

CHAPTER ONE

1. INTRODUCTION

Since industrial revolution was the major corner stone in human history in that it set in motion the battle for abundance. The world today totally is dependent on the science and technology and nations are classified now according to the degree of industrialization. As a result material engineering plays a key role in extracting wealth from the earth. This can be achieved by two sub disciplines of engineering.

- ✓ **Mining**:- is the extraction of minerals from the earth like petroleum.
- ✓ **Metallurgy**:- is the study of metals by optical & electron microscopes.

1.1 PRODUCTION OF STEEL

Steel refers to any iron-carbon alloy, although steels usually contain other elements as well. It is one of the most important and widely used products in the world. Currently, the steel industry is undergoing a process of change. As a result of ongoing technical and economic developments, the production and use of electric arc furnace steel is, beneath the steel production in a blast furnace, becoming increasingly important, continuously gaining share of world-wide steel production over the past 30 years.

Steel is indispensable to our modern way of life and critical to economic growth. The intrinsic benefits of steel make it a sustainable choice in a growing number of applications.

Almost everything that we use is either made from, or manufactured with, steel. It is a uniquely versatile material and is widely regarded as a high performance, contemporary engineering material continuously being improved to meet new market demands.

In 2010, world crude steel production was 1,414 million metric tons (mmt). This was an increase of 15% compared to 2009, a new record for global crude steel production.

Steel is manufactured by the chemical reduction of iron ore, using an integrated steel manufacturing process or a direct reduction process.

1.2 RAW MATERIALS

Key raw materials needed in steelmaking include iron ore, coal /coke, lime stone and recycled steel. The two main steel production routes the integrated steelmaking route blast furnace (BF)

and basic oxygen furnace (BOF) uses raw materials including iron ore, coal, and limestone and recycled steel. On average, this route uses 1,400 kg of iron ore, 770 kg of coal, 150 kg of limestone, and 120 kg of recycled steel to produce a tonne of crude steel.

The electric arc furnace (EAF) route uses primarily recycled steels and/or direct reduced iron (DRI) and electricity. On average, the recycled steel-EAF route uses 880 kg of recycled steel, 150 kg of coal and 43 kg of limestone to produce a ton of crude steel.

1. IRON ORE

Steel is an alloy consisting mostly of iron and less than 2% carbon. Iron ore is, therefore, essential for the production of steel, which in turn is essential in maintaining a strong industrial base. Average iron content for ores is 60% to 65%, after taking into account other naturally-occurring impurities.

Iron ore is mined in about 50 countries. The majority of iron ore is mined in Brazil, Australia, China, India, the US and Russia. Australia and Brazil together dominate the world's iron ore exports, each having about one-third of total exports.

Worldwide iron ore resources are estimated to exceed 800 billion tonnes of crude ore, containing more than 230 billion tonnes of iron.

The important ore of iron used to produce steel is haematite (Fe_2O_3), magnetite (Fe_3O_4) and titanomagnetite (Fe_2TiO_4).

2. COAL AND COKE

Coke is made by baking a blend of selected bituminous coals (called metallurgical coal or coking coal) in special high temperature ovens without contact with air until almost all of the volatile matter is driven off. The resulting product, coke, consists principally of **carbon**.

Coke is used chiefly to smelt iron ore and other iron bearing materials in blast furnaces, acting both as a source of heat and as a chemical reducing agent, to produce pig iron, or hot metal.

Hot air blown into the furnace burns the coke, which serves as a source of heat and as an oxygen reducing agent to produce metallic iron.

3. LIMESTONE

Limestone which is a sedimentary rock, also called calcite, calcium carbonate, CaCO_3 , is a very commonly mined or quarried by blasting. Steel production requires vast quantities of lime to

form slag in order to prevent the steel from being oxidized. The melted slag also removes the impurities from the steel that are harmful to the process and products.

The limestone is mixed with iron ore and coke, a form of coal, and all are melted in blast furnace is converted to lime, CaO, combines with the impurities, mostly silicon dioxide, in the iron ore or hot molten metal to form a material called slag which has a general formula of calcium silicate, CaSiO₃. The slag which now is in the form of a calcium silicate floats on top of the molten metal because it is lighter. Then the molten iron which sinks to the bottom of the furnace.

4. RECYCLED STEEL

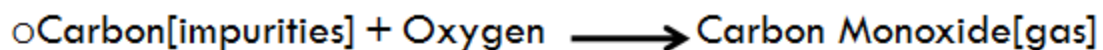
Recycled steel (scrap) can be collected from excess material in steel facilities and foundries (home scrap) or downstream production processes (industrial scrap) and from discarded products (obsolete scrap).

The availability of home and industrial scrap is closely related to current domestic steel production levels while the availability of obsolete scrap is closely related to levels of past steel production, average product lives and efficient recycling programmes.

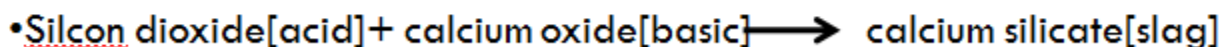
5. OXYGEN

It oxidizes Carbon to form Carbon monoxide; CO intern will be re used as a fuel gas

It reacts with other impurities to form their corresponding oxides.



•The oxides intern react with other fluxes to form slag



The oxides are reduced with carbon from coal, through the intermediate production of carbon monoxide.

The carbon initially burns in air to give carbon dioxide and the heat, which is necessary for the process. The carbon dioxide then undergoes an endothermic reaction with more carbon to yield carbon monoxide:



The oxide ores are then principally reduced by the carbon monoxide produced in this reaction, the reactions involving very small enthalpy changes:

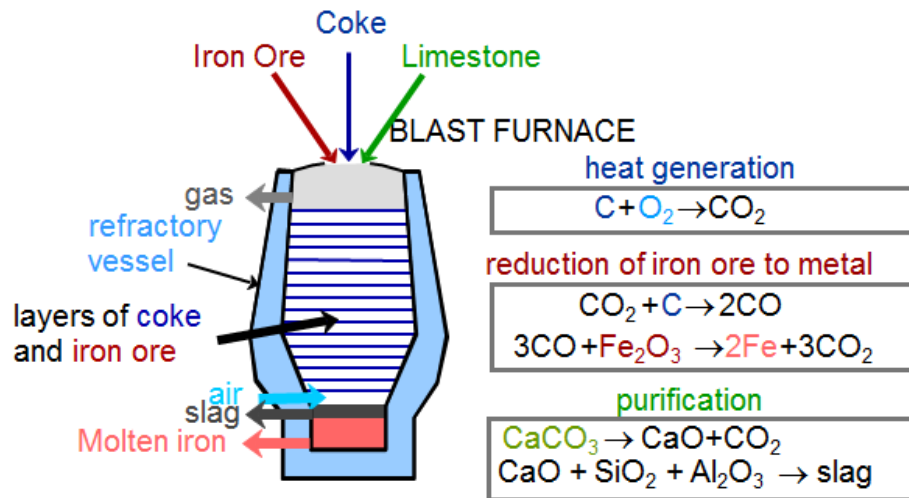
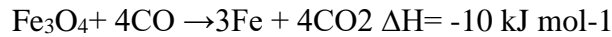


Figure 1.1: Refinement of Steel from Ore

In conventional iron making this reduction occurs in a blast furnace. The iron produced in this way always contains high levels of impurities making it very brittle.

Steel making is mainly concerned with the removal of these impurities. This is done by oxidizing the elements concerned by blowing pure oxygen through a lance inserted into the molten alloy. The oxides produced are either evolved as gases, or combine with limestone to form an immiscible slag which floats on the surface of the liquid metal and so is easily separated.

1.3 METHODS OF STEEL PRODUCTION

Steel can be produced using one of the following methods:

1. Open hearth furnace
2. Basic oxygen steelmaking
3. Electric-Furnace Steel

A. OPEN- HEARTH FURNACE

In 1865, the French engineer Pierre-Émile Martin took out a license from Siemens and first applied his regenerative furnace for making steel. Their process was known as the Siemens-Martin process, and the furnace as an "open-hearth" furnace.

Open hearth furnaces are one of a number of kinds of furnace where excess carbon and other impurities are burnt out of pig iron to produce steel. Since steel is difficult to manufacture due its high melting point, about 1370° C (about 2500° F), normal fuels and furnaces were insufficient and the open hearth furnace was developed to overcome this difficulty. This furnace can be operated at a high temperature by regenerative preheating of the fuel gas and air used for combustion in the furnace. In regenerative preheating, the exhaust gases from the furnace are drawn through one of a series of chambers containing a mass of brickwork and give up most of their heat to the bricks. Then the flow through the furnace is reversed and the fuel and air pass through the heated chambers and are warmed by the bricks. Through this method open-hearth furnaces can reach temperatures as high as 1650° C.

