Chapter 1

Production of Iron and Steel

1.1 Introduction

Since the beginning of civilization man has been continuously engaged in converting the natural resources into useful products. The entire discipline of engineering is mainly concerned with this. Often materials problem is really one of selecting the material that has the right combination of characteristics for a specific application. Therefore, the people who are involved in the decision making should have some knowledge of the available options.

Materials selection decisions may also be influenced by the ease with which metal alloys may be formed or manufactured into useful components. Alloy properties are altered by fabrication processes, and, in addition, further property alterations may be induced by the employment of appropriate heat treatments.

1.2 Extraction of ore

The first step in the production of a metal is to bring the ore to the surface. This is done by mining which is of two general types, *open pit mining and underground mining*. Open pit mining as the name suggests, is employed when the ore is at, or very close to, the surface, say, within 15meteres. In most cases the ore is covered with a layer of soil, called overburden. When the overburden is removed, the mining becomes a simple process of excavation or digging. When the ore is covered with water, the process is called *dredging*. The advantages of an open-pit mining are employment of large and varied types of machinery, lower mining cost, large-scale production and better and safer working conditions.

Most of the deposits are deep underground and have to be brought to the surface by underground mining. First ‘holes’ or shafts or tunnels are drilled to reach the ore. This limits the use of the machinery and involves the problems of risk to life, ventilation, drainage, etc. Underground mining is more expensive but widely adopted because most of the ores are found underground.

Since rich ores are few and many of them have already been worked for some time, it has become increasingly necessary to eliminate the *gangue* from the *values*. The process of physically separating the particles of the mineral from the gangue, giving concentrates or values, which contain most of the mineral, is known as *ore dressing.*

Ore dressing has two main advantages:

- Transport cost of the gangue is saved.
- It causes considerable saving in cost while extracting the metal in the furnace.

By using a concentrated ore the capacity of the furnace increases, heating cost becomes less because gangue has not be heated, and less flux needs to be used for the removal of the gangue.

In case the metallurgical works are situated near the mine, the ore dressing is done at the factory. If the mine is at a distance, the ore dressing plant is located at the mine and concentrate is transported to the main works for extraction of metal.

Ore dressing begins while mining the ore. The barren parts are not mined. Ore is obtained from the mine in pieces of different size and by hand picking, the rich portions is separated from clayey or sand portions. Hand picking is adopted where labor is cheap.

To facilitate concentration, it is necessary to reduce the size of the ore as mined. The final size depends upon the treatments that are to be given later. The primary crushers, like jaw crushers, and gyratory crushers, reduce the size to 5 cm to 20 cm.

The size is further reduced to 0.5 cm to 3 cm by crushing rolls and in hammer mills. In many cases further reduction in size is not necessary. If necessary, the ore is finely ground in grinding equipment such as a ball mill. The material is screened to remove the over size particles.

Further concentration is done on the basis of difference in the properties of values and gangue. The two commonly used concentration methods are:

- Gravity separation (Sink and float method)
- Magnetic separation

Ore dressing deals with the separation of impurities that are physically mixed with the mineral. In metal extraction the metal is liberated from chemical combination. The process of extracting metals from minerals can be considered as extractive metallurgy. Metallurgy is the science and technology of extracting metals from minerals. There are five important steps in extractive metallurgy to get the required purified metals.

- Mining (getting the ore out of the ground);
- Concentrating (preparing it for further treatment);
- Reduction (to obtain the free metal in the zero oxidation state);
- Refining (to obtain the pure metal); and
- Mixing with other metals (to form an alloy).

- Extractive metallurgy is classified under three broad divisions:
    - Pyro-metallurgy
    - Hydro-metallurgy
    - Electro-metallurgy

*In **Pyro-metallurgical*** operations the ore is heated by burning fuel to get the required temperatures to obtain concentrated mineral. The objective of drying is to remove absorbed water. If an ore is to be transported, drying reduces freight charges.

Calcination is heating of ore with high temperature to cause decomposition. Some of common examples are:

$$PbCO_3(s) \rightarrow PbO(s) + CO_2\ (g)$$

$$FeCO_3\text{-------}FeO + CO_2$$

$$2Al\ (OH)_3\text{----}\ Al_2O_3 + 3H_2O$$

Roasting is heating which causes chemical reactions between the ore and the furnace atmosphere, mostly oxidation reaction.

$$2ZnS(s) + 3O_2\ (g) \rightarrow 2ZnO(s) + 2SO_2\ (g)$$

$$4FeS_2 + 11O_2\ (g) \rightarrow 2Fe_2O_3(s) + 8SO_2\ (g)$$

- Smelting is a melting process that causes materials to separate into two or more layers.
- Slag consists mostly of molten silicates in addition to aluminates, phosphates, fluorides, and other inorganic materials.
- Refining is the process during which a crude, impure metal is converted into a pure metal.

Hydrometallurgy is the extraction of metals from ores using water. Leaching is the selective dissolution of the desired mineral. Typical leaching agents are dilute acids, bases, salts, and sometimes water. Gold can be extracted from low-grade ore by cyanidation.

Electro-Metallurgy: It is adapted to a lesser extent than pyro-metallurgy because of the high cost of electricity. The chief advantage of electro-metallurgical methods is that the purity of the metal produced is much higher than by other methods.

