ **Charging**

The raw materials charged into a blast furnace are:

- iron ore (Fe_2O_3 + gangue) as lump, sinter and/or pellets, according to availability;
- coke (C + ash) to provide the reducing agent (CO) and the heat necessary to melt the iron;
- minor amounts of limestone, dolomite and quartzite fluxes to control slag chemistry; and
- air (O_2 + N_2) to burn the coke (the air is preheated to about 1150°C).

The fluxes are added, mainly as part of the sinter or pellets, to control slag chemistry, i.e., to make slag containing typically, 34% SiO_2, 41 % CaO, 15% Al_2O_3 and 7% MgO. The gangue and ash are mainly acidic SiO_2 and Al_2O_3 so the fluxes are primarily basic CaO and MgO.

The increased availability of natural gas has resulted in it being injected with the air blast as a supplementary fuel. In some circumstances coke ovens gas is a cost effective alternative, while in countries with high energy costs, injection of pulverised coal is common. Productivity is increased by enriching the pre-heated blast air with oxygen.

Humidification of the blast air by adding steam is used to control furnace temperature. A scale car or a weigh hopper normally weighs all the solid raw materials charged to the furnace top. The flow rate of injected fuels is measured along with the blast air.

The proportions of the charges depend upon the nature of the raw materials being used. The order in which they are charged is important, because their distribution in the furnace affects efficiency

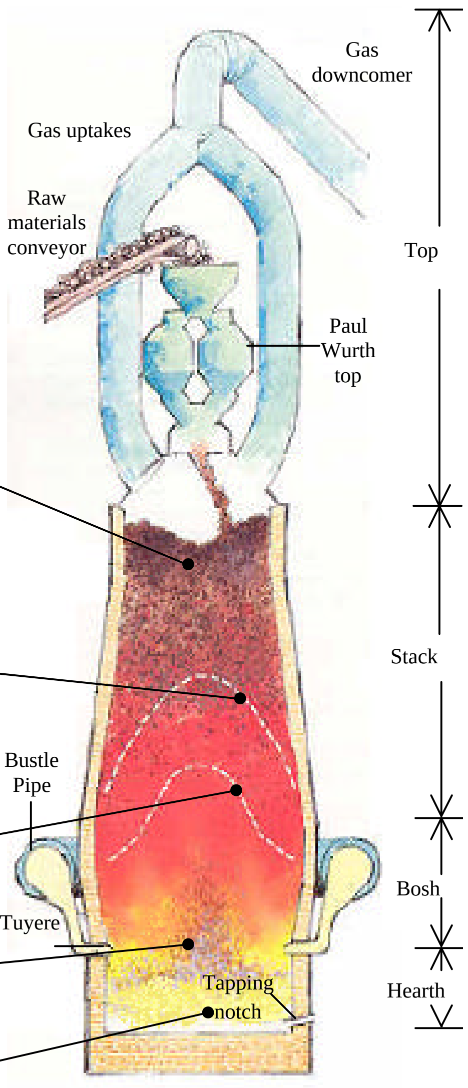


Figure 4

Cross section of a blast furnace showing major features and temperature zones. The furnace can be dividedinto five zones, from the relatively cool zone at the top to the intensely hot zone at the bottom.

1. **Lump Zone**: in which the temperature is gradually raised from ambient to approx 1200°C. Combined moisture is driven off first, then as the temperature increases the ore is gradually reduced by the ascending gas stream. The metallic iron produced here is only partially separated from the impurities.

2. The **Softening Melting Zone**: where the temperature is from 1200°C to 1450°C and the ore continues its reduction to iron. Both the metal and impurities begin to melt and separate to leave this zone as liquids

3. In the **Dripping Zone**: solid coke maintains an open bed through which the descending liquid iron and slag and ascending reducing gases can pass. The coke gradually feeds towards the tuyeres

4. The **Raceway**: the hot air blast combines with - incandescent coke at temperatures of 2000-2200"C to generate heat and the CO reducing gases required in the higher zones.

5. The **Hearth:** where melting iron and slag collect and are cast at regular intervals at temperatures of about 1500°C.

Skips carry the weighed material up a steeply inclined track to the top of the furnace where it is tipped in. On more modern furnaces, these have been replaced by an inclined conveyor belt system.

Two types of furnace tops are used with different charging systems:

The Bell Top, which is a furnace top that is closed to the atmosphere by bell-shaped valves operating one above the other, the upper bell being smaller. The charge materials are dropped. onto the small bell, which rotates 60 degrees after each skip load is tipped, preventing circumferential segregation of the charge material in the furnace.

Opening the small bell allows feed to fall onto the large bell which can accept several loads from the small bell before discharging the materials into the furnace.

When the large bell is about to be lowered (opened) the small bell is raised (closed) and the pressure in the area between the bells is equalised to that of the furnace top, preventing furnace gases escaping into the atmosphere.

Modern furnaces are equipped with moveable armour at the furnace top level to deflect charged material. This assists placement of individual material batches controlling material and gas distribution.

The Paul Wurth, or Bell-less top is newer**.** It enables more controlled radial distribution of the material in the furnace, resulting in increases in furnace productivity and efficiency. The top consists of lock hoppers equipped with seal valves and a centrally located rotating chute. The inclination of the rotating chute can be changed enabling great flexibility and accuracy in placement of materials. (Figure 5, below).

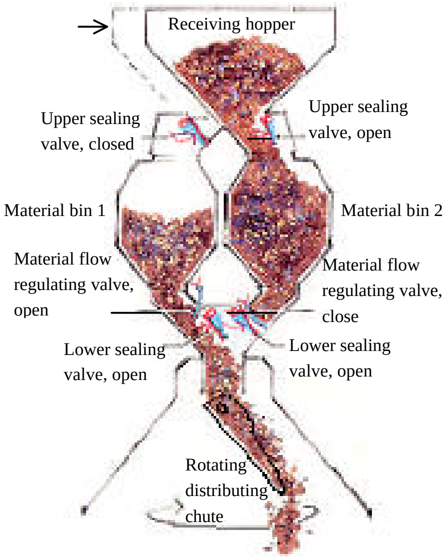


Figure 5 The Paul Wurth top provides highly efficient distribution of raw material feed

- **Blowing**

To increase productivity and efficiency most furnaces today are equipped to operate at high top pressure (increased pressure at the furnace top). This is achieved by raising the pressure of the blast air and restricting the passage of gas leaving the furnace top. The reduction in gas velocity results in greater efficiency of all the important reduction reactions.

Top Gas Energy Recovery turbines have been installed to recover the pressure energy of the high pressure off gas. Steam-driven turbo-blowers supply the furnace air blast in volumes up to 6500 m^3/minute and at pressures up to 400 kilopascals. The blast pressure is determined by the top pressure, the bed permeability and the driving rate of the furnace.

For more efficient smelting, superheated air is used. The turbo-blowers drive the air through preheated refractory chambers called 'stoves', in which the air is raised to a temperature of 900-1200°C, and then into the 'bustle pipe' which girdles the 'bosh'. The hot air enters the furnace combustion zone through water-cooled copper nozzles called 'tuyeres'.

Usually there are three stoves or four serving each furnace. These steel chambers are refractory lined pressure vessels, filled with a matrix of high duty refractory brick. They act as both heat stores and heat exchangers.

One or two stoves are 'on blast', supplying heat to the air blast while the other two are 'on gas' (or combustion) being heated by gas burners firing blast furnace gas (enriched with coke ovens gas or natural gas). The heat contained in the preheated blast produces a substantial saving in the coke and/or fuel consumption which improves the productivity of the furnace.

- **Reduction**

The heat and carbon monoxide gas generated by combustion of coke and any supplementary fuel, preheats and reduces the iron ore, as it descends through the furnace.

The melting point of pure iron is 1537°C. Because iron passing through the blast furnace absorbs carbon and other elements, its melting point is lowered to approximately 1150°C. Despite its low melting point, the liquid iron in the furnace hearth must be maintained at about l500°C, with slag reaching temperatures about 50°C higher (1550°C). This temperature is necessary to obtain sufficient fluidity of the iron and slag to sustain proper drainage from the furnace hearth and to keep it flowing freely from the taphole. It is also important to note that the slag melting point changes with composition and this makes accurate raw material control and weighing very important.

- **Tapping**

The furnace is 'cast' or 'tapped' intermittently about every two hours on smaller furnaces and almost continuously on large furnaces with multiple tapholes. A typical analysis of product iron is shown in Table 5. Between 250 and 800 tonnes of iron are obtained from each cast, depending on the size of the furnace. Automatic drilling machines are used to drill through a plug of refractory clay which seals the taphole. The iron is separated from the slag by a 'skimmer' and then flows along 'runners' lined with refractory clay; into 'hot metal' ladles below the cast house floor.

These ladles are torpedo-shaped steel shells, refractory-lined and mounted on railway bogies. The brick lining is sufficiently thick to hold the iron in its molten state for many hours. Ladles can hold up to 300 tonnes of molten iron.

Diesel locomotives haul the hot metal ladles from the blast furnace to the steelmaking shop. The hot metal may require pre-treatment such as desulphurisation prior to use in steelmaking. The molten iron is poured into transfer ladles ready for charging to the basic oxygen steelmaking furnaces.

Table 5 - Typical analysis range of iron used for steel making

	Approximate Percentage
Iron (Fe)	93 to 94
Carbon (C)	4.0 to 5.0
Manganese (Mn)	0.3 to 0.6
Silicon (Si)	0.3 to 0.6
Phosphorus (P)	0.07 to 0.11
Sulphur (S)	0.010 to 0.030

Iron, made to special analysis, can be cast into a series of small moulds moving on an endless strand. The product is "pig iron", used in foundries to make a variety of castings such as car engine blocks, and parts for light and heavy machinery. Pig iron is usually remelted and suitably treated to make castings. 'Cast iron' is therefore more highly refined than 'pig iron'. In most steelmaking plants, almost all molten iron is fed directly into the BOS process.

Chemical Reactions

The basic reactions that control the ironrnaking processes are relatively few and simple. They are the reactions between carbon, oxygen, iron and its oxides, and those that lead to the formation of slag.

- **Reactions of carbon**

The oxygen in the blast reacts with the incandescent carbon (coke) to produce very high temperatures:

$C + O_2 \rightarrow CO_2$

The incandescent carbon rapidly reduces the CO2, thus: $C+C0_2 \rightarrow 2CO$

The first reaction is highly "exothermic" (heat releasing); and the second, which mildly absorbs heat, is called "endothermic".