The furnace is charged with a mixture of pig iron (either molten or cold), scrap steel, and iron ore that provides additional oxygen. Limestone is added for flux and fluorspar to make the slag more fluid. After the furnace has been charged, the furnace is lighted and the flames play back and forth over the hearth as their direction is reversed by the operator to provide heat regeneration.

Chemically the action of the open-hearth furnace consists of lowering the carbon content of the charge by oxidization and of removing such impurities as silicon, phosphorus, manganese, and sulphur, which combine with the limestone to form slag. These reactions take place while the metal in the furnace is at melting heat, and the furnace is held between 1540° and 1650° C (2800° and 3000° F) for many hours until the molten metal has the desired carbon content. Experienced open-hearth operators can often judge the carbon content of the metal by its appearance, but the melt is usually tested by withdrawing a small amount of metal from the furnace, cooling it, and subjecting it to physical examination or chemical analysis. When the carbon content of the melt reaches the desired level, the furnace is tapped through a hole at the rear. The molten steel then flows through a short trough to a large ladle set below the furnace at ground level. From the ladle the steel is poured into cast-iron molds.

The process is far slower than that of Bessemer converter and thus easier to control and take samples for quality control. Preparing a heat usually takes 8 h to 8 h 30 min to complete into steel. As the process is slow, it is not necessary to burn all the carbon away as in Bessemer process, but the process can be terminated at given point when desired carbon contents has been achieved.

Compared to Bessemer steel, which it displaced, its main advantages were that it didn't expose the steel to excessive nitrogen (which would cause the steel to become brittle), was easier to control, and it permitted the smelting and refining of large amounts of scrap iron and steel.

Most open hearth furnaces were closed by the early 1990s, not least because of their slow operation, being replaced by the basic oxygen furnace or electric arc furnace.

B. BASIC OXYGEN STEEL MAKING

The oldest process for making steel in large quantities, the Bessemer process (also known as basic), made use of a tall, pear-shaped furnace, called a Bessemer converter that could be tilted sideways for charging and pouring.

Accounting for 60% of the world's total output of crude steel, the Basic Oxygen Steelmaking (BOS) process is the dominant steelmaking technology.

Great quantities of air were blown through the molten metal; its oxygen united chemically with the impurities and carried them off.



Figure1.1: Basic oxygen steel making plant

In the basic oxygen process, steel is also refined in a pear-shaped furnace that tilts sideways for charging and pouring. Air, however, has been replaced by a high-pressure stream of nearly pure

oxygen. After the furnace has been charged and turned upright, an oxygen lance is lowered into it. The water-cooled tip of the lance is usually about 2 m (about 6 ft) above the charge although this distance can be varied according to requirements. Thousands of cubic meters of oxygen are blown into the furnace at supersonic speed. The oxygen combines with carbon and other unwanted elements and starts a high-temperature churning reaction that rapidly burns out impurities from the pig iron and converts it into steel.

Very high temperature (**1600°C**) is required in this process, so the ingoing gas and air need to be preheated. This is achieved by using two set of pre heaters (regenerators). One set is being used to preheat the incoming gases. The other is being heated by the exhaust gases. The flow will be reversed periodically so that the incoming gas is effectively preheated.

In the BOF process, coke making and iron making precede steel making; these steps are **not necessary with an EAF**. Pig iron is manufactured from sintered, pelletized, or lump iron ores using coke and limestone in a blast furnace. It is then fed to a BOF in molten form along with scrap metal, fluxes, alloys, and high-purity oxygen to manufacture steel. In some integrated steel mills, sintering (heating without melting) is used to agglomerate fines and so recycle iron-rich material such as mill scale.

BOF is typically used for high-tonnage production of carbon steels, while the EAF is used to produce carbon steels and low tonnage specialty steels.

Basic oxygen steelmaking is a primary steelmaking process for converting the molten pig iron into steel by blowing oxygen through a lance over the molten pig iron inside the converter. The converter used for steel making is called as **Basic Oxygen Furnace** because of the exothermic heat generated by the oxidation reactions during blowing.

The basic oxygen steel-making process is as follows:

1. Molten pig iron (sometimes referred to as "hot metal") from a **blast furnace** is poured into a large refractory-lined container called a **ladle**;
2. The metal in the ladle is sent directly for basic oxygen steelmaking or to a pretreatment stage. High purity oxygen at a pressure of 100-150 psi(pounds per inch square)is introduced at supersonic speed on to the surface of the iron bath through water cooled lance, which is suspended in the vessel and kept at few feet above the bath. Pretreatment of the blast furnace hot metal is done externally to reduce **Sulphur**, **silicon**, and **phosphorus** before charging the hot metal into the converter.

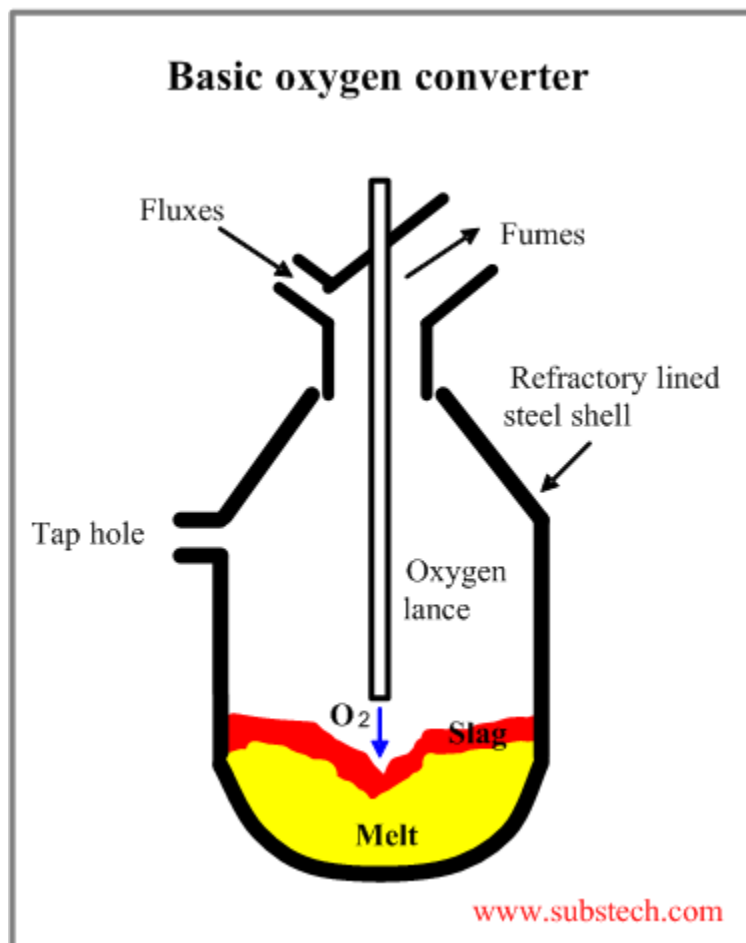
3. Filling the **furnace** with the ingredients is called *charging*. The BOS process is autogenous, i.e. the required thermal energy is produced during the oxidation process. Maintaining the proper *charge balance*, the ratio of hot metal, from melt, to cold scrap, is therefore very important. BOS vessel can be tilted up to 360° and is tilted towards the deslagging side for charging scrap and hot metal. The BOS vessel is charged with steel or iron scrap (25%-30%) if required. Molten iron from the ladle is added as required for the charge balance. A typical chemistry of hot metal charged into the BOS vessel is: 4% C, 0.2–0.8% Si, 0.08%–0.18% P, and 0.01–0.04% S all of which can be oxidized by the supplied oxygen except sulphur (requires reducing condition).
4. The vessel is then set upright and a water-cooled, copper tipped lance with 3-7 nozzles is lowered down into it and high purity oxygen is delivered at supersonic speeds. The lance "blows" 99% pure oxygen over the hot metal, igniting the carbon dissolved in the steel, to form **carbon monoxide** and **carbon dioxide**, and causing the temperature to rise to about 1700°C. This melts the scrap, lowers the **carbon** content of the molten iron and helps remove unwanted **chemical elements**. It is this use of pure oxygen instead of air that improves upon the **Bessemer process**, as the nitrogen (a particularly undesirable element) and other gases in air do not react with the charge.
5. **A Fluxes** (burnt **lime** or **dolomite**) are fed into the vessel to form **slag**, to maintain basicity more than 3 and absorbs impurities during the steelmaking process. During "blowing," churning of metal and fluxes in the vessel forms an **emulsion**, that facilitates the refining process. Near the end of the blowing cycle, which takes about 20 minutes, the temperature is measured and samples are taken. A typical chemistry of the blown metal is 0.3–0.9% C, 0.05–0.1% Mn, 0.001–0.003% Si, 0.01–0.03% S and 0.005–0.03% P.

