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Steel and Iron Handbook



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Modern civilization as people know it would not be possible without Iron and Steel. Iron has been a vital material in technology for well over three thousand years. However, since ancient times, steel is made by alloying iron with carbon to produce a harder, stronger metal that will take a much keener edge. Owing to its intense connections with core infrastructural segments of the economy, steel industry is of high priority and importance. Steel has probably the widest range of applications of any material. The wide range of alloy compositions, mechanical properties and product forms available make it a versatile material that is used in components and products that may be small or large, high-tech or low-tech, everyday or specialist. In an introduction to modern steel making, an attempt has been made to cover, as the space would permit, the entire field of steel making with equal emphasis on the general practices and the underlying principles. This book is intended as a resource and as an introduction to the layman about our most important metal system. This book provides basic information covering every aspect of iron and steel production as well as a practical aid for workers engaged in the field. After an introduction that deals with the history and production of iron and steel, the rest of the book examines their physical properties and metallurgy. Beginning with a brief introduction to the ferrous alloys and metals, types and production of cast iron, production of compacted Graphite Irons, Ductile Iron, Malleable Cast Iron and current status of steel making together with the reasons for obsolescence of Bessemer converter and open hearth processes, the book moves on to: elaborate the physiochemical principles involved in steel making; explain the operational principles and practices of the modern processes of primary steel making (LD converter, Q-BOP process, and electric arc furnace process); provide a summary of the developments in secondary refining of steels; discuss principles and practices of ingot casting and continuous casting of steels; discusses the defects in the steel produced and also the remedies for their removal. This book provides considerable information in an easily assimilable form and makes an ideal introduction to the complex subject of steel technology.

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This flexibility depends on the heat treatment procedures, which modifies the micro structure. Examples of ferrous alloys include, carbon steel, alloy steel, stainless steel, tool steels, cast iron, cast steel, maraging steel and specially or proprietary iron based alloys. Iron alloys containing chromium, manganese, molybdenum, silicon, titanium, tungsten, vanadium and other elements in varying properties, ferro alloys are added to steel during the manufacturing process to achieve the desired degree of corrosion resistance, heat resistance, tensile strength, yield strength and other qualities. The principal ferro alloys are ferromanganese, ferrochromium ferromolybdenum, ferrotitanium, ferrovanadium, ferrosilican, Ferroboron, and Ferrophosphorus.

Type of Ferrous Alloys

Carbon steels are ferrous alloys that contain carbon and small levels of other alloying elements such as manganese or aluminium. Alloy steels contain low to high levels of element such as chromium, molybdenum vanadium and nickel.

Cast steel alloy grades are made by pouring molten iron into a mold.

Cast iron alloy and Iron alloy are two major ferrous alloys used in most industrial applications.

Specifications and Properties

Selecting metal alloys requires an analysis of the desired dimensions and specifications. Dimensions to consider in diameter (OD) inner diameter (ID), overall length and over all thickness. Other specifications of importance (based-application) include product shape tensile strength, yield strength, melting point, conductivity, corrosion, resistance and malleability. These properties differ based on the forming method and alloy composition.

Types of Ferrous Metals

There are following types of ferrous alloys are used:

1. Carbon Steel
2. Alloy Steel
3. Stainless Steel
4. Tool Steel
5. Cast Iron
6. Cast Steel

Carbon Steel

Carbon steel is an alloy of iron and carbon with varying quantities of phosphorus and sulphur. To this alloy is added a deoxidiser to remove or minimise the last traces of oxygen. manganese is added to such an alloy to neutralise sulphur, either alone or in combination with silicon or other deoxidisers.

Free Cutting Steels

Free cutting steels of the three Bessemer grades B1111, B1112 and 31113, which differ mainly in sulphur content and of the resulphurized open hearth steels from C1 108 to C1 151. The high sulphur content in these grades promotes machinability in bar or plate, and gives wear resistance in some application.