The great quantities of heat released by carbon reactions melt the burden materials (except the coke itself) in the melting zone of the furnace. Coke is the only charge material which retains its solid structure while passing through the furnace. The coke thus provides the necessary porosity in the hearth and melting zone as liquid slag and iron are formed, refined and drained away.

- **Reactions involving iron**

Reaction 1. At 400-700°C: $Fe_2O_3 + CO \rightarrow 2 FeO + CO_2$
Reaction 2. At 700-1000°c: $FeO + CO \rightarrow Fe + CO_2$
Reaction 3. At 1000-1400°C: $FeO + C \rightarrow Fe + CO$
Reaction 4. At 1400-1450°C: Fe melts as it dissolves carbon.

Carbon monoxide is the main reducing agent but, at temperatures of above l000C, the resultant CO_2 reacts with the coke to produce more CO, so the FeO appears to react directly with the C, (reaction 3).

Hydrogen (H_2), from the moisture (steam) in the hot blast and from supplementary fuels, behaves similarly to CO. The fully reduced iron can only become molten after it absorbs carbon, and so the final reduction/carburisation in the melting zone is extremely complex.

- **Slag formation**

In modern practice, the great majority of flux is introduced through sinter as calcined CaO. Note that, when present, MgO reacts similarly throughout. Any lump limestone added with the burden decomposes rapidly and the decomposition is normally completed at l000°C. The reaction $CaC0_3 \rightarrow CaO + CO_2$ is highly endothermic. It is much preferable for this reaction to occur elsewhere than in the furnace bosh.

The resultant CaO enters the fusion zone and combines with silica (SiO_2) and alumina (Al_2O_3) to form a liquid slag. The most significant properties of the slag are its melting point and fluidity (so that it can be removed from the furnace easily) and its basicity (the ratio of basic oxides, mainly CaO, to acid oxides, mainly SiO_2), which determines its chemical affinity for sulphur, silicon and manganese.

➢ Other reactions

The percentage of silicon and sulphur in the molten iron can be controlled to a certain degree by the furnace operators. The percentages of phosphorus and manganese, however, are dependent on the composition of the raw materials.

The total silica load, temperature in the furnace hearth, and composition of slag, control the amount of silicon which will be dissolved in the iron. High hearth temperatures, high silica and low basicity slag tends to increase the silicon content of the product, since more of this element can be reduced.

Sulphur readily combines with iron and can only be removed by contact with a basic slag in the presence of carbon at the high temperature of the hearth.

$FeS + CaO + C \rightarrow CaS + Fe + CO$

All of the oxides of phosphorus in the raw materials are reduced and the resultant phosphorus dissolves in the iron.

$P_2O_5 + 5C \rightarrow 2P + 5CO$

About 60% of the manganese oxide in the charge will be reduced and enter the iron; the slag takes up the remainder in the form of dissolved MnO.

While there is scope for control of the silicon and sulphur content of the hot metal, there is no way to prevent all the phosphorus from reporting to the metal. In some plants, there are facilities for external treatment of the hot metal, prior to charging it to the steelmaking furnace. This can take various forms, such as injection of gases containing entrained fine materials into the torpedo ladle or into the metal after it is separated from the slag at the blast furnace. These may be oxidising, such as sinter fines to decrease the Si content, or desulphurising, such as CaC_2, soda ash, CaO or Mg pellets. If the Si content is sufficiently low, it is possible to dephosphorise the hot metal, which may be beneficial for steelmaking, as is desulphurisation and desiliconisation. More recently, the de-phosporising technique has also been developed as part of the pre-treatment process.

By-Products

➢ Slag

At the blast furnace, slag is run off in an adjacent pit, poured into ladles for transfer to a slag dump ("rock slag"), or granulated by rapid cooling with a high velocity water stream. The slag contains the impurities in the raw materials. Liquid slag is immiscible (cannot be mixed) with liquid iron and floats on its surface. Control of slag chemistry is complex, and in many respects, slag properties control furnace efficiency. Rock slag is allowed to cool and is then broken up and crushed into various sizes for reclamation, road-making, bitumen sealing materials, and for manufacture of insulating material. A significant proportion of slag is granulated. The resulting material has a self-cementing tendency, and the finely ground portion may be added to cement to produce a concrete of lengthened durability. It has also been used as a high quality road base and soil enhancer.

➢ Gas

Another product of the blast furnace operation is gas which is extracted from the top of the furnace. It has the following composition:

CO_2	22%	H_2	5%
CO	22%	N_2	51%

Its calorific value is about 3.4 MJ/m^3. As the gas passes through the furnace it carries with it small particles of solid raw materials, which then have to be removed. This is done sequentially in dust catchers, scrubbers and electrostatic precipitators, cleaning the gas thoroughly. The flue dust, because of its high iron content, is collected and recycled as a feed for the making of sinter. The gas is used as a fuel. It is this ongoing use of the products and by-products of a plant which gives it the term 'integrated steelworks'.

3.2 Alternative Ironmaking Methods

As many iron ores can be almost completely reduced at relatively low temperatures (<1000°C), it is realistic that the traditional blast furnace method can be replaced by alternate ironmaking techniques such as direct reduction and smelting reduction in certain circumstances. These include:

- locations where iron ores and coals are not of suitable quality to use in the blast furnace;
- locations which have abundant reserves of inexpensive natural gas, non-coking coals and/or hydro-electric power, and suitable iron ores;
- regions which require small steelmaking capacity. (blast furnaces operate most efficiently at a large scale, i.e. greater than 2Mt/ a).

In addition, the alternative ironmaking plants' smaller, viable size, have the advantage of eliminating the need for coke ovens and ore agglomeration processes such as sinter and pellet production. Unlike conventional ironmaking processes, direct reduction does not produce slag which requires off-site disposal, nor does it require the use of coal and limestone or the handling of very hot liquid metals.

Direct Reduction

The term **'Direct Reduction'** applies broadly to processes which remove oxygen from iron ores to produce a high metallic solid iron product without going through a molten stage. Three primary products are made by direct reduction:

- DRI (direct reduced iron) or sponge iron as it is also called;
- HBI (hot briquetted iron) which is DRI in the briquetted form for ease of transport and storage. The HBI has an approximate 93% iron content; and
- Iron Carbide (Fe_3C).

The term Direct Reduction is somewhat misleading, suggesting a process that converts iron ore to steel directly, which is not the case. DRI, HBI and iron carbide are solid forms of iron which require further processing through melting and refining to produce the final steel product, this further processing generally being carried out in an electric arc furnace (EAF).

The characteristics of DRI material vary from plant to plant. Important variables include:

- the iron content;
- the oxide content;
- the carbon content; and
- physical properties.

The iron is also used for feed in blast furnaces and BOF's when economics allow.

Reformed natural gas (a mixture of H_2 and CO) is generally used as the reducing agent for Direct Reduction plants although some processes use coal.

In recent years, increasing world EAF steelmaking capacity, coupled with a growing shortage of high quality scrap, has led to strong growth in the number of DRI/HBI plants around the world. Global DRI/HBI capacity has grown from approximately 20Mt/a in 1990 to around 34Mt/a in 1996. Further growth in DRI/HBI production is foreseen as growth in EAF steelmaking continues.

➢ Gas Based Direct Reduction

Total gas based world DRI and HBI production for 1996 was approximately 30Mt/a which was produced by four commercial processes: MIDREX, HYL, FIOR, and the iron carbide process.

When the direct reduction process was commercialised in the 1960's and 70's, the first operations to prove viable were those of HYL and MIDREX. These processes were based on the gaseous reduction of ore in lump or pellet form, and these are still by far the most widely used technologies. The MIDREX process produces around 21Mt/a of HBI and DRI while 8Mt/a is currently produced by the HYL process. Both processes use natural reformed gas in a shaft furnace.

More recently, development effort has been focussed on processes which can use ore in a fines form using a fluidised bed reactor. This type of process potentially has an economic advantage because it avoids the need for a separate process, such as sintering or pelletising, to agglomerate raw materials.

Table 6: Gas Based Direct Reduction Methods (Approximate 1996 Capacities)

	Million Tonnes/year	Reactor type	Feed
MIDREX	21	Shaft Furnace	Pellet/ Lump Ore
HYL	8	Shaft Furnace	Pellet
FIOR / FINMET	0.4	Fluidised Bed	Fine Ore
Iron Carbide	0.1	Fluidised Bed	Fine Ore

The FIOR gas based, fluid bed process has now been further developed into the FINMET technology. In FINMET direct reduction, concentrated ore is heated and fed into a series of reactors where it reacts with natural gas, previously converted to carbon monoxide and hydrogen. Oxygen is progressively removed and the ore converted to pure iron in a series of fluidised bed reactors. The iron emerges from the process as granules, which are immediately compressed into small briquettes (about the size of a cake of soap) to be transported easily and safely. The cooled briquettes can be stored or shipped to markets.

An example of a commercial iron carbide plant is one that is in operation in Trinidad with a design capacity of approximately 300,000t/a. The product is not briquetted but used as fine granular material for injection into EAFs.

- **Coal Based Direct Reduction**

Coal based direct reduction has been particularly attractive to countries with good quality iron ore but with little coking coal for conventional ironmaking, or natural gas for the better established DR processes. Foremost are India and South Africa, although only India has opted on a large scale for coal based projects. While a variety of coal based processes have been proposed or under development (eg. FASTMET, COMET, Circofer and Inmetco), the rotary kiln has been the most widely used furnace in this application to date.

The rotary kiln furnace is a revolving horizontal cylinder comprising a shell with an internal refractory lining. The furnace is tilted at an angle of three to four percent from the horizontal. Iron ore (lump, pellet or iron sands) and coal move through the kiln by rotation of the kiln and gravity. The reaction of coal and iron ore produces carbon monoxide and hydrogen which are partially combusted with air above the burden bed to supply energy for the process. Iron ore is gradually reduced as it travels along the length of the kiln.

Bluescope Steel operates the rotary kiln process for iron sand reduction at its New Zealand Steel plant. In this case, iron sands which contain a high content of TiO_2 are unsuitable for the blast furnace process. This ore is mixed with a low rank coal and fed to a multiple hearth furnace to drive off the coal volatiles and dry and preheat the ore/coal mixture to about 600°C. It is then processed through the rotary kiln to reduce the ore. The product is 80% metallised and exits the kiln at about 950°C. Pre-reduced iron and char remaining from the kiln process are then smelted in submerged electrode furnaces to make liquid iron containing about 3% carbon.

Smelting Reduction

The processes that produce a molten product (similar to blast furnace hot metal) directly from ore and coal are generally classified as smelting reduction or bath smelting or direct smelting processes. These processes are able to use coal directly without coking, and are generally intended as blast furnace substitutes. The liquid iron from these processes can either be cast into pigs for export or be further processed to steel using a BOF or EAF, as is done with blast furnace hot metal.