The majority of global steel production - about 66% - is now produced in basic oxygen facilities. The development of a method to separate oxygen from nitrogen on an industrial scale in the 1960s allowed for major advances in the development of basic oxygen furnaces.

Basic oxygen furnaces blow oxygen into large quantities of molten iron and scrap steel and can complete a charge much more quickly than open hearth methods. Large vessels holding up to 350 metric tons of iron can complete conversion to steel in less than one hour.

The cost efficiencies of oxygen steelmaking made open hearth factories uncompetitive and, following the advent of oxygen steelmaking in the 1960s, open-hearth operations began closing. The last open-hearth facility in the US closed in 1992 and in China in 2001.

Structure of a Basic Oxygen Furnace



The scheme of a Basic Oxygen Furnace (BOF) is presented in the picture. Typical basic oxygen furnace has a vertical vessel lined with refractory lining. Only 8-12% of the furnace volume is filled with the treated molten metal. The bath depth is about 4-6.5 ft (1.2-1.9 m). The ratio between the height and diameter of the furnace is 1.2-1.5. The typical capacity of the Basic Oxygen Furnace is 250-400 t. The vessel consists of three parts: spherical bottom, cylindrical

shell and upper cone. The vessel is attached to a supporting ring equipped with trunnions.

The supporting ring provides stable position of the vessel during oxygen blowing.

The converter is capable to rotate about its horizontal axis on trunnions driven by electric motors.

This rotation (tilting) is necessary for charging raw materials, sampling the melt and pouring the steel out of the converter.

The top blown basic oxygen furnace is equipped with the water cooled oxygen for blowing oxygen into the melt through 4-6 nozzles. Oxygen flow commonly reaches 200-280 ft³/(min*t) (6-8 m³/(min*t)). The oxygen pressure is 150-220 psi (1-1.5 MPa). Service life of oxygen lance is about 400 heats.

The bottom blown basic oxygen furnace is equipped with 15-20 tuyeres for injection of oxygen (or oxygen with lime powder). The tuyeres are cooled by either hydrocarbon gas (propane, methane) or oil supplied to the outer jacket of the tube.

Refractory lining of a Basic Oxygen Furnace

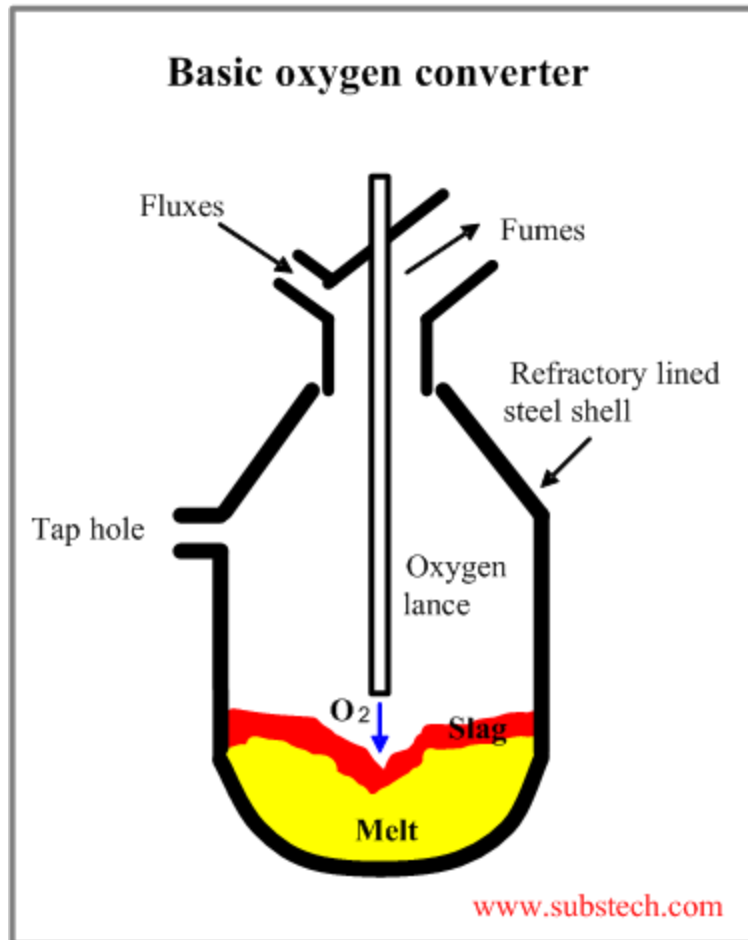
The refractory lining of basic oxygen furnaces work in severe conditions of high temperature and oxidizing atmosphere. The lining wear is fastest in the zone of contact with the oxidizing slag (slag line).

Refractory bricks for lining basic oxygen furnaces are made of either resin bonded magnesite or tar bonded mixtures of magnesite (MgO) and burnt lime (CaO). The bonding material (resin, tar) is cooked and turns into a carbon network binding the refractory grains, preventing wetting by the slag and protecting the lining the from chemical attack of the molten metal.

The following measures allow prolonging the service life of the lining:

- Control of the content of aggressive oxidizing oxide FeO in the slags at low level.
- Addition of MgO to the slags.
- Performing “slag splashes” - projecting residual magnesia saturated slag to the lining walls by Nitrogen blown through the lance.
- Repair the damaged zones of the lining by gunning refractory materials.

Properly maintained lining may serve 20000 heats.

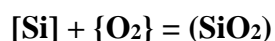
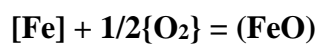


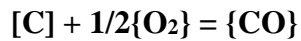
Chemical and physical processes in a Basic Oxygen Furnace

The basic oxygen furnace uses no additional fuel. The pig iron impurities (carbon, silicon, manganese and phosphorous) serve as fuel. Iron and its impurities oxidize evolving heat necessary for the process.

Oxidation of the molten metal and the slag is a complicated process proceeding in several stages and occurring simultaneously on the boundaries between different phases (gas-metal, gas-slag, slag-metal). Finally the reactions may be presented as follows:

(square brackets [] - signify solution in steel, round brackets () - in slag, curly brackets { } - in gas) $\frac{1}{2}\{O_2\} = [O]$





Most oxides are absorbed by the slag.

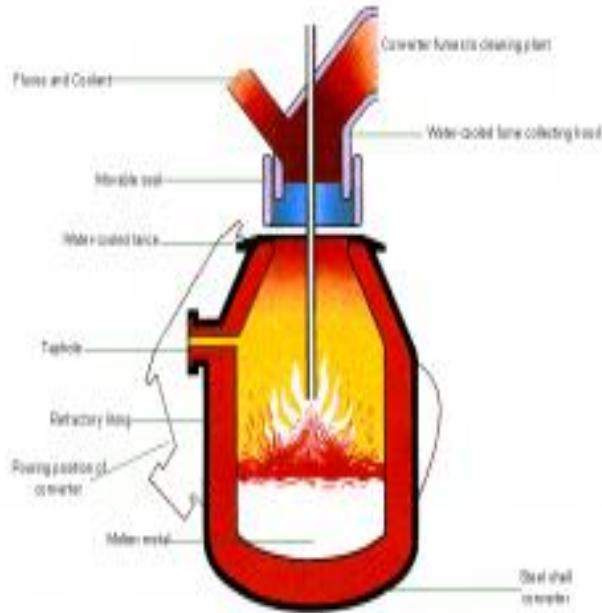
Gaseous products CO and CO₂ are transferred to the atmosphere and removed by the exhausting system. Oxidizing potential of the atmosphere is characterized by the **post-combustion ratio**: $\{\text{CO}_2\}/(\{\text{CO}_2\}+\{\text{CO}\})$.

Basic Oxygen Process has limiting ability for desulfurization. The most popular method of desulfurization is removal of sulfur from molten steel to the basic reducing slag.

However the slag formed in the Basic Oxygen Furnace is oxidizing (not reducing) therefore maximum value of distribution coefficient of sulfur in the process is about 10, which may be achieved in the slags containing high concentrations of CaO to top

Operation of a Basic Oxygen Furnace

- Charging steel scrap (25-30% of the total charge weight).
- Pouring molten pig iron from blast furnace.
- Charging fluxes.
- Starting oxygen blowing. Duration of the blowing is about 20 min.
- Sampling. Temperature measurements (by disposable thermocouple) and taking samples for chemical analysis are made through the upper cone in tilted position of the furnace.
- Tapping - pouring the steel to a ladle. Special devices (plugs, slag detectors) prevent penetration (carry-over) of the slag into the ladle.
- De-slagging - pouring the residual slag into the slag pot. The furnace is turned upside down in the direction opposite to the tapping hole. The Basic Oxygen Furnace has a capacity up to 400 t and production cycle (tap-to-tap) of about 40 min.