Different metals will found with varied quantities in the earths crust. Among the metals, iron comes next only to aluminium in abundance on the earth’s surface. The following three chemical properties of iron are the most significant ones for practical purposes:

- Iron oxidizes easily in moist air, thus it gets rusted (disadvantage)

- It can be reduced from its oxides at temperatures above 260^0c, thus it can easily and cheaply be extracted from its ores;
- It has a great affinity for carbon; this is responsible, directly as well as indirectly, for most of its engineering uses. Likewise *strength, magnetism and adaptability* are the three important physical properties of iron. It is adaptable in the sense that by proper manufacturing and treatment, involving addition of not more than 5% of foreign elements, it can be strong or very weak, very hard or very ductile or very brittle. Its *corrodibility, conductivity, coefficient of expansion, etc.*, can also be altered greatly. Added to all this is *its low cost*. Thus it is easy to realize why iron and steel play such an important role in the present civilization.

1.3 Manufacturing of Pig Iron

Pig iron is the metallic product obtained by the reduction of iron ore smelted in a blast furnace. Most of this material, while still in a molten state, is converted in to steel. The remainder is cast in to small shapes or pigs. A few decades back the molten metal was run into cavities in a sand floor and allowed to cool. The resulting shape looked like a pig, hence the name pig iron. The following are the important raw materials used in its manufacture.

1. **Iron Ore**: Iron ores are rocks and minerals from which metallic iron can be economically extracted. The ores are usually rich in iron oxides and vary in color from dark grey, bright yellow, deep purple, to rusty red. The iron itself is usually found in the form of magnetite (Fe_3O_4), hematite (Fe_2O_3), limonite ($Fe_2O_3.(OH)_2$) or siderite.

After mining to get the required concentration, iron ores crushed into fine particles, the impurities are removed by various means (such as magnetic separation) and it is formed into pellets (balls) using binders and water. This process is called pelletizing. Pelletizing turns very fine-grained iron ore into balls of a certain diameter, also known as pellets, which are suitable for blast furnace and direct reduction. Pellet plants can be located at mines, near harbors or be attached to steel mills. Equipped with advanced environmental technology, they are almost pollution-free, generating no solid or liquid residues.

Why pelletize? In the face of shrinking world reserves of high-grade ores, ores must now be concentrated before further processing. Pellets form one of the best options, thanks to their excellent physical and metallurgical properties. Moreover, due to their high strength and suitability for storage, pellets can be easily transported over long distances, with repeated transshipments if necessary.

Pellets' benefits:

- *Standardization* – uniform size range, generally within a range of 9–25 mm
- *Purity* – 63–68 % iron, mainly Fe_2O_3
- *Cost-effectiveness* – virtually no loss on ignition while a high and uniform porosity of 25–30 % allows fast reduction and high metallization rates
- *Strength* – high and uniform mechanical strength even under thermal stress in reducing atmospheres
- *Transportable* – low degradation under abrasive influences

Fig.1.1 Pellets

Typically, pellets are about 65% pure iron and 25mm in diameter. The concentrated iron ore is referred to as beneficiated. Some iron rich ores are used directly without palletizing.

- *Hematite* Fe_2O_3: This is the principal iron ore contains up to 70% of iron.
- *Magnetite* Fe_3O_4: It is not as easily reducible as hematite. Good deposits of magnetite.
- *Limonite* $2Fe_2O_3.3H_2O$: this seems to be the ore from which iron was made in ancient India. At present its deposits are not of commercial significance in India. Its important deposits occur on the German, French, Belgian border.
- *Siderite or Spathic Iron ore* $FeCO_3$:

Fig.1.2 Hematite: the main iron ore in Brazilian mines

Fig.1.3 The heap of iron ore pellets, this will be used in steel production

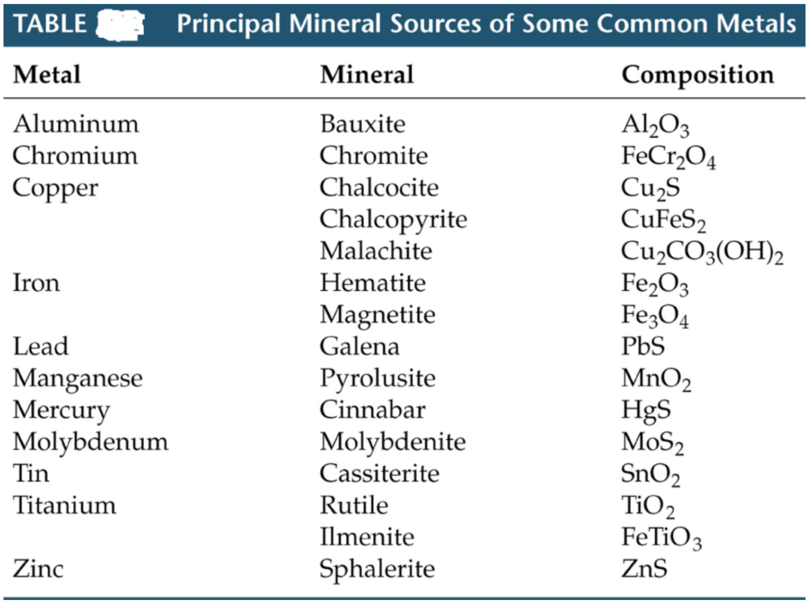


TABLE [redacted] Principal Mineral Sources of Some Common Metals

Metal	Mineral	Composition
Aluminum	Bauxite	Al_2O_3
Chromium	Chromite	$FeCr_2O_4$
Copper	Chalcocite	Cu_2S
	Chalcopyrite	$CuFeS_2$
	Malachite	$Cu_2CO_3(OH)_2$
Iron	Hematite	Fe_2O_3
	Magnetite	Fe_3O_4
Lead	Galena	PbS
Manganese	Pyrolusite	MnO_2
Mercury	Cinnabar	HgS
Molybdenum	Molybdenite	MoS_2
Tin	Cassiterite	SnO_2
Titanium	Rutile	TiO_2
	Ilmenite	$FeTiO_3$
Zinc	Sphalerite	ZnS