The high sulfur content leads to the formation of inclusions (for example, manganese sulfide) disposed along the grain. These inclusions facilitate shearing and promote grinding and easy chip formation. For these purposes, free-cutting steel is sometimes alloyed with lead and tellurium. The mechanical properties of free-cutting steel along the grain (depending on the grade of steel and the rod diameter) are typically as follows for hot rolled rods the ultimate strength $Q_y=420$.

These carbon steels have an increased sulphur content (resulphurized steels) which result in a relatively high manganese sulphide, Mns content of controlled globular shape. This steel has excellent machining properties. Free cutting or free machining steels may contain an insoluble, soft element, primarily lead

(0.15-0.35%) (leaded steels) instead of higher percentage of sulphur.

Plain Carbon Steel

Plain carbon steels are those containing only two elements-iron and carbon, silicon, manganese, sulphur and phosphorus exist as impurities and not as ingredients. These constituents have negligible effect on steels when their extent does not exceed: 0.3-0.4% Si, 0.5-0.8% Mn, 0.08% P and 0.04% S.

Limitations of Plain Carbon Steels

Plain carbon steels have the following limitations:

- (1) At reasonable toughness, Carbon steels possess a maximum strength of 500 N/MM².
- (2) Hardenability of plain carbon steels is low. Even on drastic quenching, plain carbon steels can be hardened to limited thickness only.
- (3) Poor corrosion resistance.
- (4) Poor fatigue and creep resistance.

Effects of Alloying Elements in Steel

Chromium: The addition of chromium results in the formation of various carbides of chromium which are very hard. Yet the resulting steel is more ductile than a steel of the same hardness produced by a simple increase in carbon content. Chromium also refines the grain structure so that these two combined effects result in both increased toughness and increased hardness. The addition of chromium increases the critical range of temperatures and raises the strength at high temperature. Alloy of chromium resists abrasion and wear. Chromium also increases resistance to corrosion and oxidation.

Spring Steels

Spring steels are plain carbon and alloy steels which are used for the manufacture of springs and spring parts for static duty and dynamic duty applications. They are produced by closely controlled manufacturing practices to ensure a low content of non-metallic inclusions, and freedom from harmful surface imperfections and decarburization. These steels in the cold worked or heat treated condition are characterized by high elastic limit, high tensile and fatigue strength, good toughness and good formability. One type contains 17% Cr, 7% Ni, 1% Al, and a small amount of titanium and is martensitic at room temperature and is aged at 482°C. These are available in coils, sheets strips, plates, forgings, billets, bars, rods, etc.

Magnetic Steels

Magnetic steels and alloys may be classified as soft magnet and permanent magnet types. Soft magnet steels and alloys are used in the production of pole cores. transformers, generators, motors and electromagnets.

Bearing Steels

Bearing steels are alloy special steels which are used for the manufacture of ball and roller bearing components. They are produced by closely controlled manufacturing practices to ensure internal soundness. Uniformity of chemical composition, low content of non-metallic inclusions and freedom from harmful surface imperfections. For satisfactory performance these steels should be hard enough to withstand high compressive loading without sinking, and resist wear and fatigue. These steels should also possess adequate toughness, and high dimensional stability at the operating temperatures.

Types of Cast Irons

Cast iron is generally produced in a cupola. The charge consists of Pig iron, coke and limestone. Coke acts as a source of heat and carbon. It melts the charge, while limestone acts as flux and removes the impurities. However, cast irons produced in a cupola contain a large number of impurities. Quality grade cast irons are produced in electric furnaces.

Types of Cast Iron

The product of the blast furnace pig iron is unsuitable for casting as it contains impurities in high

percentage. To render it suitable for desired purpose it is refined in the furnace known as cupola. The refined product is formed as cast iron.