These processes contain a smelting reactor where iron ore (either unreduced or partially reduced) and coal are added directly to a molten slag and metal bath. Final reduction of ore to metallic iron occurs in the liquid bath at high temperature. Reaction of iron ore and coal produces carbon monoxide and hydrogen, which are partially combusted with pure oxygen above the liquid bath to provide process energy. Because high temperature operation increases the reduction rate of iron ore, smelting reduction reactors can be built with a smaller working volume than DRI or blast furnace processes and thus can achieve a lower capital intensity.

The COREX process is currently the only direct smelting technology in commercial operation. This process makes liquid iron by pre-reducing lump ore and pellets in a shaft furnace and melting in a melter gasifier. The shaft reduces the ore whilst the melter gassifier produces gas for the shaft from coal and liquid pig iron. The first commercial COREX plant was commissioned in 1989 by ISCOR in South Africa. The second plant was commissioned in 1996 by POSCO in Korea.

Compared with the conventional blast furnace/ coking plant route, the benefits of the COREX process are claimed to be:

- elimination of a coking plant through the use of non coking coal;
- elimination of agglomeration plants through the input of 100% lump ore (pellets or sinter can also be used);
- minimisation of environmental emissions, and
- high operational flexibility with respect to production capacity, raw material changes and stopping times.

Several other processes are under development, which use an injection of gas, fine ore and coal to produce liquid pig iron. These include the HISMELT process (Western Australia), DIOS (Japan), Romelt (Russia), Ausmelt (Australia) and AISI (USA). However, significant technological development is still required before large scale commercialisation of these technologies occurs.

Direct Reduction and Direct Smelting accounted for approximately 4.5% of the world's steel production in 1996. The total production is expected to increase from approximately 35 million to 65 million tonnes by the year 2000. The steel produced is for higher quality applications such as flat products for automobile parts.

4 Steelmaking – the refining process

4.1 General Characteristics of Steelmaking – the refining process

All steelmaking processes have to complete three basic steps:

Step 1 - removal of impurities (oxidation),
Step 2 - control of temperature (charging), and
Step 3 - addition of alloy elements.

Some steps can occur simultaneously, e.g. the heat generated from oxidation of impurities (step 1) is used to melt the scrap and bring the metal to the required temperature for tapping (step 2). A second example is the addition of the alloys Mn and Si, primarily added to give steel specific properties (step 3) also help to remove impurities (step 1). These steps have to be accomplished at very high temperatures using large amounts of energy.

Steelmaking is a batch process, partly because a range of products is required, though there have been attempts to develop a continuous process.

Oxidation

The impurities are oxidised out of the steel more or less in the order of their oxide stabilities (under the influence of slag chemistry) and the slag may contain 15% Fe as a mixture of FeO and Fe_2O_3. Thus Si is one of the first to be removed but Ni, Sn and Cu cannot be oxidised, their oxides being less stable than FeO, Cr, Mn and P are partially oxidised, depending on slag chemistry and temperature.

In general, sufficient oxidation is done to remove the most difficult impurity to the requisite low content, which often results in unnecessary oxidation of other materials. Depending on circumstances, some of these may be recoverable by reduction from the slag, e.g. of Cr with the aid of Si.

Charging

Temperature in the BOS process is controlled by using a thermally balanced charge of hot metal and scrap. The charge generally contains more carbon than is required in the final steel. The carbon reacts with the oxygen to produce heat and CO gas. In the electric furnace, this is often done on purpose so that some CO is formed and evolved from the liquid metal to achieve some stirring.

Addition of alloy elements

The majority of alloys are added after the end of oxidation, first for de-oxidation (reaction with dissolved oxygen to form fine oxide particles which slowly float out of the liquid steel), then for composition adjustment. Note that this processing can be in two or more vessels - the furnace for maximum reaction or heating, then the ladle for close control in the final stages.

4.2 Basic Oxygen Steelmaking

The Basic Oxygen Steelmaking (BOS, sometimes called BOF for Basic Oxygen Furnace) process was developed in Austria in the early 1950s. In Europe the process is known as 'LD' steeImaking, after the two Austrian steelworks at Linz and Donawitz where experimental work was carried out.

The basic oxygen process converts iron into steel using gaseous oxygen to oxidise the unwanted impurities in molten iron. The oxygen used must be of high purity, usually 99.5% minimum, otherwise the steel may absorb harmful nitrogen.

The BOS furnace is simply a barrel-shaped steel shell with a refractory lining and supported on a tilting mechanism. The vessel can swing through a vertical plane of 360° and can be held in any position.

The term "basic" is used because the refractory linings of the furnace are made of alkaline materials (dolomite and magnesite), The flux used in this process is primarily burnt lime (calcined limestone).

Refractory linings must have specific properties to withstand high temperatures, the corrosive action of the highly oxidised and basic slags, and abrasion during charging and blowing.

BOS furnaces range in size from a few tonnes to 400 tonnes, but most are in the 100-250 tonne range. A typical BOS shop has two furnaces, one operating while the other is rebricked and held in readiness. The aim is to maximise the period when both furnaces are available for use. In this way, furnace delays are minimised. Some have three furnaces, operating two out of three.

World capacity of steel plants grew from less than five million tonnes in 1960 to more than 550 million tonnes by 1980. Current world steelmaking capacity is over 1000 Mt/a.

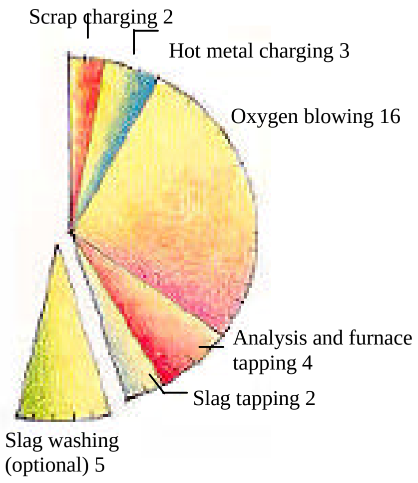


Figure 6 A typical BOS production cycle. The complete cycle of production required to produce 280 tonnes of molten steel is about 27 minutes

Process

Before the beginning of the cycle the hot metal is weighed out, sampled for chemical analysis and for temperature. This data, together with grade specifications, is used to calculate the amount of scrap, fluxes and oxygen required (final heat balancing is controlled by the addition of small quantities of iron ore). These amounts also depend on the levels of silicon, carbon etc., and temperature of the hot metal, since the heat generated by impurity oxidation must balance the requirements of bringing the scrap, fluxes and hot metal to the required temperature.

To begin the cycle the furnace is tilted for scrap charging. The scrap loading crane tips the required material into the furnace from a large scoop.

The furnace is then tilted to receive the hot metal from a transfer ladle.

The vessel is returned to the vertical position and a lance lowered. The lance blows oxygen on to the charge at high velocity and reactions commence. Seconds later ignition occurs when the carbon monoxide from the reaction burns to carbon dioxide, producing a brilliant, luminous flame at the mouth of the furnace. The amount of oxygen used is about 50 m^3 for each tonne of steel produced.

After ignition, burnt lime and dolomite together with some fluorspar are dropped into the vessel from overhead chutes. These are the fluxes that form the slag. It is necessary early in the blow to form a fluid slag, which has the function of preventing "sparking", the ejection of metal from the furnace due to the impact of the oxygen jet.

To promote quick formation of slag, burnt lime is used. If raw limestone was used, its calcination would absorb heat from the process. This would reduce the amount of scrap that could be used. Fluorspar is added to promote the fluidity of the slag. Any iron ore required (to adjust temperature) is then added with the remainder of the flux charge, whilst blowing continues. The complex flux charge is added within the first few minutes of the blow.

Chemical Reactions

The reactions in a BOS furnace take place rapidly because the liquid metal mixes instantly with the oxygen.

$2Fe + O_2 \longrightarrow 2FeO$

$4Fe + 3O_2 \longrightarrow 2Fe_2O_3$

$Si + O_2 \longrightarrow SiO_2$
removal of silicon

$2C + O_2 \longrightarrow 2CO$
removal of carbon

$2Mn + O_2 \longrightarrow 2MnO$
removal of manganese

$4P + 5O_2 \longrightarrow 2P_2O_5$
removal of phosphorous

The height of the lance above the metal has an important effect on blowing characteristics and on the analysis of the steel. The operation starts with the lance in a "high blow" position, about 3 metres above the metal level. After a few minutes, after the flux is added and sufficient slag has formed, the lance is lowered to the "low blow" position, up to two metres above the metal.

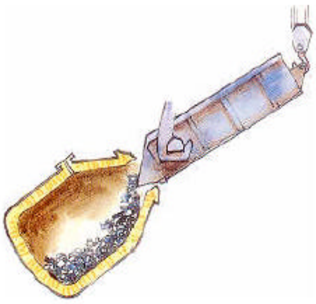
Composite blowing, or bottom injection, is the injection of supplementary gases through porous plugs or tuyeres in the bottom of the vessel. The gas can be either inert or oxidising. If oxygen is used then a coolant such as hydrocarbon is often required to prevent localised overheating at the injection point. Bottom injection promotes mixing and gives improved yield due to decreased slopping. (Slopping occurs when a slag and steel are expelled from the furnace during oxygen blowing).

Sub-lances allow samples of the metal bath to be taken before the end of the blow. They permit computer attainment of the "end point" and a significant reduction in the time between end of blow and tapping.

A steel sample is sent by pneumatic tube to the laboratory. A chemist completes a reading in approximately three minutes using a spectrometer. The result is then reported by computer in terms of carbon, phosphorus, manganese, silicon, sulphur, nickel and chromium content.
On the basis of the temperature and the analysis, it is decided whether further adjustment is necessary. Coolant may be added to lower the temperature to the required tapping temperature, or there may be a short re-blow of oxygen to correct the analysis or increase the temperature, or both.

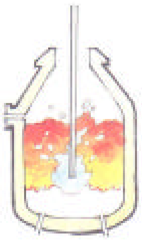
When the tests and temperature readings are satisfactory the furnace is tilted to the tapping position.

The molten steel pours through the taphole from under the floating slag, into the ladle below. The taphole is located on one side of the vessel below the mouth. Weighed amounts of alloys are added to the ladle during tapping. The highly oxidised slag is contained in the vessel by use of a slag stopping device, known as a slag dart. After the steel is tapped the slag is poured into a slag ladle.