1) BOS furnace or converter 2) Scrap being loaded into the BOS furnace



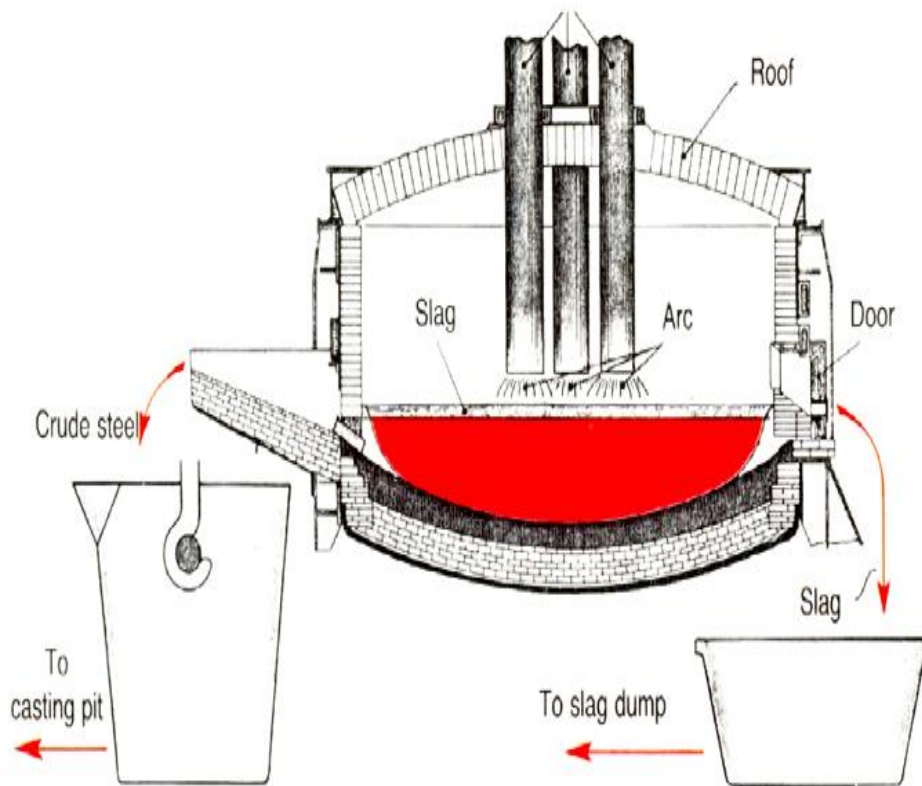
3) Charging hot metal to the BOS furnace

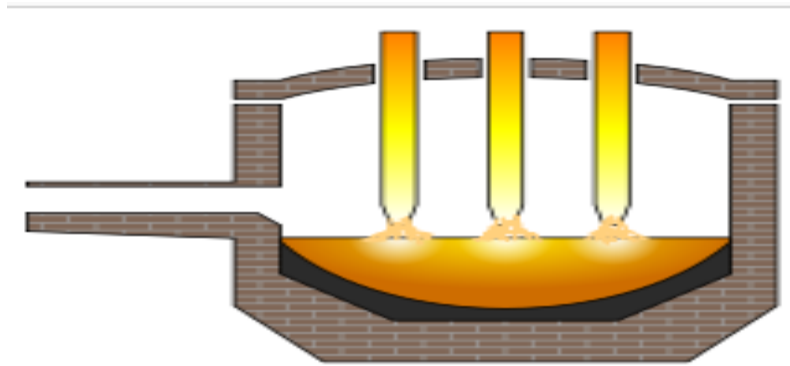
C. ELECTRIC-FURNACE STEEL

In some furnaces, **electricity instead of fire supplies the heat for the smelting and refining of steel**. Because refining conditions in such a furnace can be regulated more strictly than in open-hearth or basic oxygen furnaces, electric furnaces are **particularly valuable for producing stainless steels and other highly alloyed steels** that must be made to exacting specifications. Refining takes place in a tightly closed chamber, where temperatures and other conditions are kept under rigid control by automatic devices.

The Electric Arc Furnace process, or mini-mill, does not involve iron-making. It reuses existing steel, avoiding the need for raw materials and their processing. The furnace is charged with steel scrap, it can also include some direct reduced iron (DRI) or pig iron for chemical balance.

The EAF operates on the basis of an electrical charge between two electrodes providing the heat for the process. The power is supplied through the electrodes placed in the furnace, which produce an arc of electricity through the scrap steel (around 35 million watts), which raises the temperature to 1600°C, melting the scrap.





A schematic cross-section through an EAF. Three electrodes (yellow), molten bath (gold), tapping spout at left, refractory brick movable roof, brick shell, and a refractory-lined bowl-shaped hearth.

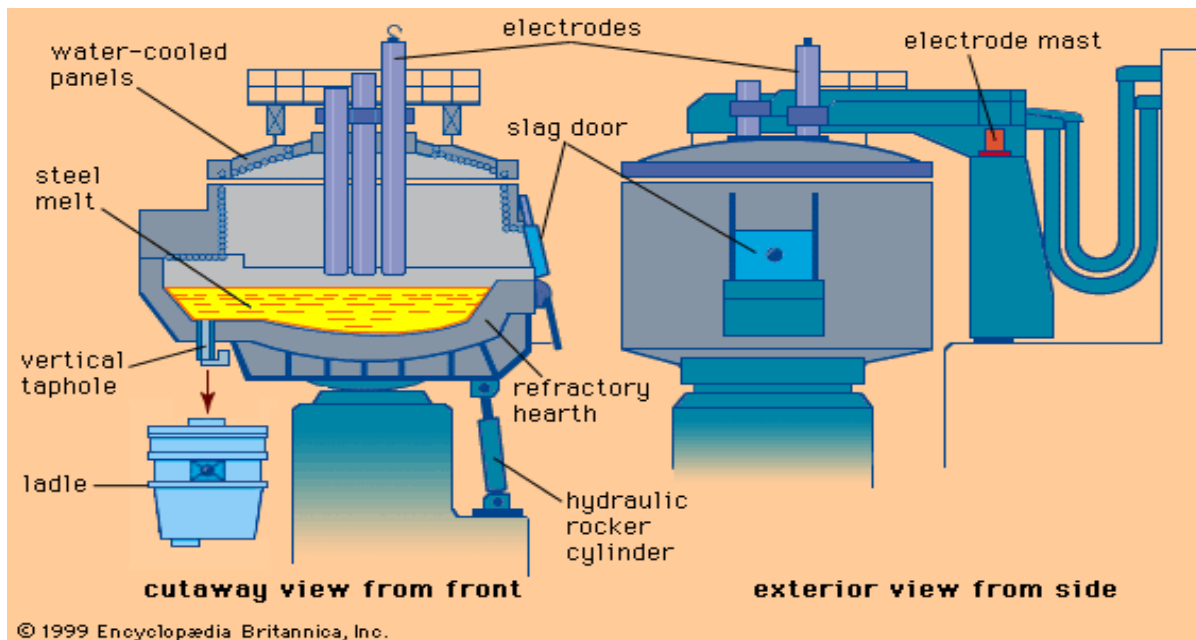


Figure 1.3: Scheme of an Electric Arc Furnace

Most often the charge consists almost entirely of scrap. Before it is ready to be used, the scrap must first be analyzed and sorted, because its alloy content will affect the composition of the refined metal. Other materials, such as small quantities of iron ore and dry lime, are added in order to help remove carbon and other impurities that are present. The additional alloying element goes either into the charge or, later, into the refined steel as it is poured into the ladle. After the furnace is charged, electrodes are lowered close to the surface of the metal. The current enters through one of the electrodes, arcs to the metallic charge, flows through the metal, and then arcs back to the next electrode. Heat is generated by the overcoming of resistance to the

flow of current through the charge. This heat, together with that coming from the intensely hot arc itself, quickly melts the metal. Electric Arc Furnaces do not use coal as a raw material, but many are reliant on the electricity generated by coal-fired power plant elsewhere in the grid.

Heat generation in electric furnace:-

- The electrodes will be lowered.
- The current enters through one of the electrodes, arcs to the metallic charge, flows through the metal, and then arcs back to the next electrode.
- Heat is generated by the overcoming of resistance to the flow of current through the charge. This heat, together with that coming from the intensely hot arc itself, quickly melts the metal.
- In another type of electric furnace, heat is generated in a coil.