N.B *A metal from sulphide ore cannot be directly obtained by reduction smelting. The sulphide has to be first oxidized to oxide and then reduced.*

2. Fuel:

Charcoal had been used as fuel but coke is the most extensively used fuel. All integrated steel plants have their own coke oven plants. The fuel should have the following properties:

- *Strength*: It should be strong and have resistant to abrasion. The fuel is subject to rough handling and it should not disintegrate easily in to fine particles. Fine particles are undesirable because they prevent the free movement of gases, which are responsible for the main reactions, and they may be easily carried away along with the total charge.
- *Porosity*: The more porous the fuel is the more readily it comes in contact with the oxygen of the blast and thus supplies more heat per unit volume of the total charge.
- *Combustibility*: The fuel should be as combustible as possible, i.e., the rate of reaction with oxygen should be as high as possible. A more reactive fuel increases the intensity of combustion thereby increases the productivity of furnaces.
- *Purity*: The impurities present in the fuel can be transferred to the pig iron. Sulphur is a common impurity and is highly undesirable as most of it is taken up by pig iron. The ash content should also be low as it means not only waste of heat but also that additional flux is needed for its removal in the form of slag.

  Coke is *stronger, more porous and more combustible than coal*. Coke is there fore more suitable than coal in spite of the fact that coke contains a higher percentage of ash than the coal from which it is made. The most serious disadvantage of coal is its poor mechanical strength and sulphur content. Coal, if used, will be crushed to smaller pieces or under the weight of the charge in the blast furnace; thereby flow of gases will be obstructed.

  Coke is obtained from special grades of bituminous coal, which are heated in vertical coke ovens to temperatures of 1150^{o}c and cooled with water in quenching towers.

  Coke has several functions in steel making:

    - To generate high level of heat required for chemical reactions to take place in iron making.
    - To produces carbon monoxide (a reducing gas) which is then used to reduce iron oxide to iron.
    - The chemical by-products of coke are used in making plastics and chemical compounds.
    - Coke oven gases are used as fuel for plant operations, and power generation.

3. **Flux**: Iron ores mostly contain silica as the gangue. Some alumina also present in the ore and in the coke ash. If the amount of alumina present is small it may form aluminum

silicate. Limestone is commonly used as flux to remove the gangue materials in the form of slag. The slag is later used for making cement, fertilizers, glass, building materials, rock wool insulation and road ballast. Some times dolomite (CaMgCO3) is used as flux. It is more expensive than limestone, but the slag produced has lower melting point.

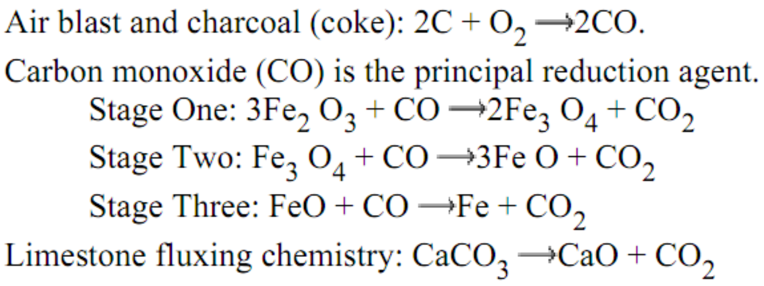
1.4 Iron Ore beneficiation

The basic ingredient for steel is one of several forms of naturally occurring oxides of iron. The pure metal unfortunately does not exist in nature. Hematite (Fe_3O_2) and magnetite (Fe_3O_4) are two principal iron ores.

The principles of extraction of iron from ore are simple. The reactions taking place in different parts of the furnace. The furnace is known as blast furnace. The raw materials which are solid are introduced from the top. These slowly move down wards and react with the upward moving hot gases, which are produced in the lower part of the blast furnace.

As the solid charge consisting of ore, coke and lime stone descends to two or three meters in the furnace, the moisture and combined water are removed. It meets upward moving gases consisting mainly of nitrogen, carbon monoxide and carbon dioxide. Step by step carbon monoxide reduces the heated Fe_2O_3 progressively to Fe_3O_4, FeO and Fe.

Chemical Reactions that will take place during ore beneficiation is shown as follows:



Air blast and charcoal (coke): $2C + O_2 \longrightarrow 2CO$.

Carbon monoxide (CO) is the principal reduction agent.