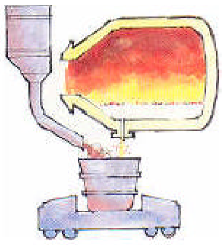


1 Charging scrap

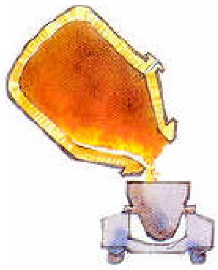
2 Charging Molten iron



3 Oxygen blowing



4 Tapping and addition of alloys



5 Slag tapping

Secondary steelmaking or ladle refining (e.g. vacuum treatment, inert gas stirring, ladle furnace metallurgy) occurs in the ladle after molten steel has been tapped from the steelmaking vessel. The purpose is to increase furnace productivity by performing some of the operations normally done in the steelmaking vessel. It also improves steel quality.

Inert gas is injected through the steel to create a stirring action and therefore, thorough blending. This also helps to reduce the inclusion content (level of non-metallic impurities produced by the deoxidation reactions) of the steel as impurities are swept up and contained by the slag. The injection of powdered re-agents further removes impurities from the steel.

For some high quality steels, **vacuum de-gassing** is used to ensure a minimum content of dissolved gas, particularly hydrogen and oxygen. A number of different systems have been developed, all of which expose the liquid steel to a vacuum, creating a turbulence to free the dissolved gases. This ensures greater internal soundness in the final product.

The BOS process develops a dense brown fume of iron oxide in the waste gas. Electrostatic precipitators or wet gas scrubbing systems are used to clean this material which is then collected as solids or slurry while the clean gas passes to the atmosphere through a stack.

4.3 Electric Arc Furnaces

The Electric Arc Furnace (EAF) has been in use for nearly 100 years as a method for making steel. In the early years of the 20th century, its use was restricted to small scale (several tonnes) operations, producing special types of steel. In more recent years the EAF has grown in popularity as technical problems have been solved and the availability of low cost, reliable electrical power supplies have become widespread.

In the last 20 or so years, the EAF has experienced something of a renaissance as technical innovations have led to very significant improvements in productivity, steel quality and operating cost. These developments have proceeded to the point where the EAF is generally preferred as a low capital, flexible route for producing a large proportion of flat products and almost exclusively, long products.

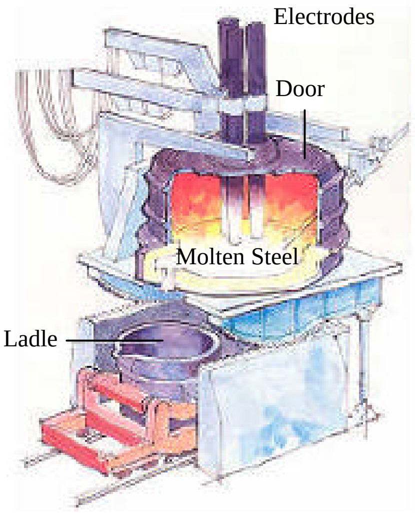


Fig 8 Electric Arc Furnace

Process

The modem EAF consists of a refractory lined steel shell or hearth that holds the scrap charge while it is being melted and retains the liquid steel until it is ready to tap. The upper walls of the hearth (above the metal level) are typically water cooled copper panels. The furnace has a water cooled roof that can be swung aside as necessary for scrap charging.

In most cases, scrap is added to the EAF via steel buckets or baskets that are positioned over the hearth. The buckets have doors in the bottom that open in a clam shell fashion to release the scrap. All types of scrap and scrap substitutes can be added this way. Charge carbon and fluxes (lime and dolomite) are sometimes added via the scrap bucket. For regular sized materials such as DRI/HBI, these are preferably added via conveyor belt to a "fifth hole" opening in the roof. This is known as continuous charging. It is normal to charge at least two buckets and as many as five per heat. The density of the scrap charge determines the number of buckets required to reach the tap weight.

EAFs can be either AC (3 electrodes, each with its own phase) or DC (single or twin electrode). In an AC furnace, the roof has at least five openings, one for each of the three electrodes, one for fume evacuation and the above mentioned additions hole. In AC, the current path is from the electrode tip to the bath and back to the next electrode (in the phase rotation). In DC, the current passes from the electrode through the bath to a return electrode in the furnace hearth.

The electrodes are made of graphite that has been manufactured to have special properties of conductivity and strength at high temperature.

The electrodes are consumed in the process and need to be continually replaced. This is done by "slipping" the electrode down lower in the holder arm and adding a new section to the top. Electrode sections are screwed together. The melting energy is supplied from the resistive heat generated when an arc is struck in air.

Electrical power is supplied from a grid to a substation, then to a step-down transformer. The furnace also has its own transformer that serves to alter the furnace electrode's voltage value. These voltage "taps" are usually automatically selected but can be manually selected by the furnace operators. The electrode voltage determines the maximum arc length and therefore the melting energy that is supplied. The EAF electrode position is regulated so that the desired arc current and power is maintained at the chosen setting. This is usually achieved by constantly measuring the impedance (voltage divided by current) and feeding it back to a control system that raises or lowers the electrode arms, as conditions inside the furnace change during melting.

Oxygen is used to assist in refining the steel and removing impurities such as phosphorus. A lime rich slag is used to collect such unwanted elements and provide a base material to be foamed by CO evolution. This foamy slag helps improve energy efficiency during heating by preventing direct radiation of the unshielded arc to the furnace roof. The foaming action causes the slag to be continuously flushed from the EAF up until tap time. When the appropriate steel chemistry and temperature has been achieved, the steel is tapped through either a spout (i.e. like a teapot) or a submerged taphole, into a ladle and then on to a ladle furnace for secondary treatment.

Mini-mills

The EAF is associated with the concept of the mini-mill, which first became popular in the late 1960s. The original mini-mill consisted of a single or multiple small EAFs, melting scrap collected from the local area and feeding a continuous billet caster. The billets would be rolled in a small bar or rod mill on the same compact site. Typically these early mini-mills had an annual capacity of 100,000-300,000 tonnes. Their product was sold into the local market and the number of grades and product types kept to a minimum. This concept has been so successful that virtually all structural quality grades of rod and bar products are now produced this way. Additionally, most other types of long products are also produced in EAFs.

Nowadays, the typical long products mini-mill is not so mini, with capacity ranging between 400,000 and 1,500,000 tonnes per annum.

As the product mix has expanded, increasingly sophisticated secondary metallurgy such as ladle furnaces and vacuum de-gassers have been combined with near net shape casters to better meet the user requirements. The scrap feed mix has grown to include substitutes such as DRI (direct reduced iron), HBI (hot briquetted iron), blast furnace hot metal, and various types of pig iron. The original simple concept has been greatly augmented and varied.

The EAF is a process still in evolution. The two main driving forces behind most changes in recent times have been a push to improve firstly productivity, and secondly, availability. These two together have also helped to reduce operating costs.
The main method to improve productivity of EAF's has been to augment the electrical energy input with "chemical energy".

Chemical energy can be in the form of:

- oxygen/fuel burners to help melt down the scrap;
- carbon/oxygen injection lances to foam the slag and also produce heat from combustion reactions; and
- oxygen tuyeres combined with submerged carbon injection and above bath post-combustion oxygen.

In the last ten to fifteen years, much effort has focused on recovering energy from the off-gases. The idea of ducting the hot gas to pre-heat scrap buckets has been only partly successful. Very good success has been achieved with water cooled scrap preheating shafts placed on top of the

EAF roof. These shafts are charged periodically with a bucket and the scrap absorbs the heat of the off-gas.

Availability has been improved by replacement of refractory components with water cooled sections. Most notably, the walls of the hearth, the roof and delta section are all replaceable metal panels.

Other innovations include water cooled supersonic oxygen injection lances, submerged tapholes and electrode spray cooling. Refractory quality has also greatly improved. Carbon magnesia is typically used in the hearth area.

The development of the ladle furnace has allowed the EAF to concentrate on melting and refining, with the job of superheating and alloy adjustment being done in the ladle.

Continually larger transformers are being employed, with bigger electrodes. Recent EAF installations (known as ultra high powered, or UHP) have transformer rating to tap weight in excess of 1,000 kVA per tonne. Some DC EAFs use electrodes of 760 mm in diameter.

The versatility of the EAF is demonstrated by the fact that commercial installations range in size from 1.0 up to 350 tonnes tapping weight. Steel production rates typically range from 60 to 150 tonnes per hour, depending on transformer size and the degree of use of augment energy. In the latest plants, there is a high degree of automation, with activities such as oxygen injection, burner operation, electrode assembly and refractory gunning being either semi-automatic or at least remotely controlled.

4.4 Special Steels

The EAF is the preferred method for making high alloy and special steels. Steelmaking practice and EAF design is similar to that for carbon steel production, with a few notable exceptions. High alloy steels are normally produced on a much smaller scale due to the more specialised nature of the product and the lower tonnages required. Alloy steelmaking is typically done in a foundry and products are **ingot** cast.

Alloy steels are melted from a charge of selected alloy scrap and ferroalloys. Ferroalloy is the common term for a mixture of iron and an alloying element such as silicon or manganese. Iron is normally 25-30% of the total with the alloying element and other residuals making up the balance. The residual element is often carbon, as an outcome of the ferroalloy production process. During melting, multiple slag practices may be required to remove phosphorus and sulfur, and decarburise. In these processes, careful attention is paid to ensure that precious alloying elements are not lost during each refining step.

The most significant special steel industry is stainless steel production. Stainless steels are more resistant to rusting due to the addition of chromium into the alloy. In most cases, the chromium content is of the order of eighteen percent, the carbon content is approximately 0.10% but as low as 0.01 %, with various combinations of nickel (up to 15 percent), molybdenum (up to 4%), titanium, manganese and silicon.

The production process is essentially one of removing carbon from liquid steel in the presence of chromium. Many different processing options exist but in principle they follow the same basic logic, making use of different raw materials as dictated by local economic conditions and minimisation of operating costs.