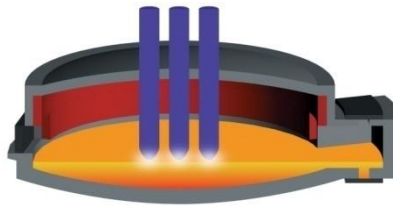
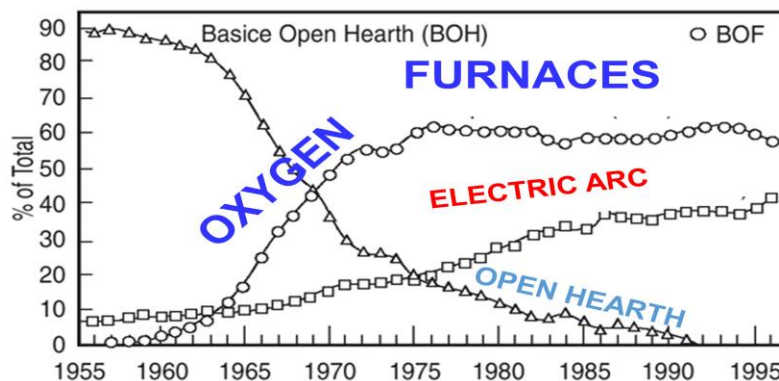


Figure 1.4: Heat generation in the EAF.

COMPARISON OF DIFFERENT FURNACES



1.3 BY- PRODUCTS OF STEEL PRODUCTION

Steelmaking is nearing zero-waste, with current material efficiency rates at around 98%. This means that 98% of raw materials used are converted to products or by-products that are used or recycled.

Slag:- is the main steelmaking by-product; it is mostly used in cement production, reducing CO₂ emissions by around 50%. It can also be used in roads (substituting aggregates), as fertilizer (slag

rich in phosphate, silicate, magnesium, lime, manganese and iron), and in coastal marine blocks to facilitate coral growth thereby improving the ocean environment.

Gases:- produced during steelmaking are fully reused as an energy source either in the blast furnace and reheating furnaces or in power generation plants within the steelworks, saving fossil fuels. Coke oven gas contains about 55% hydrogen and may prove an important hydrogen source in the future.

1.4 EFFECT OF ALLOYING ELEMENTS ON STEEL

(C, Mn, Si, Cr, Mo, Ni, V, Ti & W)

Alloying elements are added to effect changes in the properties of steels. The basis of this section is to cover some of the different alloying elements added to the basic system of iron and carbon, and what they do to change the properties or effectiveness of steel.

Carbon(C)

The hardness of steel (or more accurately, the hardenability) is increased by the addition of more carbon, up to about 0.65 percent. Wear resistance can be increased in amounts up to about 1.5 percent. Beyond this amount, increases of carbon reduce toughness and increase brittleness. The steels of interest to knife-makers generally contain between 0.5 and 1.5 percent carbon.

Carbon is the single most important alloying element in steel.

Manganese (Mn)

Manganese slightly increases the strength of ferrite, and also increases the hardness penetration of steel in the quench by decreasing the critical quenching speed. This also makes the steel more stable in the quench. Steels with manganese can be quenched in oil rather than water, and therefore are less susceptible to cracking because of a reduction in the shock of quenching. Manganese is present in most commercially made steels.

CHROMIUM (Cr)

As with manganese, chromium has a tendency to increase hardness penetration. This element has many interesting effects on steel. When 5 percent chromium or more is used in conjunction with manganese, the critical quenching speed is reduced to the point that the steel becomes air hardening. Chromium can also increase the toughness of steel, as well as the wear resistance. Probably one of the most well-known effects of chromium on steel is the tendency to resist

staining and corrosion. Steels with 14 percent or more chromium are referred to as stainless steels.

A more accurate term would be stain resistant. Stainless tool steels will in fact darken and rust, just not as readily as the non-stainless varieties. Steels with chromium also have higher critical temperatures in heat treatment.

1. Improves hardenability and strength
2. Improves wear resistance and sharply increases corrosion resistance at high concentrations (> 12%).

Chromium is the element that makes stainless steel stainless. It is essential in forming the passive film.

Other elements can influence the effectiveness of chromium in forming or maintaining the film, but no other element by itself can create the properties of stainless steel. At about 10.5% chromium, a weak film is formed and will provide mild atmospheric protection. By increasing the chromium to 17-20%, the stability of the passive film is increased. Further increases in the chromium content will provide additional protection.

SILICON (Si)

Silicon is used as a deoxidizer in the manufacture of steel. It slightly increases the strength of ferrite, and when used in conjunction with other alloys can help increase the toughness and hardness penetration of steel.

1. Improves strength and elasticity
2. Imparts acid resistance and promotes large grain sizes,
3. Which cause increasing magnetic permeability.

NICKEL (Ni)

Nickel increases the strength of ferrite, therefore increasing the strength of the steel. It is used in low alloy steels to increase toughness and hardenability. Nickel also tends to help reduce distortion and cracking during the quenching phase of heat treatment.

1. Increases strength, impact strength and toughness
2. Imparts corrosion resistance in combination with other elements.
3. Improves hardenability, ductility and wear resistance

MOLYBDENUM (Mo)

Molybdenum increases the hardness penetration of steel, slows the critical quenching speed, and increases high temperature tensile strength.

Molybdenum, in combination with chromium, is very effective in stabilizing the passive film in the presence of chlorides.

It is effective in preventing crevice or pitting corrosion.

Molybdenum, next to chromium, provides the largest increase in corrosion resistance in stainless steel.

Industries use 316 stainless because it contains 2-3% molybdenum, which gives protection when chlorine is added to the water.

1. Increases hardenability and strength particularly at high temperatures and under dynamic conditions.
2. Improves corrosion resistance

VANADIUM (V)

Vanadium helps control grain growth during heat treatment. By inhibiting grain growth it helps increase the toughness and strength of the steel and also limits grain size.

1. increases strength and hardness,
2. Increases creep resistance and impact resistance due to formation of hard vanadium carbides,

TUNGSTEN (W)

Used in small amounts, tungsten combines with the free carbides in steel during heat treatment, to produce high wear resistance with little or no loss of toughness. High amounts combined with chromium gives steel a property known as red hardness. This means that the steel will not lose its working hardness at high temperatures. An example of this would be tools designed to cut hard materials at high speeds, where the friction between the tool and the material would generate high temperatures.

1. increases hardness particularly at elevated temperatures due to stable carbides,
2. Refines grain size.

Copper

The addition of copper in amounts of 0.2 to 0.5 percent primarily improves steels resistance to atmospheric corrosion. It should be noted that with respect to knife steels, copper has a detrimental effect to surface quality and to hot-working behavior due to migration into the grain boundaries of the steel.

Niobium

In low carbon alloy steels Niobium lowers the transition temperature and aids in a fine grain structure. Niobium retards tempering and can decrease the hardenability of steel because it forms very stable carbides. This can mean a reduction in the amount of carbon dissolved into the austenite during heat treating.

Boron

Boron can significantly increase the hardenability of steel without loss of ductility. Its effectiveness is most noticeable at lower carbon levels. The addition of boron is usually in very small amounts ranging from 0.0005 to 0.003 percent.

Titanium (Ti)

This element, when used in conjunction with Boron, increases the effectiveness of the Boron in the hardenability of steel. Titanium and Niobium are used to reduce the sensitization of stainless steel. When stainless steel is sensitized, inter granular corrosion can occur. This is caused by the precipitation of chrome carbides during the cooling phase when parts are welded. This depletes the weld area of chromium. Without the chromium, the passive film cannot form. Titanium and Niobium interact with carbon to form carbides, leaving the chromium in solution so a passive film can form. 1. Improves strength and corrosion resistance.

1.5 CLASSIFICATION OF STEEL

Steels can be classified by a variety of different systems depending on:

- The composition, such as carbon, low-alloy or stainless steel.
- The manufacturing methods, such as open hearth, basic oxygen process, or electric furnace methods.
- The finishing method, such as hot rolling or cold rolling
- The product form, such as bar plate, sheet, strip, tubing or structural shape
- The deoxidation practice, such as killed, semi-killed, capped or rimmed steel
- The microstructure, such as ferritic, pearlitic and martensitic
- The required strength level, as specified in ASTM standards
- The heat treatment, such as annealing, quenching and tempering, and thermo- mechanical processing.

Steels are grouped into five main classifications. These are:

1. Carbon Steels: More than 90 percent of all steels are carbon steels. They contain varying amounts of carbon and not more than 1.65 percent manganese, 0.60 percent silicon, and 0.60 percent copper. Machines, automobile bodies, most structural steel for buildings, ship hulls, bedsprings, and bobby pins are among the products made of carbon steels.

Table 1.2: Type and application of carbon steel

Carbon steels	Carbon content	Uses
Low carbon steel	< 0.3%	Rivets, wires, nails
Medium carbon steel	0.3% to 0.8%	Railroad rails, axles
High carbon steel	0.8% to 2%	Tools, springs, files

2. Alloy Steels: These steels have a specified composition, containing certain percentages of vanadium, molybdenum, or other elements, as well as larger amounts of manganese, silicon, and copper than do the regular carbon steels. **Automobile gears and axles, roller skates, and carving knives** are some of the many things that are made of alloy steels.