Stage One: $3Fe_2O_3 + CO \longrightarrow 2Fe_3O_4 + CO_2$

Stage Two: $Fe_3O_4 + CO \longrightarrow 3FeO + CO_2$

Stage Three: $FeO + CO \longrightarrow Fe + CO_2$

Limestone fluxing chemistry: $CaCO_3 \longrightarrow CaO + CO_2$

$$2CaO + SiO_2 \text{--------------} 2Ca.SiO_3 \text{ (slag)}$$

These reactions take place mostly at 200 to 800 degree Celsius and with in less than 10 m below the stock line. As CO_2 cannot exist in the presence of free carbon above 1000 degree Celsius it is not formed in the lower part of the furnace. Thus the reduction of iron ore takes place in the upper part of the furnace and CO is the main reducing agent. The spongy iron thus produced absorbs carbon and melts in the lower part of the furnace. The molten iron trickles down over the white hot coke and dissolves carbon until it is practically saturated.

Lime stone (CaCO3) decomposes to give calcium oxide which reacts with silica present in the gangue, and forms calcium silicate. Calcium silicate is in molten state at the temperature prevailing in the furnace. A material like this is known as slag. It also helps in the elimination of sulfur. Manganese oxide, phosphorus oxide and a part of silica are reduced in the lower part of the furnace and the elements are absorbed by the molten metal.

The general principle “all reduced elements join the metal and that oxidized go to or form slag” may help to remember the distribution of the materials between the molten iron and the slag. Iron, which is already practically saturated with carbon, dissolves silicon, manganese, sulfur and phosphorus. The slag contains CaO, SiO_2, Al_2O_3, MgO, CaS and some MnO. Composition of pig iron can be controlled to some extent by controlling the temperature. Pig iron produced in a furnace working at a high temperature contains less sulfur but more silicon and manganese.

Most of the coke burns in the bosh in the hot blast of air supplied through the tuyeres. As very hot coke burns in hot air the temperature attained is higher than calculated from the heat of reaction. Any moisture present in the air is reduced to H_2 and CO. The reaction being endothermic helps to prevent excessively high temperature in the bosh. The nitrogen of the air moving upwards helps to transfer heat to the stack portion of the furnace.

The molten metal accumulates at the bottom of the blast furnace, while the impurities float to the top of the metal. At intervals of four to five hours, the molten metal is tapped, into ladle cars. Each ladle car can hold as much as 160 tones of molten iron. The molten metal at this stage has a typical composition of 4% to 5% carbon, 1.5% silicon, 1% manganese, 0.04% sulphur, and 0.4% phosphorus, with rest being pure iron. The molten metal is referred to as pig iron.

1.5 Blast Furnace Plant

Blast furnace plant gives a diagram of a modern blast furnace showing the furnace dimensions and the chemical reactions. The blast furnace is a tall vertical furnace which is designed with great skill. Its dimensions and profile are designed so as to take care of the volumetric changes and to allow proper time for the chemical reactions to be completed and for the separation of the metal from the slag. The outer structure is made of steel plates lined with fireclay refractoriness. Refractoriness of different qualities is used in different parts. Carbon blocks are used for lining the hearth. High alumina fireclay bricks, carbon mass, diatomite bricks, etc. have been used in these furnaces for refractory linings.

The proportions of the raw materials charged (i.e., the charge) in the furnace depends up on the composition of the raw materials. For the Indian conditions it may be taken that for 1,000 tonnes of pig iron about 1,700 tonnes of ore, 1,000 tonnes of coke and 400 tonnes of limestone are needed. The charge is dropped through a double cup and cone arrangement, known as double bell charging system which prevents the escape of the blast furnace gas while introduce the charge.

The main body of the furnace is made of thick steel plates lined with fireclay refractory bricks. The temperature in the hearth may be 1800^0c, hence carbon blocks are used for lining the hearth. The refractory lining of the hearth and bosh are very thoroughly cooled by circulating water through pipes built in the lining.

Near the top of the furnace is an outlet for the gases. This gas contains about 25% CO, 5% H_2, 15% CO_2, and 55% N_2. A blast furnace producing 1000 tonnes of pig iron per day gives out about 4 million cubic meters of the gas which carries in suspension from 50 to 250 tonnes of dust. Heating value of this gas is about 40% of the heating value of the coke charged in the furnace.

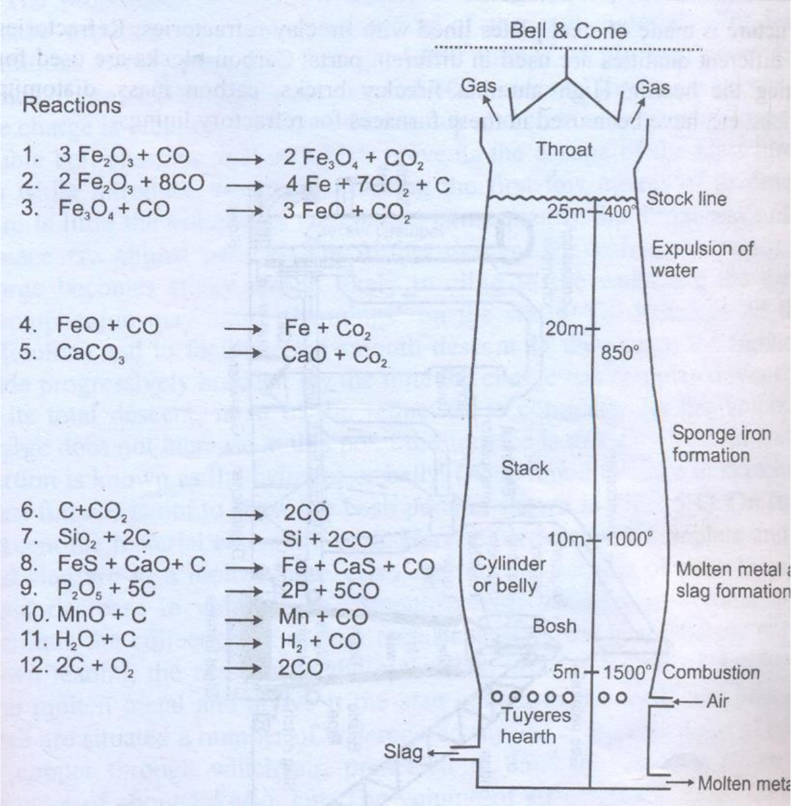


Fig.1.4 Diagram of a blast furnace showing the chemical reactions.