5 Shaping

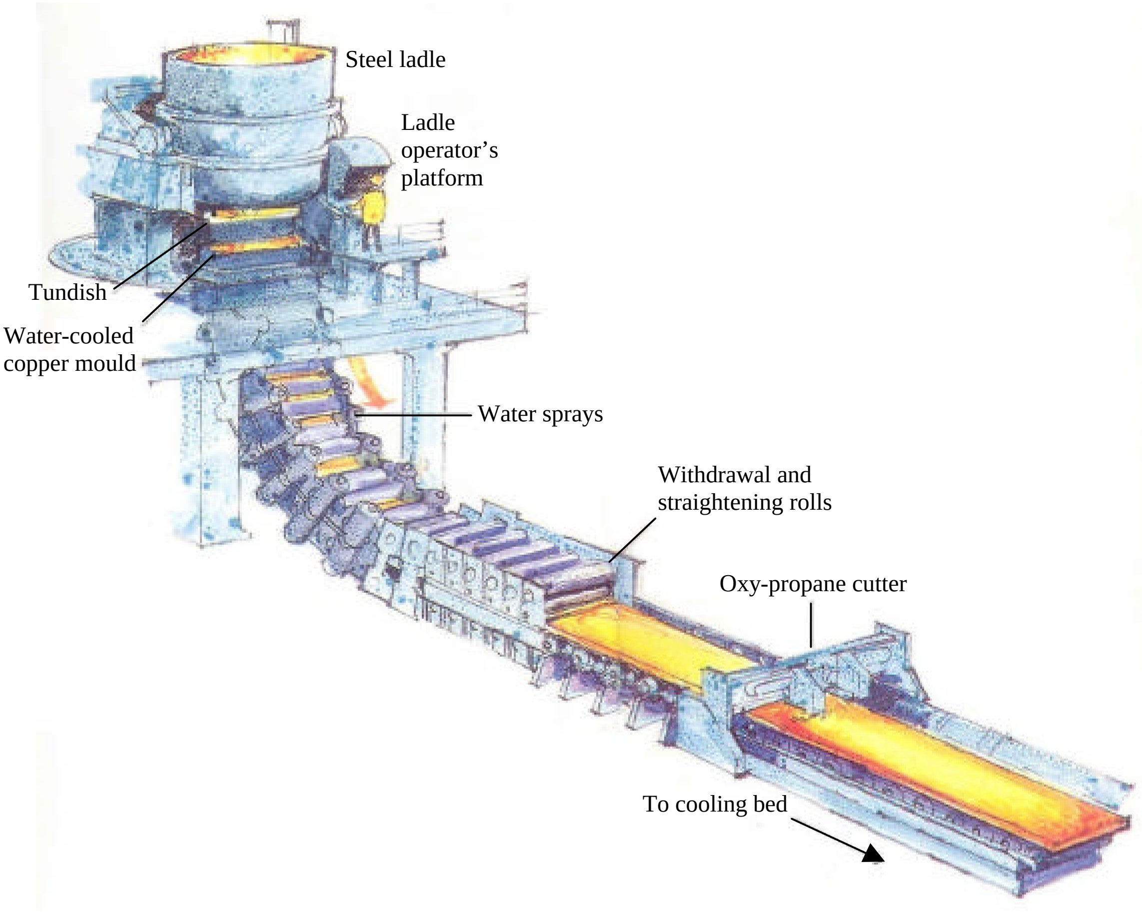
5.1 Casting

The conventional **casting** process consists of tapping molten steel from the furnace into ladles of up to 300 tonne capacity, the ladle is then moved to a **teeming** platform where molten steel is poured into moulds and allowed to solidify into ingots. These ingots are subsequently reheated and rolled to produce semi-finished shapes such as slabs, blooms and billets.

In the last three to four decades, a process known as the **continuous** casting process has emerged. This process has been successfully employed for direct casting of molten steel into semi-finished steel shapes, replacing the ingot casting-reheating-primary rolling operations.

The major components of a continuous casting machine, schematically illustrated in Figure 9, include:

- liquid metal reservoir/distribution
- system called a tundish;
- water-cooled, oscillating, open-ended copper mould having a length of 900 mm;
- secondary cooling;
- containment section; and
- withdrawal rolls.



Process

The casting process involves delivery of molten steel from the ladle, to the tundish, and into the mould where it starts to solidify. Since both ends of the mould are open prior to the beginning of casting, a dummy bar is inserted into a mould, closing its bottom. After the steel in the mould has reached a desired level, the dummy bar is pulled downward, withdrawing the partially solidified strand from the mould. The partially solidified strand is continuously withdrawn and solidification is completed below the mould where additional heat removal is achieved by spraying water onto the surface of the cast strand.

Casting conditions are such that the solidified shell leaving the mould is strong enough to withstand the ferrostatic pressure of the molten steel contained within the cast shell. The mould oscillates at 60 to 400 cycles per minute to prevent sticking between the strand and mould. As well, lubricants such as oil or fluxes are added to the mould to minimise strand/mould friction. This assists in the smooth withdrawal of the strand.

The rate at which the strand is withdrawn is referred to as the casting speed, which is equivalent to the molten steel delivery rate into the mould. The casting speed is strongly governed by strand size and steel quality, and is usually maintained between 0.5 and 2.0 m/min.

Solidification of the liquid steel which begins in the mould continues progressively as the strand moves through the casting machine. After exiting the mould, the strand enters the secondary cooling zone which consists of a series of water or air mist spraying nozzles designed to provide optimum cooling of the strand. Furthermore, in the secondary cooling zone, the strand is mechanically supported by rolls to prevent it from bulging which results from the action of ferrostatic pressure of the molten steel within the casting.

The final solidification point which is profoundly influenced by casting speed can vary depending on section size anywhere between 10 to 30m from the mould top. After completion of solidification, the strand is cut into desired lengths by gas torches or mechanical shears for further processing.

The continuous casting process has been well established and adopted by steel industries worldwide. The rapid growth of this process in the last three decades can be attributed to its inherent advantages of low cost, higher yield, flexibility of operation and ability to achieve high product quality compared to the conventional ingot-casting route. It is well recognised that despite distinct advantages, the complexities associated with the operation of this process can be enormous owing to stringent requirements in the design of strand support, bending and straightening operations and rapid cooling rates. Consequently, any inadequacies in the control of the process will increase the strand susceptibility to defects. The attainment of quality clearly requires the ability to monitor and control the casting operation very effectively.

Another casting process is the horizontal continuous casting process which although not widespread in use has nevertheless found some applications particularly in the casting of special steel grades. The main advantages of this process are low overall machine height and more importantly, strand bending and straightening operations, as done in vertical casters, are avoided.

5.2 Working

Continuous casting produces semi-finished shapes like slabs, blooms and billets, which have to be further rolled into more useful shapes. Rolling mills are designed for processing either flat product or shaped product.

Basically the rolling process consists of passing the steel between two rolls revolving at the same speed but in opposite directions. The gap between the rolls is smaller than the thickness of the steel being rolled, so that the steel is reduced in thickness and at the same time, lengthened.

A set of rolls is called a stand, and in anyone mill there may be a number of stands. The rolls in contact with the steel are called work rolls. Often back-up rolls are provided to increase the rigidity of work rolls for improved dimensional control. A mill with no back-up rolls is called a two-high mill. A mill with one pair of back-up rolls is called a four-high mill.

In some special mills, the configuration can be up to 30 high. Steel may pass through a number of stands (continuous), or back and forth though one stand a number of times (reversing), before it reaches the required thickness or shape. Each mill is designed for a particular product range.

Rolling or working steel changes the mechanical and physical properties of the steel to give it certain characteristics necessary to the final product. Steel, like most other metals, is crystalline, consisting of aggregates of small, irregular shapes known as "grains". The grain structure has a significant influence on its mechanical properties. Steels having a fine grain size have the best mechanical properties such as greater toughness and strength.

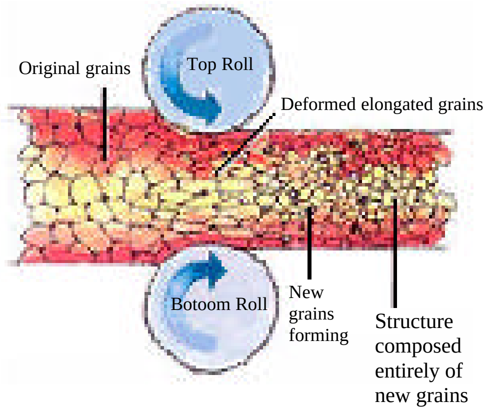


Figure 10. *Deformation of steel grain structure under rolling, and development of a new grain structure.*

Hot Working

The grain size of continuously cast steel is coarse and uneven. When this steel is worked by forging or rolling (deformation) while hot, its structure is refined. Hot work is generally carried out in a series of steps, so the grains gradually become smaller and smaller with each successive reduction of the steel.

During deformation, the metal grains are fragmented and a strained condition is set up in the crystalline lattice. Blow holes and porosity which make the steel unsound are eliminated by compression working during the working. At proper hot working temperatures and reduction levels the strained condition is quickly relieved as the highly mobile atoms recrystallise to form new smaller grains.

In general, the more hot work performed, the smaller the average grain size, and consequently, the better the mechanical properties of the steel. However, once formed, the new grains grow in size, although their rate of growth diminishes as the temperature of the steel falls.

Finally, the steel cools below the critical temperature range, grain growth ceases, and the grains are transformed to a new physical structure. The critical temperature range varies, depending on the carbon and alloy content of the steel. For normal carbon steels, the temperature at which the physical change occurs, known as the '1ower critical limit", is 727°C.

Cold Working

Cold working is a finishing process applied to steels that have been hot worked and cleaned of scale (the surface layer of oxides formed at high temperatures).

Cold working increases strength, enables improved accuracy in dimensional control, produces a bright smooth surface finish and thinner gauges. It may also improve machinability of certain grades of steel.

Cold work is usually carried out at room temperatures, with lubricants to reduce friction. Grains in the structure are made longer, giving increased strength and hardness, and decreased ductility. These effects are cumulative, and will build up to a limit beyond which the steel will fracture if cold work is continued. Appropriate heat treatment can restore ductility, and allow further cold work to be carried out if necessary.

The main cold working methods are: cold rolling (for sheet and strip) and cold drawing (for bars, wire and tubes).

The essential difference between hot and cold working is that when the grain structure is distorted during cold working it does not automatically recrystallise and form new, small grains. Instead, the distorted grains remain “frozen” in a strained condition.

5.3 Hot Rolling

Slabs may be rolled in a plate mill or hot strip mill. Blooms are rolled in a bloom/billet mill to produce billets. Billets are then further rolled in merchant bar mills (sometimes called bar mills) or rod mills. Both slabs and blooms may go to a structural mill. The plate mill, hot strip mill, billet mill, merchant and structural mills are all hot rolling mills.

Process

The relative plasticity of steel at temperatures between 800°C and 1200°C makes it possible to roll steel into a variety of useful shapes, while improving its mechanical properties. Generally, the more steel is hot rolled, the denser and tougher it becomes.

As a first step in the production of hot rolled products, the steel must be reheated at a temperature suitable for rolling.

Slabs, blooms and billets may be charged hot (400°C) or cold (room temperature) into the furnace. Hot charging has the advantage of reducing heating energy.