3. High-Strength Low-Alloy Steels (HSLA steels)

They are the newest of the five chief families of steels. They cost less than the regular alloy steels because they contain only small amounts of the expensive alloying elements. They have been specially processed, however, to have much more strength than carbon steels of the same weight. For example, freight cars made of HSLA steels can carry larger loads because their walls are thinner than would be necessary with carbon steel of equal strength; also, because an HSLA freight car is lighter in weight than the ordinary car, it is less of a load for the locomotive to pull. Numerous buildings are now being constructed with frameworks of HSLA steels. Girders can be made thinner without sacrificing their strength, and additional space is left for offices and apartments.

4. Stainless Steels

Stainless steels contain chromium, nickel, and other alloying elements that keep them bright and rust resistant in spite of moisture or the action of corrosive acids and gases. Some stainless steels are very hard; some have unusual strength and will retain that strength for long periods at extremely high and low temperatures. Because of their shining surfaces architects often use them for decorative purposes.

Stainless steels are used for the pipes and tanks of petroleum refineries and chemical plants, for jet planes, and for space capsules. Surgical instruments and equipment are made from these steels, and they are also used to patch or replace broken bones because the steels can withstand the action of body fluids. In kitchens and in plants where food is prepared, handling equipment is often made of stainless steel because it does not taint the food and can be easily cleaned.

5. Tool Steels: these steels are fabricated into many types of tools or into the cutting and shaping parts of power-driven machinery for various manufacturing operations. They contain tungsten, molybdenum, and other alloying elements that give them extra strength, hardness, and resistance to wear.

Depending on the composition of alloying element it can be divided into:

- Low carbon steel, medium carbon & high carbon steel.

Low carbon steel:

- + It contains less than about 0.25wt% of C
- + Un responsive to heat treatments intended to form martensite and it can be strengthened by cold working
- + Main microstructures are ferrite and pearlite
- + It is soft and weak and also it has an outstanding ductility and toughness, in addition to that they are machinable, weldable etc.
- + They are the least expensive and mainly employed in car body.

Medium carbon:

- + Carbon concentration is 0.25wt% to 0.6wt%
- + It is heat treatable and medium carbon steel have low hardenability
- + The addition of chromium, nickel, and molybdenum improves the capacity of these alloys.
- + The heat treated alloys are stronger than the low carbon steel, but they are less ductile and tough.

They are applied in railway wheels and tracks, gears, crank shaft and other machine parts and high strength structural components.

High carbon steel:

- ✚ Carbon content 0.6wt%-1.4wt%.
- ✚ It the hardest and strongest and Least ductile and toughness.
- ✚ It is used in the hardened and tempered condition.
- ✚ They are wear resistant and capable of holding sharp cutting edges.
- ✚ The alloying elements like; Chromium, vanadium, tungsten and molybdenum are employed to enhance the strength.
- ✚ High carbon steel used: as a tool of: drill , lathe and planner, punches , Shear blades, Pipe cutters and Concrete drills.

1.6 CORROSION AND OXIDATION

Corrosion is defined as the destructive and unintentional attack of a metal it is electrochemical and ordinarily begins at the surface. Approximately 5% of an industrialized nation's income is spent on corrosion and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions.

Corrosion is a natural process that occurs when a material breaks down because of exposure to the elements or chemicals in the environment that cause a reaction. Rust is one of the most common forms of corrosion. Although minor corrosion is often easy to repair, there are steps you can take to prevent corrosion from occurring in the first place.

Familiar examples include the rusting of automotive body panels and radiator and exhaust components.

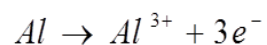
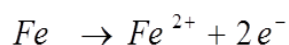
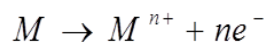
Corrosion is a process of gradual, spontaneous destruction deterioration of metal, beginning from its surface due to its chemical, electrochemical and biochemical interaction with the environment.

ELECTROCHEMICAL CONSIDERATIONS

For metallic materials, the corrosion process is normally electrochemical, that is chemical reaction in which there is transfer of electrons from one chemical species to another.

Metal atoms characteristically lose or give up electrons in what is called an oxidation reaction.

Hypothetical metal M that has a valence of n (or n valence electrons) may experience oxidation according to the reaction.

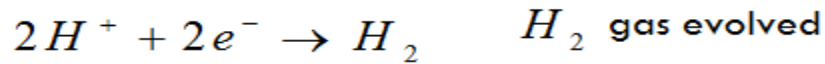


The site at which oxidation takes place is called the **anode**.

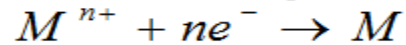
The electrons generated from each metal atom that is oxidized must be transferred to and become a part of

another chemical species in what is termed a reduction reaction.

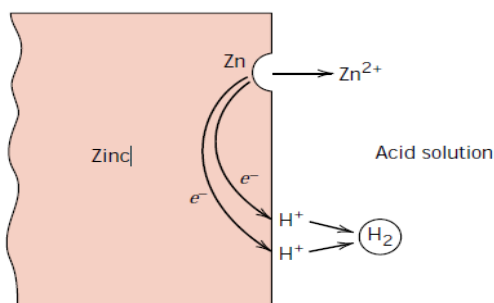
Example, some metals undergo corrosion in acid solutions, which have a high concentration of hydrogen (H) ions; the H ions are reduced as follows



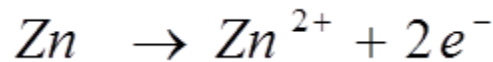
- metal may be totally reduced from an ionic to a neutral metallic state according to



That location at which reduction occurs is called the **cathode**.



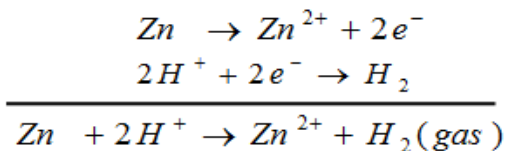
Zinc will experience oxidation or corrosion

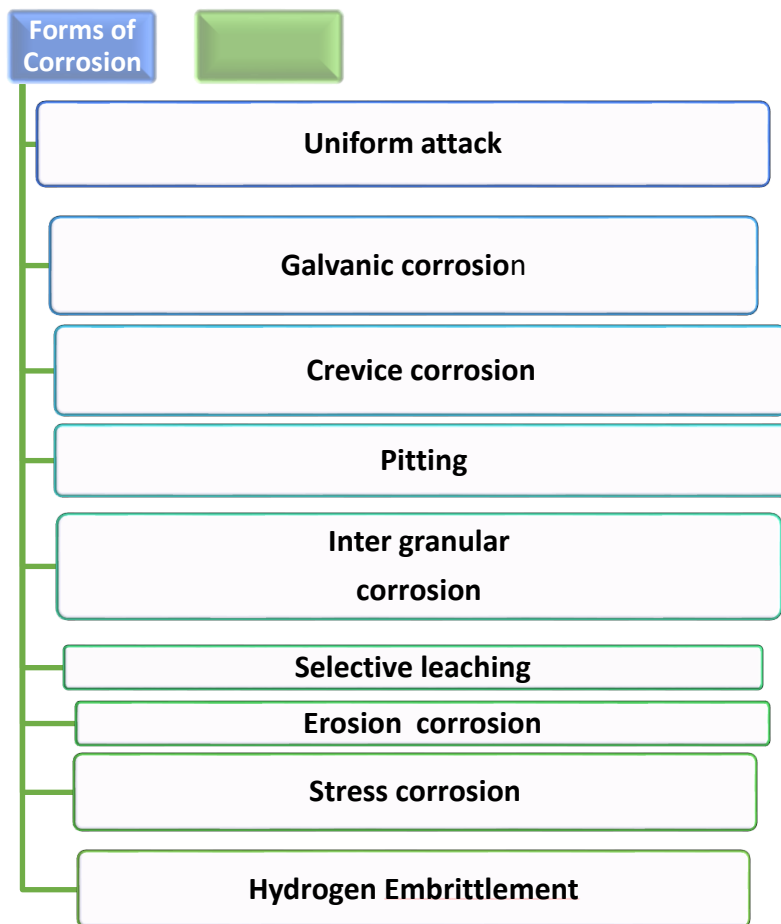


The electrochemical reactions associated with the corrosion of zinc in an acid solution

Since zinc is a metal, and therefore a good electrical conductor, these electrons may be transferred to an adjacent region at which the H ions are reduced according to

Total reaction:



B.TYPES OF CORROSION**1.Uniform attack**

Uniform attack is a form of electrochemical corrosion that occurs with equivalent intensity over the entire exposed surface and often leaves behind a scale or deposit.

In a microscopic sense, the oxidation and reduction reactions occur randomly over the surface.