1.6 Steel making process

Steel by definition is an alloy of iron and carbon, but this statement must be qualified by placing limits on carbon content. When iron- carbon alloys have less than 0.005% carbon present at room temperature, they are considered to be pure iron. Pure iron is soft, ductile, and relatively, weak. It is not normally used as an engineering material because of its low strength, but it is used for special applications, such as magnetic devices and enameling steels (steels that are glass coated such as bath-tubs). From the commercial standpoint, steels have a low carbon limit of approximately 0.06% carbon. On the other end of the carbon content scale, iron-carbon alloys with more than approximately 2% by weight of carbon are considered to be cast irons. Above this carbon level, casting is about the only way that a useful shape can be made from alloy, because the high carbon makes the iron alloy too brittle for rolling, forming, shearing, or other fabrication techniques. Thus steels are alloys of iron and carbon with carbon limits between approximately 0.06% and 2.0%.

Typically the carbon content in pig iron may be 4% to 5%, which is too high to use as steel. In addition of to the high carbon content, the pig iron may contain high amounts of silicon, sulfur, phosphorus, and manganese, as well as physical inclusions of nonmetallic materials from the ore. All these substances would be detrimental to steel’s properties if allowed to remain at their uncontrolled high level. Thus to make steel from pig iron, a number of other impurities besides carbon must also be removed.

There are different processes that can be used to remove impurities from pig iron, but they all involve one basic process i.e oxidation.

In the blast furnace, carbon was used in the form of coke to remove oxygen through the mechanism of combination of the oxygen with C and CO. Now oxygen must be used to remove the carbon in the iron. In the molten state the carbon in solution in the iron readily combines with the oxygen that is introduced in the form of air or pure oxygen and forms CO once again. The oxygen, as well as additional fluxing ingredients, reduces the level of the other impurities in the pig iron.