Reheating in furnaces is a continuous process. Steel is charged at one end of the furnace and extracted from the opposite end. As the steel moves through the furnace it passes through a number of heating zones with preset temperatures. Apart from ensuring the correct temperature, the reheating process must be controlled to minimise the formation of scale (iron oxide, which leads to a loss in yield) and decarburisation, where the surface layer of the steel is depleted in carbon content resulting in a loss of strength.

After the slabs have been reheated to about 1225°C they are de-scaled with high pressure water jets and passed through a reversing roughing mill. Slabs can pass through this reversing **stand** several times, which reduces a thick slab (typically between 200 to 300mm) into a "transfer bar" of about 30mm thickness.

The transfer bar may be fed into a train of finishing mills (4 to 6 stands) to roll to its final thickness, or it may be first formed into a coil via a "coilbox" machine. The coiling operation is then reversed and the new head is fed into the finishing mill. This process ensures uniform rolling temperatures along the length of the coil in the subsequent finish rolling stage.

The steel strip is then water cooled on a long "run- out" table before coiling. Its final thickness varies between 1.2 mm to 13 mm.

Products

Plate and strip are two products that are hot rolled from reheated slabs. (Modern compact mills may have the slabs fed directly into the rolling mill from the caster in which case reheating is not required.) They are called flat products, and account for over half of all steel produced.

The industry regards steel rolled to a thickness greater than 5 mm as plate; widths usually range up to about 3250 mm. Its principal applications are in shipbuilding, the manufacture of large pipes, steel boilers and tanks.

The transformation from slab to strip wound in a coil ready for delivery takes about 3.5 minutes. In a typical plant, a slab weighing up to 25 tonnes, and measuring 6.7 metres long and 230 mm thick, will be reduced to a 3000 metres long thin ribbon of steel strip.

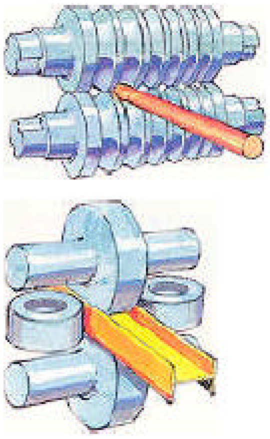


Figure 12. *Top: Typica/2-high merchant strand. Bottom: Arrangement of rolls in* a *universal beam mill, rolling all four sides of the beam in* a *single pass.*

Most of the hot-rolled strip goes to feed cold rolling mills, but some is used to manufacture a variety of pressings and formings for the automotive and general engineering industries.

Structural and bar products are also hot rolled. These mills differ from flat products mills in that the rolls used for structural and bar products are profiled. In most cases many passes are required to produce the final shape. (Figure 11).

Structural steel is rolled from blooms into a wide range of shapes and sections. They are used in the framework of buildings and ships, rail and sleeper construction, in heavy vehicles and machines and in piling foundations. The development of universal mills to roll beams and columns with wide and parallel flanges has greatly facilitated the more efficient use of steel. The wide flange sections are readily bolted or welded into frames.

Merchant bar is used in the manufacture of machinery, tools, hardware, leaf and coil springs, and automobile engine parts. Some sections in this group are also used for concrete reinforcing and light structural work.

The term merchant bar is used to describe a range of shapes and small sections, such as rounds, squares, hexagons, angles, flats, beams and channels. The name originated from the fact that these sections were, and still are, stocked and distributed by steel merchants.

5.4 Cold Rolling

Process

Before rolling, the strip is uncoiled and cleaned, or "pickled", in a long tank containing acid. This process removes blue/black oxide and scale from the surface. Following the pickling process the steel is rinsed and trimmed before continuing on to the cold reduction mill. The leading end of the clean pickled coil is fed through a set of rolls and onto a recoiler.

Cold reduction mills comprise up to six stands, and most are of the four-high variety. The steel is rolled through the stands at a high speed of about 60-80 km/hour. By a combination of very high roll force and strip tension, the steel thickness is reduced progressively at each stand. Strip 2.5 mm thick and 1200 metres long would typically be cold reduced to 0.5 mm thick and 6000 metres long. The amount of rolling to which the steel is subjected and the rapidity with which it is reduced in cross section, have far reaching effects on its characteristics.

In some plants, the pickling and cold reduction is a continuous process. After being pickled, strip is joined end to end before passing through the reduction stands. After cold rolling the steel may be annealed or tempered to enhance the metallurgical properties of steel. (see 6.1 Metallic Coating - Process)

5.5 Cold Drawing

Some steel products are made by **drawing** the cold metal through one or more tapered dies in the final stages of their manufacture. Cold drawn bars are made in round, hexagonal or square sections, and also in special shapes for particular applications. The material has a high quality surface finish, and accurate sizing.

Wire is produced by drawing steel rolled in a rod mill. A modern high speed rod mill produces steel coils in gauges from 5.5mm diameter to 16mm. This is then cleaned of scale, and drawn into wire through a succession of tapered dies to the required final gauge. The dies are made of tungsten carbide. The wire may then be coated (with zinc, tin, copper, or one of the polymer materials) and then may be formed into different shapes such as ropes or netting.

Wire is one of the most ubiquitous forms of steel and is used to make fences, springs, nails, staples, steel wool, and even the humble pin. In all more than 150,000 different uses of wire have been recorded.

5.6 Tubemaking

Steel pipes and tubes are arteries of civilisation, carrying water, air and fuels into homes and factories, and playing an important role in transport. They also find a place in all sorts of metal structures.

In a typical operation to make welded pipe, hot rolled strip is heated and passed through a series of specially grooved rolls. These curl the hot steel into the shape required, and press the hot, bevelled edges together to form a weld. This is called "continuous butt welding".

The other commonly-used process is electric weld. Strip or plate is cold formed to the required diameter, and then joined together by electric resistance welding (ERW), in which the electric current heats the edges very rapidly before they are pressed together, or by fusion welding, in which an electrode is melted to complete the weld.

Uses for welded tube range from the smaller diameter thin-walled tubes used in furniture and conduit in light engineering applications, to large diameter heavy-walled water mains, penstocks, and high pressure gas and oil pipelines.

6 Coating

Cold rolled strip is often coated with organic or metallic materials to protect the steel surface and/ or give the steel specific characteristics. Metallic materials used to coat steel include mainly zinc, aluminium and tin.

6.1 Metallic Coating

Process

Most continuous hot dip metal coating lines are also in-line **annealing** lines, where steel is heat treated before metal coating. This is done by passing the strip through a heat-up furnace, where residual surface oils are also removed, and a subsequent furnace where the strip is heat treated in a reducing atmosphere. The furnace temperatures may be as high as 1370°C.

The heat-up furnaces are vertical and utilise very rapid heating under essentially non-oxidising conditions to produce a clean steel strip surface suitable for hot dip coating. The subsequent annealing furnaces are either vertical or horizontal, and in these furnaces various heat treatment cycles are carried out in a protective atmosphere of nitrogen containing between about 5-18% hydrogen, depending on the line configuration.

From the bottom of the heat-up furnace the strip passes around a roll and enters the protective atmosphere furnace, which uses gas filled radiant tubes and/ or electric elements for heating. A jet cooling section may follow to rapidly lower the strip's temperature; cooling of the strip is accomplished by blowing inert gas onto the top and bottom of the moving strip. If jet cooled, the strip will pass through a temperature zone which will hold the strip at a reasonably constant temperature, to complete the annealing cycle.

The strip then enters a coating bath through a snout immersed in the molten alloy. This is held in a ceramic or steel pot which is heated by induction (ceramic) or electrical heating elements (steel).

After passing down the snout the strip passes around a bottom roll in the molten alloy and leaves vertically through the molten metal surface. It then passes through pneumatic coating mass control jets or gas knives, one on each side of the strip. These control the amount of liquid metal on the steel surface by blowing any excess back into the coating bath. The lines are designed so that the coating alloy solidifies before a top turn-around roll and it is then cooled further by air blowing to reduce the temperature to 50C before being treated for surface finish. The strip is finally passed through a chemical treatment tank where a thin film is applied to the surface to provide temporary protection against corrosion during transport and storage. It is then recoiled.

Products

On leaving the coating mass control process, some products will undergo a further heat treatment to alloy the new zinc coating with the steel base. A coating of zinc or zinc/aluminium is an excellent corrosion prevention system. Zinc is also anodic to steel thus offering further protection through sacrificial action at cut edges where the steel base may be exposed. This group of products is made in formable and strength grades for exterior applications such as roofing, walling, rainwater goods and steel framing.

Tinplate is steel sheet with a thin coating of tin. Cold-rolled strip is cleaned and then annealed (heated in a furnace with an inert gas atmosphere and cooled slowly) to remove the hardening effects of the heavy cold reduction process.

It is then passed through a temper mill to give the steel the exact strength and hardness required: The tin coating is then applied, usually by an electrolytic process.

Terne coated are steels that undergo a lead/tin alloy-coating. They are formable steels produced for specialised applications such as fuel tanks, radio and TV chassis and car radiator straps.

6.2 Organic Coating

Organic coating describes the continuous application of decorative and/ or protective paint or plastic film/laminates to steel strip. Organic coatings may be applied to a variety of steel strip, although it is largely used with galvanised steel, steel, and small amounts of hot and cold rolled steel and tinplate.

Process

The essential operations are:

- uncoiling;
- cleaning and pretreatment;
- primer coating and curing;
- top or finish coating; and
- curing and recoiling the finished product.

The strip is coiled after each painting stage. Before the metal is painted it is cleaned and chemically treated. Firstly the metal is alkaline degreased, possibly in stages, with or without mechanical brushing. After a hot water rinse, it is treated with a chemical solution which reacts with the surface. This is called a conversion coating. The conversion coating is then water rinsed, and given a passivation treatment by rinsing in a chromate solution followed by de-ionized water. The conversion coating can also be applied using a roll fed with solution by another roller, a similar system used to apply paint. Cleaning is carried out using spray systems, and pretreatment may be applied by this method, or by dip process. Typical pretreatments are iron phosphate solutions for aluminium, and zinc phosphate, chromate based systems or alkaline systems, containing cobalt and zinc for galvanizing.

Usually a corrosive inhibitive primer of several microns (μm) thick is applied as the first coat on both sides of the strip. The paint coatings are applied by roller coaters which consist of a steel pick-up roll, and polyurethane metering and applicator rolls, and operates with the coating roller revolving either in the same direction (forward coating) or opposite direction (reverse coating) to that of the strip travel.

Paint curing is carried out in hot air convection ovens, which heat the strip to suitable temperatures to remove solvents and cause the paint resins to react and cross-link. All the paint systems are of a type which can be completely cured in about 30 seconds or less, during which time the strip temperature peaks up to about 230°C. The paint coatings are up to 25~ thick and can be applied to the strip moving at speeds of greater than 130m/minute.