Cupola: It is very similar to a blast furnace in principle. It is a vertical shaft furnace, into which the raw materials and fuel are charged at the top. Air for combustion of fuel is introduced through one or more rows of tuyeres a short distance above the bottom. Since the cupola is only concerned with the melting of the metal and not with the reduction of ores as in the blast furnace.

Properties of Cast Iron

Cast iron is formed by remelting pig iron, and is useful for a variety of engineering purposes. Read on to know more on the unique properties of cast iron.

Cast iron is an alloy of iron and carbon, and is popular because of its low cost and ability to make complex structures. The carbon content in cast iron is 3% to 4.5% by weight. Silicon and small amounts of manganese, sulfur and phosphorus are also present in it. The products of cast iron exhibit reasonable resistance against corrosion. The mechanical properties of cast iron are very much dependent on the morphology of its carbon content. Carbon is present in the form of plates in gray cast iron, whereas it is incorporated in compound Fe_3C (cementite) in white cast iron.

Grey Cast Iron

When the carbon is not chemically combined with iron. It is known as free carbon or graphite carbon, and the resulting cast iron is then known as grey cast iron. Two conditions a slow rate of cooling and the presence of silicon will cause the carbon to change from the combined form to the graphitic form to produce grey cast iron.

White Cast Iron

The presence of cementite or iron, carbon Fe_2C either free or lamellar pearlite makes this metal hard and brittle, and the absence of graphite gives the fracture of white colour. Quick cooling (chilled casting) of iron from its molten state does not allow so much graphite to form and a large proportion of the carbon is in the combined form. When cooling is normal, the fracture of iron has a greyish black crystalline appearance and the graphite carbon may be easily discerned.

Casting of Cast Iron

Pig iron is melted in a cupola furnace, from which the molten metal is run off into a ladle. From the ladle the liquid metal is poured into the molds prepared for casting material to be desired shape. Usually some scrap iron is proportionated to the pig iron to give certain desired specification to the cast iron.

The importance of degasifying, deslagging as well as desulphurising a molten metal is fully understood, and the use of Brinella greatly assists this process which must be done to avoid unsatisfactory or even rejected castings.

Alloy Cast Iron

Chromium upto 8% is added to cast iron which has opposite effect of silicon and nickel.

It promotes the formation of carbides and inhibits the formation of graphite. It increases the corrosion resistance. Higher percentage of chromium therefore hardens the iron by increasing the percentage of combined carbon, Nickel and chromium added in 3 to 1 ratio to 4% total have their graphite and carbide forming tendencies neutralize each other, and their results in iron with improved grain refinement, hardness, and strength, with no impairment of machinability.

Wear Resistant Cast Irons

Wear resistant alloy irons are an important class of cast irons, they find wide application for the manufacture of mineral crushing plant, hammer for rock crushers, grinding balls, liners for crushing mills etc. They are also used in shot blasting machines for impellers, liners etc. Three types of cast iron are used.

Unalloyed and low alloy grades of white iron having a structure of massive carbides in a pearlitic matrix.

These alloys are extremely brittle and have been largely superseded by tougher, alloyed white irons. Ni-hard irons containing Ni to increase hardenability by ensuring that austenite transforms to martensite after heat treatment. They also contain Cr to increase the hardness of the carbide.

High-Chromium White Iron

"L" and have the chemical formula M_3C at higher cooling rate and low chromium content. When the cooling rate slows down and the chromium content increases to, for example, 30% and higher, the primary chromium carbides have a hexagonal shape with a characteristic hole in the center. The eutectic carbides are always type M_7C_3 , independent of chromium content and cooling rate.

The type $M_{23}C_6$ carbides solidify when the chromium content is approximately 50 to 60%. The same factors that affective type of carbides also influence the type of matrix, which can be austenitic but also ferrite or pearlitic. When the cooling rate is respectively slows, secondary precipitations can occur around the austenitic dendrites.

Grey Iron

Grey iron is classified according to minimum tensile strength of the test bars. The matrix is predominantly pearlitic but also can be pearlitic-ferritic, ferritic-pearlitic.