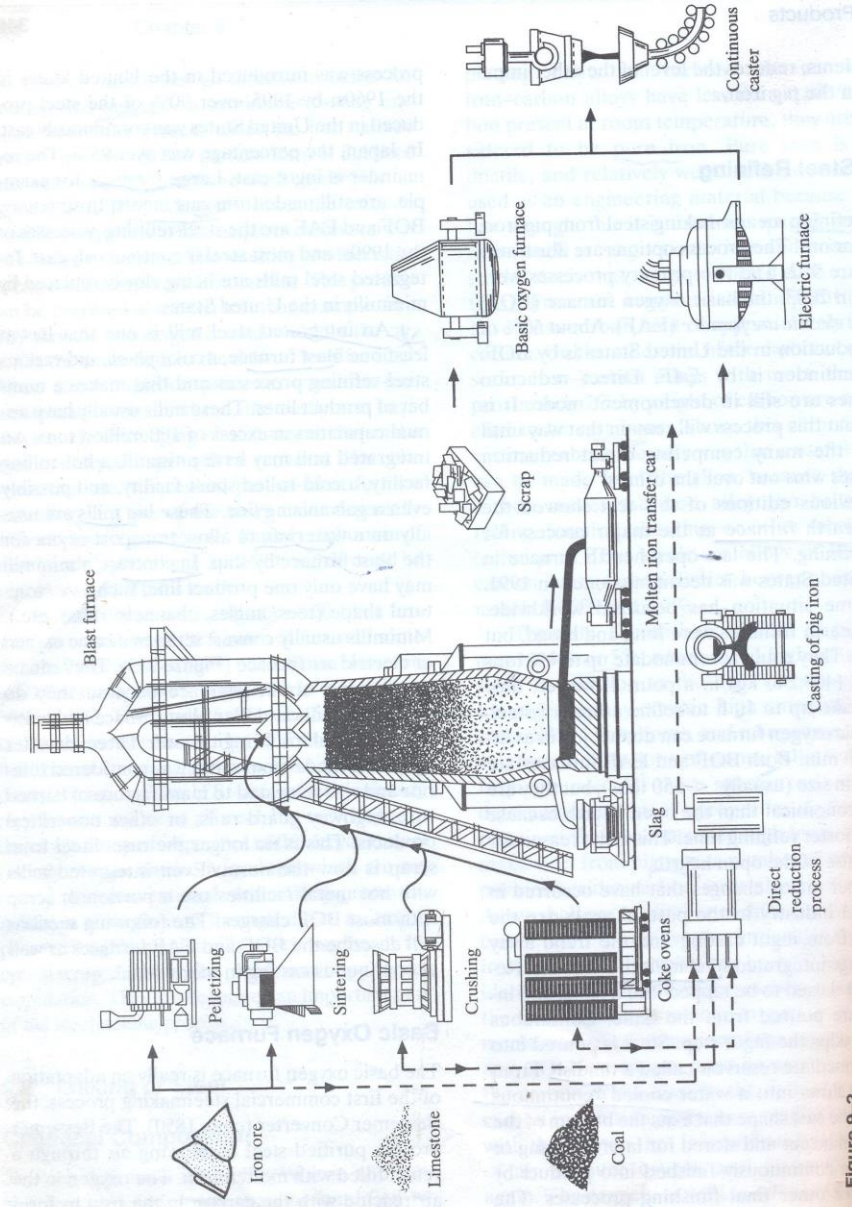


Fig.1.5 Steel making process

1.6.1 Steel Refining

Steel refining means making steel from pig iron, scrap, or ore. Now a days the two primary processes are the basic oxygen furnace and an electric arc furnace. About 60% of the production in the United States is by BOF; the remainder is by EAF. Direct reduction processes are still in development mode.

The other previously used process types are open hearth furnace and Bessemer converter. These two processes are out dated due to longer refining time than the above mentioned types.

The Bessemer process purified steel by blowing air through a vessel filled with molten iron. The oxygen in the air reacted with the carbon in the iron to form CO and CO_2, thus reducing the carbon in the iron from a few percent to a fraction of a percent, creating steel.

Open hearth furnaces were long and broad, but shallow. They could accommodate up to 450 tons of steel in a pour (at a time), however they would take up to 10h to refine it. The basic oxygen furnace can do that job in as little as 20 min.

Fig.1.6 Steel ingots

The major changes that have occurred in the steel industry in the past 25 years are the change from ingot casting and the trend away from large integrated steel mills to minimills. Refined steel used to be tapped into a ladle, and ingots were poured from the ladle. Continuous casting skips the ingot step. Steel poured into an intermediate reservoir called a tundish. From there it flows into a water cooled continuous mold, the cast shape that exists the bottom of the mold can be cut and stored for later finishing or it can be continuously finished into product by rolling or other final finishing processes.

An integrated steel mill is one that has at least one blast furnace, a coke plant, and various steel refining processes and that makes a number of product lines. These mills usually have annual capacities in excess of 100 million tons. An integrated mill may have a tin mill, a hot-rolling facility; a cold- rolled sheet facility, and possibly even a galvanizing line. These big mills are usually on a waterway to allow transport of ore for the blast furnace by ship. In contrast, aminimill may have only one product line, such as a structural shape (tees, angles, channels, rebar, etc.).

1.6.2 Basic oxygen Furnace

The basic oxygen furnace is just a refractory lined vessel that can tip to pour. It is charged with scrap, pig iron fluxing agents, and hot metal (molten pig iron) or combinations thereof. When the charge is melted, an oxygen lance is brought in or ported from the bottom to reduce the carbon, sulfur, and phosphorus. The argon and fluxes assist in the process. Alloy additions are often done in the ladle rather than in the BOF. The out put of the BOF is some times routed to secondary refining operations such as vacuum degassing to further reduce impurities or to modify the chemical composition.

1.6.3 Electric arc furnace

The source of heat in the electric arc furnace is an arc that is established between the melt and graphite electrodes. The furnace can be charged with scrap or solid pig iron. The arc melts the metal; refining is produced by an oxygen lance introduced into the melt and by the action of fluxing agents. In fact, electric arc furnaces were formerly used to produce alloy and specialty steels. The attractiveness of this process for alloy steel is based on the fact that it can be shut down between uses. It does not have to be kept hot to melt the charge.

***Secondary steel refining* process** will be applied for specialty steels such as high formability interstitial free sheet metal, heavy plates for pressure vessels, and steels for critical piping applications. It aims at altering chemical composition and reducing nonmetallic inclusions.

These inclusions are usually oxides, silicates, sulfides, or aluminas that form during conventional melting and refining. The inclusion rating of a piece of steel can be measured by sawing a thin slice from the end of a steel shape and etching it in an acid. A dirty steel will show pits when the inclusion are etched away by the acid.

Vacuum degassing is used to remove dissolved gases from steels by streaming the molten metal from the top vessel to the lower vessel in an evacuated vessel. It reduces carbon and oxides.

Ladle stirring is accomplished by bubbling argon from a lance through the melt or from a port in the bottom of the ladle. Argon and agitation promote sulfur removal and deoxidation.

Special refining process

Alloy steels, stainless steels, bearing steels, tool steels, and other noncommodity steels are frequently subjected to special refining processes that are intended to modify chemical composition and/or to remove impurities. Vacuum arc melting, vacuum induction melting, electro beam refining and electroslag refining are the various methods used for special refining process.

Pouring of Ingots

After a heat of steel is refined, it is poured into a continuous or strand casting machine or the heat is poured into ingot molds. Less than 10% of the steel goes to ingot, most is continuous cast

Pouring technique can affect chemical homogeneity and shrinkage voids in the steel. The metallurgical terms for these factors are segregation and pipe.

Segregation means the variation in chemical composition. It occurs on a microscopic scale in the dendrites that start solidification, and it occurs on a macroscopic scale in cast shape. One cause for segregation is that the first material to solidify is purer than the last.

Pipe is a cavity in the top of an ingot that is formed by volumetric shrinkage of the metal as it transforms from the liquid to the solid state. Both of these ingot defects can find their way into finished product if they are not properly dealt with at the mill.