Some familiar examples include general rusting of steel and iron and the tarnishing of silverware.

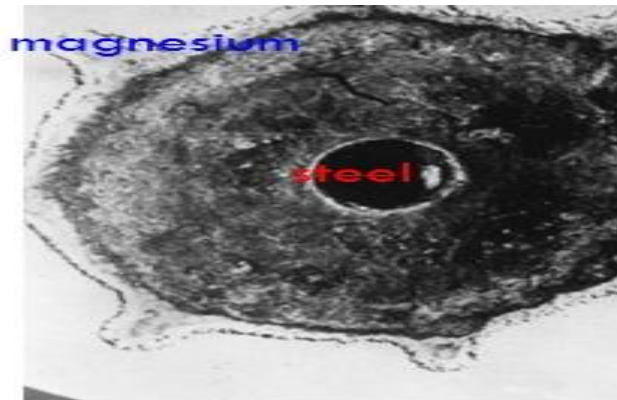
When entire surface of metal is attacked to same degree, it is uniform corrosion. Uniform corrosion is unusual in metals because their structure is homogeneous and so the surface will not corrode uniformly. It is likely to take place in impure metals or alloyed metals.

2. Galvanic corrosion

It occurs when two metals or alloys having different compositions are electrically coupled while exposed to an electrolyte. The less noble or more reactive metal in the particular environment will experience corrosion the more inert metal, the cathode, will be protected from corrosion.

For example, steel screws corrode when in contact with brass in a marine environment. If copper and steel

tubing are joined in a domestic water heater, the steel will corrode in the vicinity of the junction.

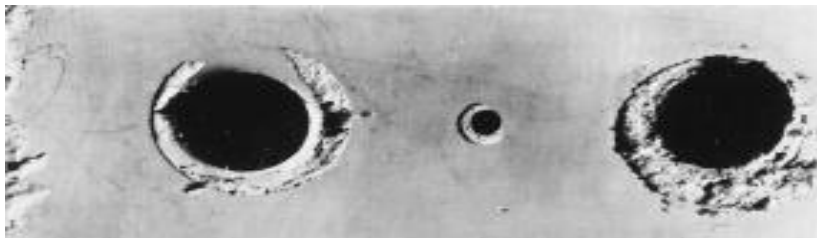


Galvanic corrosion of a magnesium shell that was cast around a steel core.

3. Crevice corrosion

It is caused by concentration differences of ions or dissolved gases in the electrolyte solution, and between two regions of the same metal piece.

A good example of this type of corrosion occurs under deposits of dirt or corrosion products where the solution becomes stagnant and there is localized depletion of dissolved oxygen.



4. Pitting corrosion

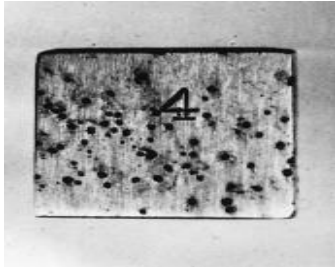
It is a non-uniform corrosion. Deep isolated holes or pits are formed on metal because of inhomogeneities in metal like inclusions, coring (difference in composition within an individual grain or from one part of casting to another part), pores, blowholes etc. These pits accelerate the corrosion process. Pitting corrosion results from an electrochemical reaction. Pitting corrosion occurs when there is a break in the protecting layer. Eg- chromium plate (film) on steel breaks then the point of film breakage becomes anode and the surrounding unbroken film as cathode.

Pitting is another form of very localized corrosion attack in which small pits or holes form. They ordinarily penetrate from the top of a horizontal surface downward in a nearly vertical direction.

The mechanism for pitting is probably the same as for crevice corrosion in that oxidation occurs within the

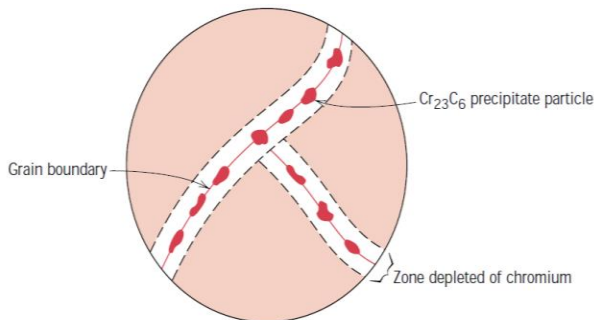
pit itself, with complementary reduction at the surface.

A pit may be initiated by a localized surface defect such as a scratch or a slight variation in compositions. Specimens having polished surfaces display a greater resistance to pitting corrosion. Stainless steels are somewhat susceptible to this form of corrosion; however, alloying with about 2% molybdenum enhances their resistance significantly.



The pitting of a 304 stainless steel plate by an acid-chloride solution.

5. Inter-granular corrosion

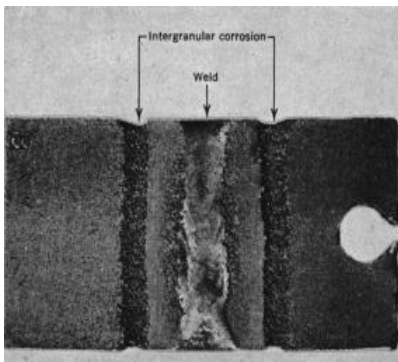


Chromium carbide particles that have precipitated along grain boundaries in stainless steel, and the attendant zones of chromium depletion

It occurs preferentially along grain boundaries. The net result is that a macroscopic specimen disintegrates along its grain boundaries.

High temperature sensitized to intergranular attack. Heat treatment permits the formation of small precipitate particles of chromium carbide (Cr_{23}C_6) by reaction between the chromium and carbon in the stainless steel.

Intergranular corrosion is an especially severe problem in the welding of stainless steels, when it is often termed **weld decay**.



Intergranular corrosion in stainless steel can be minimized by:

- (1) subjecting the sensitized material to a high-temperature heat treatment in which all the chromium carbide particles are redissolved,
- (2) lowering the carbon content below 0.03 wt% C so that carbide formation is minimal,
- (3) alloying the stainless steel with another metal

6. Selective leaching

- ❑ Selective leaching is found in solid solution alloys and occurs when one element or constituent is preferentially removed as a consequence of corrosion processes.
- ❑ The most common example is the dezincification of brass, in which zinc is selectively leached from a copper–zinc brass alloy.
 - The mechanical properties of the alloy are significantly impaired, since only a porous mass of copper remains
 - Material changes from yellow to a red or copper color.
- ❑ It can also occur with other alloy systems in which aluminum, iron, cobalt, chromium, and other elements are vulnerable to preferential removal.

7. Erosion corrosion

Erosion-corrosion arises from the combined action of chemical attack and mechanical abrasion or wear as a consequence of fluid motion. All metal alloys, to one degree or another, are susceptible to erosion–corrosion. The nature of the fluid can have a dramatic influence on the corrosion behavior. Increasing fluid velocity normally enhances the rate of corrosion

Erosion-corrosion is commonly found in piping, especially at bends, elbows and abrupt changes in pipe diameter-positions where the fluid changes direction or flow suddenly becomes turbulent. Ex. Propellers, turbine blades, valves, and pumps are also susceptible to this form of corrosion.



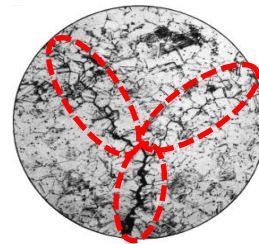
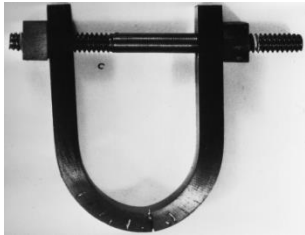
Impingement failure of an elbow that was part of a steam condensate line

Erosion corrosion refers to combined effects of-Mechanical abrasion on metal surface caused by impingement (striking) of air bubbles, abrasive particles remaining in the liquid coming in contact with the metal. Erosion corrosion is caused by breakdown of the protective film at the spot of impingement of bubbles and particles, which ultimately forms localized pits and holes forming anodic points over there. The place

where the scale has been broken forms anode whereas the unbroken protective film forms cathode and hence corrosion proceeds as same as in chemical corrosion. Erosion corrosion takes place in pump mechanisms, turbines, condenser tubes and piping and tubes carrying sea water.

8. Stress corrosion

- ❑ Stress corrosion, sometimes termed stress corrosion cracking, results from the combined action of an applied tensile stress and a corrosive environment; both influences are necessary.
- ❑ Most alloys are susceptible to stress corrosion in specific environments, especially at moderate stress levels
 - most stainless steels stress corrode in solutions containing chloride ions,
 - brasses are especially vulnerable when exposed to ammonia



Photomicrographs showing inter granular stress corrosion cracking in brass

9. Hydrogen Embrittlement

- ❑ Hydrogen Embrittlement is similar to stress corrosion
- ❑ It is the penetration of atomic hydrogen (H) into the material which reduces the strength and ductility of a material.
- ❑ the terms *hydrogen induced cracking and hydrogen stress cracking are sometimes also used*
- ❑ In order for hydrogen embrittlement to occur, some source of hydrogen must be present.
- ❑ High-strength steels are susceptible to hydrogen embrittlement, and increasing strength tends to enhance the material's susceptibility.