A common characteristic constituent of grey iron microstructures is the phosphorus eutectic known as steadite. The Fe-C-P equilibrium diagram. The transformations that occur in this system during solidification as well as in the solid state. The characteristic property of this system is a large area of the ternary phosphorous eutectic due to the strong tendency for the phosphorus to segregate.

Compacted Graphite Iron

Matrix micro structures consist of ferrite and pearlite the amount of each constituent depends on the cooling rate and the chemical composition elements that promote either ferrite or pearlite solidifications. A ferritic-pearlitic micro structure with a small amount of nodular graphite.

Nodular Graphite in Ductile Iron

The addition of magnesium in the inoculation process desulfurizes the iron and makes graphite precipitates as nodules rather than flakes. More over mechanical properties are greatly improved over grey iron: Hence: nodular iron is widely known as ductile iron. Nodule size and shape perfection can vary, depending on composition and cooling rate. Certain factors can cause weak nodularity. An irregular graphite shape due to poor inoculation or excessive fading of inoculant. Exploded graphite may occur due to excessive rate earth additions.

Foundry Process of Cast Iron

The simplest form is the cold blast cupola which does ambient temperature air to burn the coke fuel. The metal temperature that can be achieved is normally from 1350 to 1450°C but higher temperatures can be achieved through the use of divided blast or oxygen enrichment. The refractory linings of cold blast cupolas have a short life of less than 24 hours, so cupolas are operated in pairs, each used alternately while the other is re-lined.

In hot blast cupolas, the exhaust gases are used to preheat the blast to 400-600°C, reducing coke consumption and increasing the iron temperature to more than 1500°C. They may be liningless or use long life refractors giving an operating campaign life of several weeks.

Fluxes

Fluxes are added to the cupola charge to form a fluid slag which may easily be tapped from the cupola. The slag is made up of coke ash, eroded refractory, sand adhering to scrap metal and products of oxidation of the metallic charge. Limestone is normally added to the cupola charge, it calcines to CaO in the cupola and reacts with the other constituents to form a fluid slag. Dolomite, calcium-magnesium carbonate, may also be used instead of limestone.

Emissions from Cupolas

Wet scrubbers, bag filters and electrostatic precipitators can be used.

There are two types of wet scrubbers: venturi scrubbers and disintegrators. Venturi scrubbers rely on the pressure drop process a restricted throat and disintegrators on the wetting and agglomeration of dust particles by the action of water carried by a rapidly spinning rotor. Capital cost and running costs, power and maintenance, are high.

Dry bag filters are capable of achieving lower emission levels than wet scrubbers. The gases must be cooled before filtration making capital costs higher than wet scrubbers but running costs may be lower.

The Long Campaign Hot Cupola

Hot blast cupolas were, until recently, only considered economical for foundries with large continuous requirements for molten iron. Hot blast cupolas are operated on long campaigns many with unlined, water cooled steel shells. Independently fired blast systems have been used but they have high fuel costs and have now been largely abandoned.

Tapping temperatures of 1530°C are achieved. The main savings over conventional cold blast cupola practice is found in the reduced coke consumption savings of up 30% of coke usage are claimed. Long campaign cupolas can be designed for economical operation from 10 tonnes 1 hr upwards. The long campaign hot blast cupola is considered by many to be the most economical method of melting grey iron for foundries.

The Cokeless Cupola

This is a continuously melting tower furnace in which the metallic charge is supported on a water cooled grate on which is a bed of carbonaceous refractory spheres. Heat for melting is provided by gas (or oil) burners. Super heating of the liquid iron is performed by the heated refractory spheres and carbon can be added by injecting a suitable recarburiser into the well of the cupola eliminating the coke eliminates sulphur pick-up, making the cokeless cupola suitable for the production of base iron for ductile iron production. It also eliminates the main source of atmospheric pollution. The cokeless cupola retains the advantages of cupola melting continuous operation, ability to accept a wide range of raw materials including wet, oil and contaminated scrap and some refining which removes harmful elements such as lead and zinc.