Continuous casting

Steel is refined in the basic oxygen or electric arc furnace, and it is poured into a ladle. The ladle is transported to the caster facility, and it is poured into the caster tundish. The steel flow into the caster is controlled with valves so that the tundish in turn feeds the caster. The caster mold determines the semifinished shape that the caster produces.

The caster mold is water cooled, and the molten steel stays in the mold long enough to form a solid skin. The skin on the strand becomes like a continuously moving ingot mold. The center of the strand is molten for some distance after the strand exits the mold. The strand may require many rollers or a few rollers for support depending on the shape of the strand.

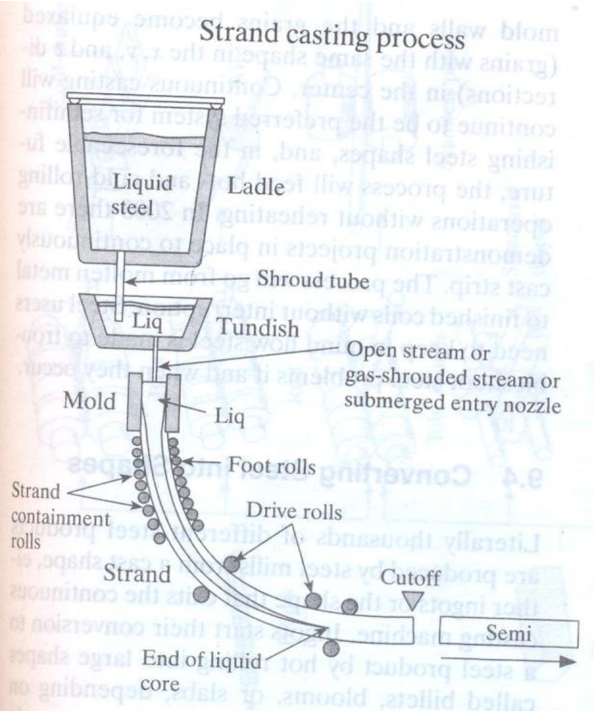


Fig.1.7 Strand (continuous) casting process

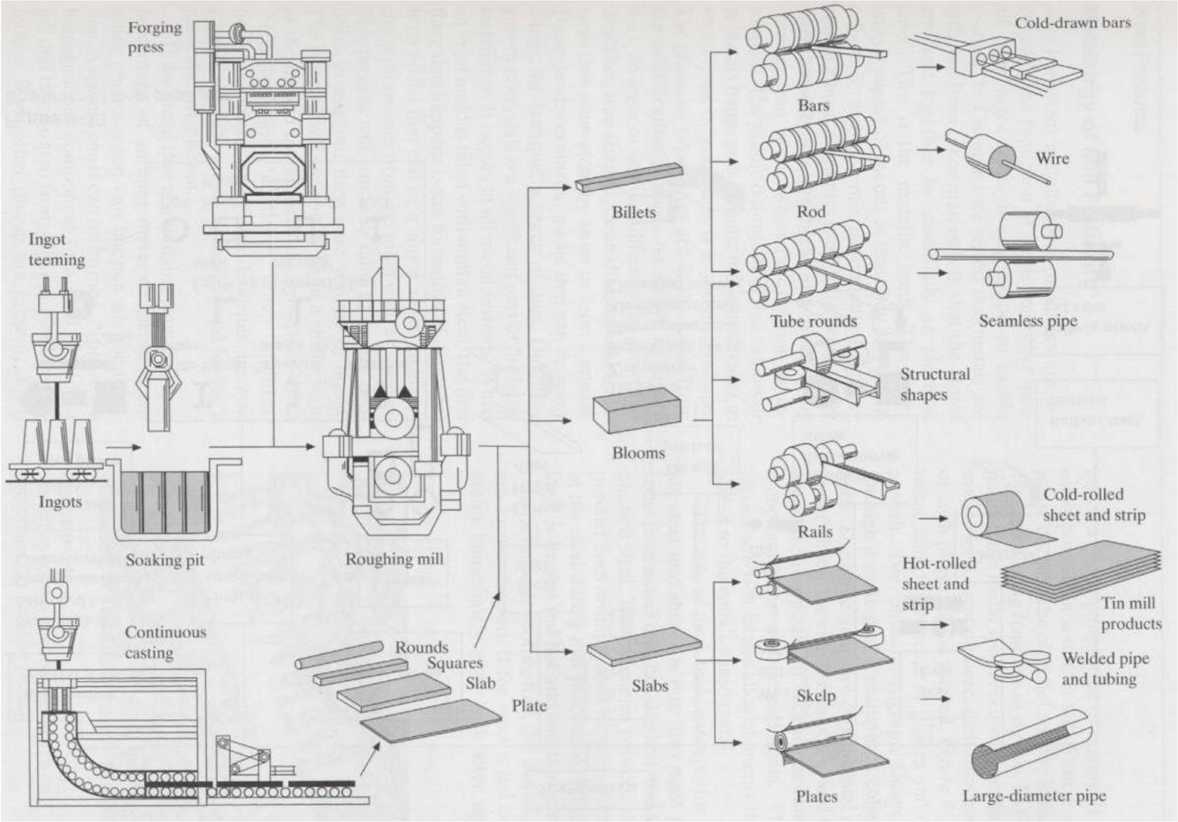


Fig.1.8 processing of refined steel into useful products

Literally thousands of different steel products are produced by steel mills from a cast shape, either ingots or the shape that exits the continuous casting machine. Ingots start their conversion to a steel product by hot rolling into large shapes called billets, blooms, or slabs, depending on their general shape.