Very flexible paints have been developed to withstand most forming operations. Paint resins include silicone polyesters, vinyls and acrylics. **PVC film/steel** laminates are adhesive bonded under heat and pressure to line pre-treated steel. Many styles and colours are bonded to a variety of steel bases to give a strong decorative product.

Electrical steels are steels with silicon content up to 3%. They have special magnetic properties produced for applications such as laminations for electrical motors and transformers. This is a continuous line process where strip is decarburized and annealed in a furnace, coated with an insulating varnish, and recoiled. Complete removal of carbon is necessary to develop the required magnetic properties in the steel; this is achieved by reaction of the carbon in the steel with a carefully controlled decarburizing atmosphere at annealing temperatures.

Products

Typical uses for painted steel, such as BlueScope Steel's premium COLORBOND" brand, include roofing and walling, swimming pools, cool room walls, kitchen appliances and furniture. Typical applications for PVC film/steel laminates are in TV and appliance cabinets, partitions, furniture and bus exteriors.

7 Steels and its Alloys

Broadly, steels are described as **carbon** steels **or alloy** steels.
Both contain carbon, but carbon steel contains only incidental or residual amounts of such elements as chromium, nickel and molybdenum. These and other elements are intentionally added in various combinations to alloy steels.

Carbon steel is general purpose steel, and it accounts for over 90% of all steel produced; alloy steels are made to meet special requirements of strength, toughness and resistance to abrasion, heat and corrosion. Some typical analyses of iron and steel in common use are shown in table 7, below.

In the steelmaking processes carefully proportioned ingredients are added to produce different grades of steel. Oxygen combines with unwanted impurities in the iron to form oxides which are retained in the slag or eliminated in gaseous form.

The timing of these additions is important in many cases, because of their different rates of oxidation. Copper, nickel and molybdenum, for instance, may be added at any time without fear of loss, because they are permanent residuals. Various other elements (because of their more rapid rates of oxidation) must be added to the molten steel towards the end of the refining process during or after tapping.

The effects of the various elements on the properties of steel are outlined in the following paragraphs. The effect of a single element often depends on its inter-relation with others, but, to simplify this:

Carbon is the principal hardening element in steel and, in plain carbon steels, it is used as the controlling element in regulating the mechanical properties. When carbon content is increased, hardness and tensile strength are improved but ductility and weldability are reduced.

Manganese increases strength and hardness but to a lesser degree than carbon. Manganese also improves the toughness and abrasion resistance of steel and acts as a mild deoxidiser.

Silicon is a powerful deoxidising agent and is used to promote soundness. **It** increases tensile strength and also enhances the magnetic permeability and electrical resistance of steel. Low carbon silicon steels containing from 0.75 to 4.0% silicon are widely used for the laminated cores of electric motors, generators and transformers.

Sulphur is generally considered an undesirable element, except where machinability is the prime consideration. Sulphides in steel improve free machining properties by promoting chip breaking, but decrease ductility and impact strength. Iron sulphides have a low melting point and promote surface cracks on hot rolling. Manganese, when present in sufficient quantity, will neutralise this effect by preferentially combining with the sulphur.

Phosphorus is usually considered an impurity as it may reduce toughness and ductility. However, phosphorus is added to some steels in small quantities as it has a beneficial effect on machinability, tensile strength and atmospheric corrosion.

Nickel provides increased toughness, tensile strength and hardness, in addition to its contribution to corrosion resistance. It is valuable for increasing the degree to which steel can be hardened by heat treabnent (i.e. it increases steel "hardenability").

Chromium increases hardenability and tensile strength, and improves corrosion and abrasion resistance. It is often associated with nickel additions to form the well-known nickel-chrome "stainless" steels in extensive use throughout the world for high performance and heat resistant applications.

Molybdenum strongly increases the hardenability of steel, and is also most effective for increasing tensile strength at high temperatures.

Copper is added mainly to improve resistance to atmospheric corrosion. In the small amounts used it has no significant effect on mechanical properties.

Boron is added to increase the hardenability of steel. Only a very small addition (two to three thousandths of 1 %) is used.

Aluminium is a valuable deoxidising agent because of its great affinity for oxygen. It is used in small quantities to subdue blowhole formation and promote soundness. Aluminium also produces a fine grain size in steel by forming fine aluminium nitride particles.

Table 7 - Typical analyses of grades of iron and steel

	Foundry grade of Pig Iron	Structural Carbon Steel	Nickel-Chrome Molybdenum Alloy Steel	Austenitic Stainless Steel
Iron	91.7%	98.91%	96.40%	71.66%
Carbon	4.2%	0.20%	0.20%	0.08%
Silicon	2.3%	0.06%	0.25%	0.07%
Manganese	0.75%	0.80%	0.50%	1.00%
Phosphorus	0.10%	0.01%	0.02%	0.02%
Sulphur	0.035%	0.02%	0.03%	0.03%
Nickel	-	-	1.85%	9.00%
Chromium	-	-	0.50%	18.00%
Molybdenum	-	-	0.25%	-

(plus smaller amounts of other elements)

7.1 The Physical Metallurgy of Steel

The advantage of steel as an engineering material is its versatility and, to a large extent, this arises from the fact that its properties can be controlled and changed by heat treatment. Thus, if steel is to be formed into some intricate shape, it can be made very soft and ductile by a particular heat treatment; if, on the other hand, it is to resist wear, it can be made very hard by a different heat treatment.

The characteristics provided by these finishing processes are inherent in the chemical composition of the steel and its physical condition. Grain structure is also important.

To examine the micro-structure, a sample is first polished to a very high finish, and then lightly etched in acid or some other reagent, so that the particular grains are revealed. The sample is then viewed under a microscope, 50 to 500 magnifications being common for routine examinations. The important structures of steel as defined by the iron-carbon phase diagram and heat treatment are austentite, ferrite, cementite and pearlite.

Steels at temperatures above the critical range (727°C) have austenite as their main micro-constituent.

The relative amounts of ferrite, cementite and pearlite in steel at room temperature depend on its carbon content, and the rate of cooling from the critical temperature range.

Austenite is basically a "solid solution" of carbon in iron. The carbon and iron are intimately mixed, as they would be in a liquid, but both remain in a solid state. Austenite is non-magnetic, so steel loses its magnetism at temperatures above the critical range.

On cooling below the critical temperature range, the austenite decomposes to form "ferrite", "cementite", "pearlite" or some combination of these. The relative amounts of the constituents in a particular steel will influence its properties.

Ferrite is almost pure iron and is very soft and ductile. Steels with a large percentage of ferrite in their structure will have relatively low strength characteristics, but will be extremely ductile.

Pearlite consists of alternate lamellae (or plates) of ferrite and cementite. It contains approximately 0.85% carbon. Pearlite is harder than ferrite but softer than cementite. Thus the amount of pearlite in the structure influences the toughness of the steel, as it combines the hardness of the cementite with the ductility of the ferrite.

Cementite is iron carbide (Fe_3C) containing approximately 6.7% carbon. It is very hard and brittle, and reduces the ductility of steel. It may occur as free cementite or as part of the pearlite constituent.

When sufficient alloying elements are present, possible to retain the austenitic structure at normal temperatures. This produces non-magnetic steels with a high tensile strength and no loss of ductility. Austenitic grades of stainless steel are examples of this category.

Heat Treatment

There are three methods of heat treatment in common use:

- annealing;
- normalising; and
- quenching and tempering.
-

The difference between the heat treatment processes is the rate of cooling. Annealing involves a slow, controlled cooling; normalising involves a faster cooling in still air, and quenching involves very rapid cooling usually in a liquid bath.

- **Annealing** is a general term describing several procedures. The process is used mainly to relieve stresses set up in the steel due to its original cooling or to its subsequent hot and cold working.

Manufacturers usually anneal to soften the steel prepare it for further machining, cold working or heat treating operations. Annealing may also be used to develop a particular micro structure in the steel. Full annealing consists of heating the steel above its critical range, holding at that tempera for an hour or two and then cooling at a slow, controlled rate. This results in a coarse, pearlitic structure which is soft, ductile and without strain. For low carbon and medium carbon grades of steel, coarse pearlite is the best structure for machinability.

Spheroidize annealing (or "spheroidizing") is generally used for high carbon grades of steel. The coarse pearlitic structure obtained by full annealing does not give a high degree of ductility. When this property is particularly required, the steel is held for prolonged periods at a temperature just below the critical range and then cooled slowly to developed "spheroids" or globules of cementite in a ferrite matrix.

Stress relief annealing is used to remove the stresses set up during cold working particularly in low carbon steels. It is also used to relieve internal stresses set up by welding. The steel is heated to temperatures below the critical range and held there for up to three or four hours to equalise the temperatures throughout, and then cooled slowly. This reduces internal stress and increases ductility. This type of annealing is not as effective in close control of hardness and micro-structure.

For applications requiring a bright smooth surface, inert gas atmosphere is used in the heating furnaces to prevent oxidation scale. This is known as "**bright annealing**”.

- **Normalising**, though not an annealing treatment, is a related process. The steel is heated to a temperature above the critical range, held for a short time, then allowed to cool in still air. This results in a refined grain size and a more uniform structure, thus removing any undesirable effects of hot or cold working. Normalised structures are tougher but less ductile than annealed structures. Normalising is also used to condition steel for further heat treatment.

- **Quenching and tempering** usually consists of three successive operations:

  a) heating the steel above the critical temperature range and holding at that temperature to develop a uniform austenitic structure,
  b) hardening the steel by quenching it in oil, water, brine or caustic bath; and
  c) tempering the steel by reheating to a selected point below the critical range to obtain the desired combination of hardness and ductility.

The rapid cooling action during quenching prevents the austenite structure from developing normally into ferrite, cementite or pearlite. Instead, a new micro-constituent called martensite is formed. The long needle-like grains of martensite are the hardest and most brittle form of steel, with an extremely high tensile strength but practically no ductility.

By carefully selecting the temperature for reheating, the martensite is reformed into a finer, tougher form called "tempered martensite". This tempering action can produce any desired combination of hardness and ductility possible for that steel.

Annealing results in a low degree of hardness, tensile strength and toughness, but gives outstanding ductility. Normalising results in medium hardness, tensile strength and toughness, but also retains fairly good ductility. Quenching and tempering is used to give the greatest hardness and tensile strength.

7.2 Quality Control

There are five main areas of control in steel manufacture:

- process;
- chemical analysis;
- mechanical properties;
- metallographic; and
- inspection.

Process control mainly applies to the raw materials and practices used in the steelmaking and rolling processes.