The Channel Furnace

All the power is induced within the inductor, heating a loop of molten metal which transfers its heat to the main body of the charge by convection and induction forces. The channel furnace will only work providing this loop is maintained 24 hours per day. The temperature of the metal in the loop is higher than that of the metal in the main vessel, which limits the operating temperature of a channel furnace, since a high loop temperature shortens the life of the refractory of the loop.

The Coreless Induction Furnace

In a coreless furnace, the coil surrounds the entire charge. The mass of refractory is much less than in the channel furnace while the shape is a simple hollow cylinder. Hence coreless furnaces are much simpler and less costly to reline, although they require more frequent relines than the channel furnace.

Therefore in a mains frequency furnace operating at 50 or 60 Hz. The turbulence is greater than in one operating at a higher frequency. Because of the high turbulence, the power input to a mains frequency furnace is restricted to around 250 kw per tonne of capacity. With higher frequency, the power density can be increased to three or four times this level.

Charge Materials

The maximum dimension of a piece of charge is around one-third of the crucible diameter. If larger, there is a danger of bridging. The valve may be exceeded when a long piece of charge is fed in a controlled manner into the crucible charge bridging can also be a problem when melting charges of cast iron borings. It is difficult to generate circulating electric currents in a cold charge having high electrical resistance between individual pieces (As found with oxidised borings) so a large sintered mass may form from which does not easily

sink down as melting occurs.

The usual practice with medium frequency furnaces is to coat the copper coil of the furnace with a layer of 'mudding' about 6mm thick, of a medium to high alumina cement. This remains in place when the hot face is knocked out. Between this and the hot face is a layer of ceramic fibre insulation. The working face is formed by compacting the silica refractory behind a steel former concentrically placed within the coil. Formers are normally constructed from mild steel sheet according to the furnace manufacturer's design. Refractory is poured between the former and the coil and compacted using vibratory ramming tools or manual compaction. Inhalation of silica dust presents a hazard and respirators should be used during installation or wrecking of the lining.

Operating Systems

Most iron foundries use two furnace bodies, identical in size, fed from a single power supply with some means of switching the power supply between the two furnaces. This allows a continuous supply of molten metal with the furnace dispensing molten metal while the other is melting the next batch switching techniques have been developed to enable a single power supply to provide melting power to one furnace while simultaneously providing holding power to the second so that temperatures control can be maintained.

Mechanised charging systems, vibratory conveyors or drop bottom charging buckets are frequently used to ensure maximum furnace utilisation. De-slagging is the most arduous and time consuming operation, back filting the furnace aids the process.

While most of the ferrosilicon and carboriser are added during furnace charging, some carbon and silicon losses will occur at high molten metal temperatures. Trimming additions of 0.2 to 0.3% C and 0.2% si are typical during the final stages of the melting process. The stirring action of the medium frequency power allowing rapid solution and consistent metal composition.

Shop Floor Control of Metal Composition

The carbon and silicon content of unalloyed cast irons can be quickly determined on the shop floor by thermal analysis. A sample of molten iron is poured into a small expandable test mould about 25mm diameter and 65mm deep made from resin bonded sand and coated with tellurium to ensure that the sample freezes white. The test mould also contains a thermo couple connected to a temperature recorder. As the sample solidifies, the temperature recorder plots a cooling curve which displays the 'liquids arrest'.

Inoculation of Grey Cast Iron

Introduction

The liquid iron must have a suitable 'graphitisation potential', this is determined mainly by its carbon equivalent value, and in particular by the silicon content. It is normal practice to adjust the graphitisation potential by controlling the silicon content. However, the effect of other elements must also be considered.