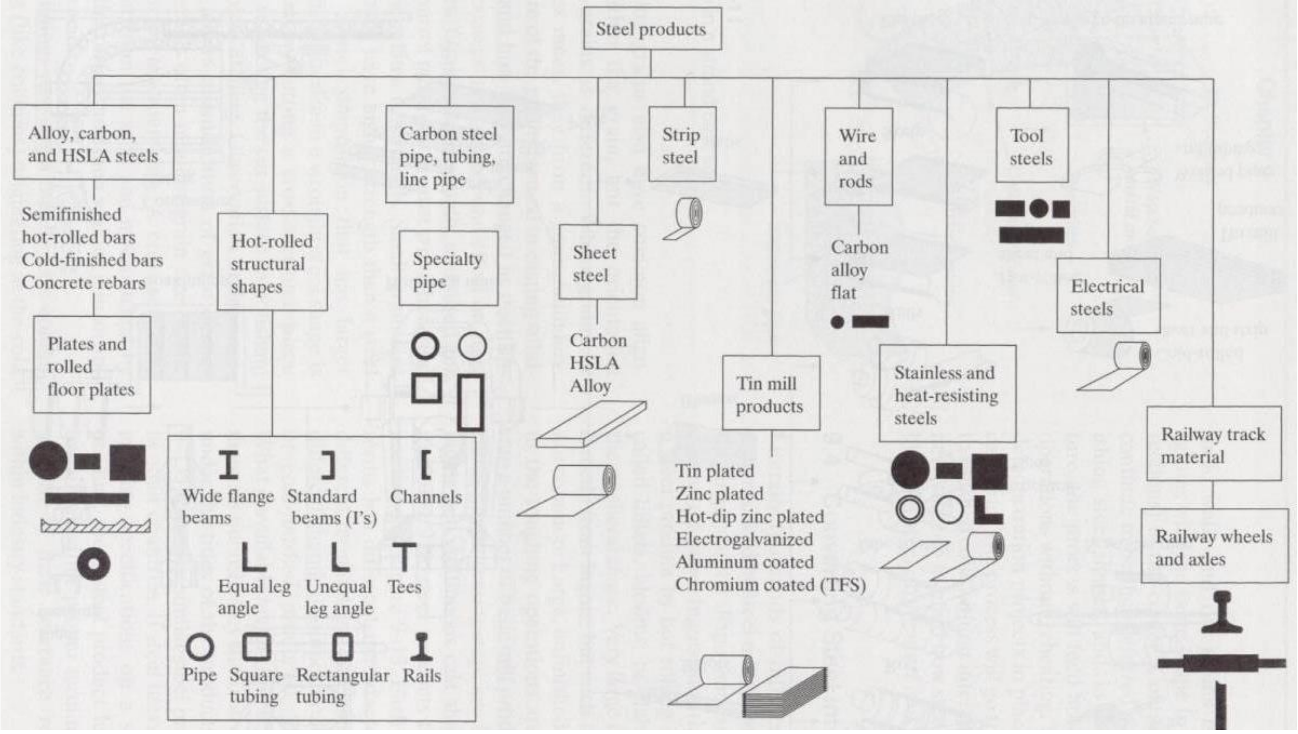


Fig.1.9 Spectrum of steel products

Effect of elements on the properties of steel

In plain carbon steels the effect of carbon on the properties may be considered apart from the effect of other elements, as carbon is not to be regarded as an impurity. The mechanical properties of carbon steels are mainly controlled by varying the proportion of carbon. Other elements are regarded as impurities.

1. ***Effect of carbon***. Carbon is the principal hardening and strengthening element in plain carbon steels. Up to 0.8% carbon the tensile strength goes on increasing with the increase in carbon content. Up to this limit the addition of every 0.01% carbon, the strength increases by almost 70 kg/cm^2. Ductility and malleability decrease with increase in carbon content. Carbon makes iron less permeable to magnetic forces.

2. ***Effect of impurities***

a) *Silicon*: A small amount of silicon increase strength without decreasing ductility. In high carbon steels it promotes decomposition of cementite to graphite, thus reducing hardness and brittleness.

b) *Sulphur*: Sulphur may be present as FeS or MnS. Presence of FeS is undesirable as it surrounds the metallic grains and melts during hot working of steel. This makes steel red short or brittle at red heat. MnS forms small globules and is less harmful. The presence of sulphides is desirable for machining operations as these break the continuity of the alloy. Up to0.3% of sulphur is helpful in cutting thread on screws.

c) *Manganese*: It improves the properties by removing sulphur. In smaller amounts, in a free state it increases strength but when it is more than 1% it increases hardness and brittleness; therefore, it is undesirable in high carbon steels.

d) *Phosphorus*: Its presence has been regarded as very undesirable because it makes steel cold short, i.e., brittle at room temperature and shock resistance becomes poor. One of the reasons for the bad effects of phosphorus is its tendency to segregate instead of being uniformly distributed throughout the mass. Up to 0.1% it adds to the strength and hardness of steel. It also increases corrosion resistance.

e) *Other elements*. Oxygen is present as FeO which remains as an inclusion and may cause fracture under load. Only traces of hydrogen are present in steel. It causes brittleness. Nitrogen is present as nitride which is very hard and is undesirable for working operations.