Corrosion prevention

I) Painting and coating (*Barrier Protection*): Provided by a protective coating that acts as a barrier between corrosive elements and the metal substrate; to exclude the environment. Coating may be:

1. Galvanizing:-The material to be coated is immersed in a bath of molten zinc maintained at temperatures over 800° F (430° C). A typical bath chemistry used in hot-dip galvanizing is 98% pure zinc. The immersion time in the galvanizing bath will vary, depending upon the dimensions and chemistry of the material being coated.

Materials with thinner sections galvanize more quickly than those with thicker sections. Surface appearance and coating thickness are the result of many process parameters, including

- ✓ steel chemistry,
- ✓ variations in immersion time and/or bath temperature,
- ✓ rate of withdrawal from the galvanizing bath,
- ✓ removal of excess zinc by wiping, shaking or centrifuging, and control of the cooling rate by water quenching or air cooling

2. **Electroplating**:- is the mechanically bonding of one metal to another for the purpose of **corrosion protection, decorative appeal, hardness, and electrical conductivity, reflectivity, and/or wear resistance**. Chromium is generally used for electroplating.

In a nut shell, plating modifies the surface properties of the base metal to make it more suitable for its intended use.

3. **Alloying**:- alloying of the metal with metals like Ni, Cr, V, etc..., make it resistance to corrosion.

1.7 HEAT TREATMENT OF STEEL

Heat Treatment is the *controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape*. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming.

Heat treatment is often associated with *increasing the strength of material*, but it can also be used to *alter certain manufacturability* objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics.

In the process of forming steel into shape and producing the desired microstructure to achieve the required mechanical properties, it may be reheated and cooled several times. Heat treatment of large carbon steel components is done to take advantage of crystalline defects and their effects and thus obtain certain desirable properties or conditions.

Objectives of heat treatment (heat treatment processes)

- to increase strength, hardness and wear resistance (bulk hardening, surface hardening)
- to increase ductility and softness (tempering, recrystallization annealing)
- to increase toughness (tempering, recrystallization annealing)
- to obtain fine grain size (recrystallization annealing, full annealing, normalizing)

- to remove internal stresses induced by differential deformation by cold working, non-uniform cooling from high temperature during casting and welding (stress relief annealing)
- to improve machinability (full annealing and normalizing)
- to improve cutting properties of tool steels (hardening and tempering)
- to improve surface properties (surface hardening, corrosion resistance-stabilizing treatment and high temperature resistance-precipitation hardening, surface treatment)
- to improve electrical properties (recrystallization, tempering, age hardening)
- to improve magnetic properties (hardening, phase transformation)

1.7.1 QUENCHING

Heating the steel above upper critical temperature and then cool in water or in oil. Structure after quenching is fine martensite which is complex, hard and brittle structure.

Four commonly used quenching media:

1. **Brine** – the fastest cooling rate
2. **Water** – moderate cooling rate
3. **Oil** – slowest cooling rate
4. **Gas** – used in automatic furnaces, usually liquid nitrogen can be very fast cooling.

1.7.2 ANNEALING

The term **annealing** refers to a heat treatment in which a material is exposed to an elevated temperature for an extended time period and then slowly cooled. Ordinarily, annealing is carried out to (1) relieve stresses; (2) increase softness, ductility, and toughness; and/or (3) produce a specific microstructure. A variety of annealing heat treatments are possible; they are characterized by the changes that are induced, which many times are microstructural and are responsible for the alteration of the mechanical properties.

In general, the main purpose of annealing heat treatment is to soften the steel, regenerate overheated steel structures or just remove internal tensions.

It basically consists of heating to austenitizing temperature (800°C and 950°C depending on the type of steel), followed by slow cooling.

Any annealing process consists of three stages: (1) heating to the desired temperature, (2) holding or “soaking” at that temperature, and (3) cooling, usually to room temperature. Time is an important parameter in these procedures. During heating and cooling, there exist temperature gradients between the outside and interior portions of the piece; their magnitudes depend on the size and geometry of the piece. If the rate of temperature change is too great, temperature gradients and internal stresses may be induced that may lead to

warping or even cracking. Also, the actual annealing time must be long enough to allow for any necessary transformation reactions. Annealing temperature is also an important consideration; annealing may be accelerated by increasing the temperature, since diffusion processes are normally involved.

1. Process Annealing

Process annealing is a heat treatment that is used to negate the effects of cold work, that is, to soften and increase the ductility of a previously strain-hardened metal. It is commonly utilized during fabrication procedures that require extensive plastic deformation, to allow a continuation of deformation without fracture or excessive energy consumption. Recovery and recrystallization processes are allowed to occur. Ordinarily a fine-grained microstructure is desired, and therefore, the heat treatment is terminated before appreciable grain growth has occurred. Surface oxidation or scaling may be prevented or minimized by annealing at a relatively low temperature (but above the recrystallization temperature) or in a non-oxidizing atmosphere.

2. Stress Relief annealing

Internal residual stresses may develop in metal pieces in response to the following: (1) plastic deformation processes such as machining and grinding; (2) non-uniform cooling of a piece that was processed or fabricated at an elevated temperature, such as a weld or a casting; and (3) a phase transformation that is induced upon cooling wherein parent and product phases have different densities. Distortion and warp age may result if these residual stresses are not removed. They may be eliminated by a **stress relief** annealing heat treatment in which the piece is heated to the recommended temperature, held there long enough to attain a uniform temperature, and finally cooled to room temperature in air. The annealing temperature is ordinarily a relatively low one such that effects resulting from cold working and other heat treatments are not affected.

Generally annealing used to:

1. Reduce hardness, remove residual stress (stress relief)
2. Improve toughness and Refine grain size
3. Restore thus the heat treatment is terminated before any appreciable grain growth is occurred ductility

If you keep the metal hot too long, or heat it up too much, the grains become large; Usually not good and Low strength.

1.7.3 NORMALIZING

Normalization is an annealing process. The objective of normalization is to intend to leave the material in a normal state, in other words with the absence of internal tensions and even distribution of carbon. For the process the high temperatures are maintained until the complete transformation of austenite with air cooling.

It is usually used as a post-treatment to forging, and pre-treatment to quenching and tempering. Induction is used in most applications of annealing and normalizing in compared to conventional ovens.

Steels that have been plastically deformed by, for example, a rolling operation, consist of grains of pearlite (and most likely a pro-eutectoid phase), which are irregularly shaped and relatively large, but vary substantially in size. Normalizing is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution; fine-grained pearlitic steels are tougher than coarse-grained ones. Normalizing is accomplished by heating at least above the upper critical temperature—that is, above for compositions less than the eutectoid (0.76 wt% C), and above for compositions greater than the eutectoid. After sufficient time has been allowed for the alloy to completely transform to austenite—a procedure termed austenitizing—the treatment is terminated by cooling in air.

1.7.4 CARBURIZING

Carburizing is a process of adding Carbon to the surface. This is done by exposing the part to a Carbon rich atmosphere at an elevated temperature and allows diffusion to transfer the Carbon atoms into steel. This diffusion will work only if the steel has low carbon content, because diffusion works on the differential of concentration principle. If, for example the steel had high carbon content to begin with, and is heated in a carbon free furnace, such as air, the carbon will tend to diffuse out of the steel resulting in Decarburization.

1.7.5 NITRIDING

Nitriding is a process of diffusing Nitrogen into the surface of steel. The Nitrogen forms Nitrides with elements such as Aluminum, Chromium, Molybdenum, and Vanadium. The parts are heat-treated and tempered before nitriding. The parts are then cleaned and heated in a furnace in an atmosphere of dissociated Ammonia (containing N and H) for 10 to 40 hours at 500-625 °C (932 - 1157 °F). Nitrogen diffuses into the steel and forms nitride alloys, and goes to a depth of up to 0.65 mm (0.025 in). The case is very hard and distortion is low. No further heat treatment is required; in fact, further heat treatment can crack the hard case. Since the case is thin, surface grinding is not recommended. This can restrict the use of nitriding to surfaces that require a very smooth finish.

COMPARISON OF DIFFERENT HEAT TREATMENTS

	Annealing	Normalizing	Quenching
Hardness	Low	Medium	High
Toughness	Low	Medium	High
Tensile Strength	Low	Medium	High
Ductility	High	Medium	Low

The end!!!