Ladle Inoculation

The selected grade of inoculin for ladle inoculation should always be added to the metal stream when tapping from furnace to ladle, or ladle to ladle. Additions should begin when the ladle is one-quarter full and be completed when the ladle is three quarters full, so that the last metal merely mixes.

Control Methods

The wedge chill test is a simple and rapid method of assessing the degree of chill reduction obtained by the use of inoculin in grey cast irons. Carried out on the foundry floor the wedge test is frequently used as a routine check even when full laboratory facilities are available. The most common dimensions for the wedge are illustrated.

The wedge is made in a mould prepared from silicate or resin bonded sand. After pouring, it must be allowed to cool in the mould to a dull red heat (C.600°C), after which it can be quenched in water and fractured. The width at the point where clear chill ceases is measured and this gives a good indication of

the need for inoculation and of the effectiveness of an inoculation process. In general, casting sections should be not less than three times the wedge reading if chill at the edges and in thin sections is to be avoided.

Mould Inoculation

There are several ways in which mould inoculation can be performed. Powdered inoculant can be placed in the pouring bush, or it can be placed at the bottom of the sprue. A more reliable method is to use sachets or precast slugs of inoculant in the pouring bush or in the running system.

INOPAK sachets are sealed paper packets containing 5,10,020 gm of graded, fast-dissolving inoculant which can be placed in the runner bush, at the top of the sprue or in some other situation where there is a reasonable degree of movement in the metal stream. For most purposes, the addition rate should be 0.1%, i.e. 5g of INOPAK for each 5 kg of iron poured.

INOTAB cast mould inoculant tablets are designed to be placed in the runner where they gradually dissolve in the metal stream as the casting is poured, giving uniform dissolution. This ensures that inoculation takes place just before the INOTAB tablet.

A minimum pouring temperature of 1370°C (2500°F) is recommended. It is important that the INOTAB tablets is located where there is continual metal flow during pouring to ensure uniform dissolution and the typical application methods are shown in.

Production of Compacted Graphite Irons

Production of Compacted Graphite Iron

There are several methods by which compacted graphite may be produced:

Cerium addition

Magnesium additions

Nitrogen additions

Magnesium plus titanium addition

One method involved the joint addition of a nodularising and a denodularising agent, usually magnesium and titanium often with a small cerium addition as well special treatment alloys have been developed for the production of CG iron.

Mg	Ti	Ce	Ca	Al	Si	Fe
4.5-5.5	8.0-10.0	0.3-0.4	1.0 max	1.5 max	50-54	balance

Foundry Properties of Compacted Graphite Iron

The fluidity is governed by carbon equivalent (CE) and temperature and is similar to grey or ductile irons of the same CE. Because CG irons are stronger than grey irons, a higher CE can be used to obtain the same strength. This allows greater fluidity and easier running of thin sections. CG iron is dross forming, just as ductile iron, and filtration of casting is desirable, CG irons are more prone to chill than grey irons but less likely to chill than ductile iron. Good inoculation is necessary, fading occurs, but to a smaller extent than in ductile iron, but excessive delays between treatment, inoculation and casting should be avoided.

Production of Ductile Iron

Ductile iron, also known as spheroidal graphite (sg) iron or nodular iron is made by treating liquid iron of suitable composition with magnesium before casting. This promotes the precipitation of graphite in the form of discrete nodules instead of inter connected flakes. The nodular iron so formed has high ductility allowing castings to be used in critical applications such as:

Crankshafts, steering knuckles, differential carriers, brake callipers, hubs, brackets, valves, water pipes, pipe fitting and many others. Ductile iron production now accounts for about 40% of all iron castings and is still growing.

Melting Ductile Iron Base

While the cupola can be used for the production of ductile iron, the need for high liquid iron temperatures

and close composition control has encouraged the use either or duplexing with an induction furnace, or using a coreless induction furnace as prime matter.