Extensive preparation of raw materials is carried out to im~rove their physical and chemical composition and rninimise variations that can influence the final product. In general terms, blast furnace operators aim to produce iron of consistent characteristics. Steelmakers aim to produce one of hundreds of grades of steel. The differences between grades may be slight, but they are vital for the end-use of the metal. The refining of steel involves close control of physical size, chemical composition and quantity of the charged materials.

Regulation of steel temperatures at all production stages is vital, affecting the surface and internal quality of the product. Practices employed during the shaping and forming operations also have a direct effect on product quality. Rates of cooling and reheating the steel and the rate of rolling must be closely controlled to produce a high standard of surface and internal quality.

Chemical analysis control of iron and steel composition ensures that the customer receives material of the required specification.

Most analysis uses instrumentation, including computer controlled atomic emission spectrometers, x-ray fluroscence spectrometers, atomic absorption and ultra violet - visible spectrometers and gas chromatographs.

However, these instruments are supported with classical chemical techniques and skills.

Chemical analysis monitors products at all stages from the blast furnace to finishing mills. Developments in instruments and techniques have resulted in very significant reductions in the time between sampling and analysis printout. For example, atomic emission spectrometers are able to produce accurate results of 18 elements within 70 seconds of a sample being placed in the machine.

Mechanical properties control checks such factors as:

- yield strength,
- tensile strength,
- elongation,
- reduction of area,

- impact strength,
- compressive strength,
- hardness, and
- bending properties. .

The types of test used to evaluate these mechanical properties depend on the product's end use.

Tension tests provide a means of determining tensile strength, yield stress, per cent elongation, per cent reduction of area and ductility. A test specimen is gripped at each end and a steadily increasing load applied until the sample breaks. A typical structural steel would have a tensile strength of 400 to 500 megapascals.

Bend tests give an indication of the ductility of the steel by bending a steel sample around a mandrel of a specified diameter. The angle of bend is usually between 45 and 180 depending on the steel specification. The test piece is generally required to show no signs of cracking on the outside surface.

Impact tests are used to measure the toughness of steel under sudden loading or impact. For this purpose, a specially prepared 10mm square specimen, notched to concentrate the stresses at the base of the notch, is struck and broken by a single blow of a free swinging pendulum. The energy absorbed in breaking the specimen is measured to determine impact strength.

Hardness tests determine a steel's resistance to penetration, by measuring the degree of penetration of a steel ball or diamond indentor into the metal surface. A constant load connected by a system of levers, delivers a constant pressure to the indentor.

Hardness values are measured on standard scales such as Brinell, Rockwell or Vickers, depending on the equipment used. Steel for special applications may require creep, fatigue, hardenability, corrosion magnetic particle, x-ray and ultrasonic tests.

Special tests are used for particular steel products such as cupping tests for sheets, hydrostatic pressure tests for tubular products, and torsion tests for wire.

Metallographic control involves macro-examination (by naked eye or low magnification) and micro-examination (at high magnification).

Macro-examination of small specimens cut from the product reveals details of grain structure, heat treated condition or non-metallic inclusion (e.g., small particles or refractory materials absorbed from furnace or ladle linings).

Inspection or Quality Assurance ensures that the steel products shipped to the customer comply with dimensional requirements and are free from harmful surface defects. Operators at each mill have a wide range of facilities and instruments to check products for surface quality, shape, strength, straightness and dimensional accuracy. The basic object of all quality control procedure is to eliminate or reduce rejects at the earliest opportunity.

8 Glossary of steelmaking terms

Alloy steel	steel with one or more specific elements added to create special properties
Annealing	the controlled heating and cooling to soften steel
Bar	steel shapes up to 75mm in diameter produced in straight lengths, such as rounds, squares, hexagons, angles, channels, flats, T -bar or reinforcing bar
Basic Oxygen Steelmaking (BOS) Vessel	a furnace where blasts of oxygen are used to transform iron into steel
Battery	a series of 10-100 tall, gas-fired, air-tight brick ovens in which coal is baked to form coke
Billet	a 12 metre long semi-finished steel shape, produced from caster or rolled from a bloom
Bloom	a steel shape, the product of continuous casting, varying in dimension. Usually about 630mm by 400mm and 5-6m in length
Carbon steels	represent the major percentage of steel production. As well as carbon, these steels may contain up to 1.65% manganese, 0.60% silicon and 0.60% copper
Casting	the process of pouring molten metal into a mould, so that the cooled solid metal retains the shape of the mould
Charging	feeding the furnace with raw materials
Coke	the end product after coal has been baked in coke ovens for about 18 hours
Cold strip mill	hot rolled steel strips are cold rolled to produce cold rolled steel strips, O.03rnm-3.2mm in thickness
Continuous casting	continuous forming of semi- finished steel sections ego slabs, blooms, billet, direct from molten steel thus eliminating primary rolling operations
Continuous mill	mill with a number of stands of rolls arranged in tandem through which steel is rolled in one direction
Direct reduction	is a process which extracts iron from its ore without going through a molten stage. It produces solid iron which can be used as a scrap substitute
Drawing	pulling steel shapes through tapered dies to produce wire
Electric Arc Furnace (EAF)	a furnace that uses electric power to melt scrap steel to produce new steel
Fine ore	iron ore which ha~a very small particle size and tends to be powdery in nature
Fluxing material	materials used in a furnace to assist in the refinement process. They generally lower the melting point of impurities in the molten steel, and combine with the impurities to form 'slag'.
Galvanise	the coating of iron or steel with zinc to protect it from rust
Heat	one batch of steel from a steelmaking furnace
Hot Briquetted Iron (HBI)	a form of direct reduced iron, used mainly as feedstock in Electric Arc Furnace steel mills.
Hot metal	molten iron taken from the blast furnace for conversion to steel
Hot strip mill	a mill which rolls reheated slabs into strips, 1.2mrn-22mm in thickness
Ingot	an outdated method of shaping molten steel. Under this method solidified steel castings, ranging in size from a few tonnes up to about 30 tonnes, were made by teeming molten steel into a mould for forging or rolling into slabs, blooms or billets
Integrated steelworks	works including all major production stages from converting raw materials, such as coke and iron ore into iron and steel through to rolling mills
ladle	a 'bucket' lined with refractory bricks used to transport molten steel from process to process in a steel plant
Lump ore	a rich iron ore which, when crushed, has a size range between six and 35mm

Lance	a long metallic tube through which oxygen is blown into the 80S vessel under high pressure
Mini-mill	a small self-contained plant which melts scrap in an electric arc furnace, casts the molten steel, then reheats and rolls the steel into a variety of products
Open hearth furnace	steel refinement process largely superseded by Basic Oxygen Steelmaking
Pass	the opening between two grooved steel rolls which gives the shape to the steel being rolled
Pellets	fine particles of iron ore mixed with bonding clay and roasted into hard, round balls for use as a blast furnace feed. Production is usually located near ore source
Pickling	Use of hot acid solution to remove oxides, scale and dirt from steel to ensure good surface quality in cold rolling
Pig iron	blast furnace iron cast into small ingots or 'pigs' weighing 20-30kg
Plate	wide flat rolled steel product at least 3mm thick, hot rolled from the slab
Plate mill	slabs are hot rolled to produce plates of maximum size up to 20cm in thickness and up to 4.45mm in width
Plating and Coating	lines zinc, tin or special organic material is plated or coated on strips to produce corrosion resistant steel strips
Precipitators	equipment used to collect solid particles from a flow of gas or air
Primary mill	originally where steel ingots were rolled into semi-finished steel shapes ego slabs, blooms, billets, as a feed for product mills. Now used to describe any mill where steel is initially rolled
Product mill	mill which rolls semi-finished steel shapes into finished products to meet customer requirements, such as plates, bars, rods etc
PVC Steel	sheet steel coated with plastic used in white goods manufacture such as washing machines and refrigerators
Refractories	heat resistant materials used to line furnaces and ladles
Reheat furnace	gas-fired furnace used to heat steel shapes (billets, slabs etc) to the temperature required for rolling mill operations
Rods	round steel bars, ranging from 5.5mm to 18mm thick, produced in coils. Used as feed for wire mills
Rollforming	rolling coated steel into different profiles for roofing, fences, garage doors etc
Scarfing	use of oxygen flame jets to remove surface defects from semi-finished steel
Steel scrap	good quality steel such as the cropped ends of semi-finished steel products, steel that may have been damaged in production, and old steel goods such as car bodies, refrigerators etc
Section	hot rolled beam, channel, angle etc other than flat or strip steel
Semi-finished	products such as blooms, billets or slabs intended for further processing by rolling or forging
Sheets and strip	flat rolled steel product less than 3mm thick
Sinter	fine particles of iron ore, coke and limestone, roasted into lumps (agglomerated) for use as blast furnace feed. Production is usually at ironmaking plants.
Slabs	rectangular semi-finished steel shapes ranging up to about 250mrn x 2000mm
Slag	produced by the chemical combination of the flux and the impurities removed from the metal in ironmaking and steelmaking
Smelting	is a process used to separate iron from the impurities in iron ore
Stand	an arrangement of rolls through which steel is passed to alter its shape. A mill may consist of one or more stands
Strand	bar and rod mill term referring to the number of steel bars which can be rolled through a mill simultaneously, side by side (eg a 4 strand rod mill)
Strip	flat steel product of a hot or cold strip mill (hot rolled between 1.2rnm and 25mm thick, cold rolled between 0.1mm and 8mm thick)

Sub-lance	device for molten steel temperature measurement and sampling
Tapping	running off molten steel from a furnace or vessel
Teeming	the pouring of molten steel from a ladle into an ingot mould or the tundish of a casting machine
Terne steel	sheet steel coated in a lead/tin alloy coating
Tinplate	sheet steel coated with a thin layer of tin, used for food cans, paint tins etc
Tundish	vessel that feeds molten steel into the top of a continuous caster
Tuyeres	copper nozzles arranged in a ring around the base of a blast furnace, through which the air blast is injected
Vacuum de-gassing	process which removes impurities from steel by extracting unwanted gases
Wire	wire is made by drawing (pulling) the cold rod through a series of tapered dies (steel blocks with holes) of diminishing size. This causes the wire to become longer and thinner. The dies are made from extremely hard material to withstand the wear and pull of wire

Elements in the steelmaking process

Al	aluminium	Mn	manganese
Ar	argon	N	nitrogen
B	boron	Ni	nickel
C	carbon	P	phosphorus
Ca	calcium	Pb	Lead
Co	cobalt	S	sulphur
Cr	chromium	Si	silicon
Cu	copper	Sn	tin
Fe	iron	Ti	titanium
H	hydrogen	W	wolfram (tungsten)
Mo	molybdenum	Zn	zinc