In the US survey referred to above, coreless induction furnaces were used by 84% of the smaller foundries (producing less than 200+/week) almost all larger foundries duplexed iron from an acid cupola to an induction furnace, with channel furnaces being favourite.

Pure Magnesium Converter Process

The Georg Fischer converter has a reaction chamber formed by a graphite-clay plate of semi-circular section set into the lining of the convertor. Molten iron is charged with the converter in the horizontal position. The reaction chamber is charged with pure mg lumps and other additives (if required) and sealed with the mag a locking stopper. The converter spout is closed by a Pneumatically operated lid.

The standard converter allows upto 2.5 tonnes of iron to be treated 6-8 times per hour. Larger unit with capacity upto 10 tonnes are available. The reaction chamber wall has a limited life of 200-800 treatments. Temperature loss is 22-33°C in a 1 tonnes converter but less in larger converters. Since no Si is added during treatment, an unlimited amount of ductile iron returns can be used.

The process is operated under license from Dasa Georg Fisher.

Cored Wire Treatment

The equipment and principle of the method is shown which show the foseco IMPREX-station. The treatment station consists of a coil of hollow mild steel to be filled with mg metal, a feeding machine, a guide to be and a ladle with a close fitting lid. On entering the molten metal, the sheathing of the wire dissolves releasing the core material below the metal surface. Wires vary in size from 4 mm to 13 mm. Typical feed rates of 9 mm wire are 30-50 metres per minute 1500 kg of metal can be treated in about 2 minutes. Treatment temperature starts at around 1450°C, dropping to around 1410°C at the finish.

Specifications for Ductile Cast Iron

A number of national and international specifications for ductile iron, it is necessary to consult the original specification for details of the methods of testing and the mandatory values that must be achieved. In recent years, specifications in different countries have been converging so they are now all quite similar. Lists the suggested chemical compositions required to produce castings that meet the specifications in the as cast state.

Heat Treatment of Ductile Iron

It is obviously desirable to achieve the required properties in the as-cast form, but this is not always possible because of variations of section thickness etc. Heat treatment of the castings will eliminate carbides in thin sections. Produce more consistent matrix structure and for a given structure, the mechanical properties are often improved by heat treatment especially by normalising where tempered martensite structures are needed, heat treatment is essential.

Casting Ductile Iron

Ductile Iron differs from grey iron in its casting characteristics in two important respect. Unlike grey iron, ductile iron is a dross-forming alloy. The residual magnesium which is needed to ensure nodular graphite formation rapidly oxidises whenever the liquid metal is exposed to air: in the ladle, during metal transfer and in the mould. A magnesium silicate dross is formed which may give rise to defects at or just below the casting surface, usually on the upper surfaces of the casting. For this reason, it is common practice to filter ductile iron casting through ceramic filters.

Malleable Cast Iron

Introduction

Malleable irons are cast white, that is, their as-cast structure consists of metastable carbide in a pearlitic matrix. The castings must then be annealed to convert the brittle carbide structure and develop a structure of roughly spherical graphite aggregates in a matrix which can be either ferritic or pearlitic, depending on

composition and heat treatment.

Malleable iron was widely used for automotive and agricultural components, pipe fittings, valves etc. but since the development of spheroidal graphite ductile iron its use has declined, due to the high and cost of the annealing treatment which requires expensive furnace equipment malleable iron is still widely used for small pipe fittings, electrical fitting and builders hardware, particularly for thin section castings and castings which are subsequently galvanised.

White Heart Malleable

In the white heart process, the white, as cast iron is decarburised during annealing leaving a structure of iron carbide in a metallic matrix, when fractured the appearance is whitish, giving rise to the name, 'white heart' Decarburisation is only possible in thin sections in heavier sections some conversion of carbide to graphite nodules occurs so that the annealed casting has a white rim with a core having different structure and mechanical properties. This limits the application to which it can be put.

Black Heart Malleable Iron

The iron is typically melted in a cupola and duplexed into an electric furnace where temperature and composition are adjusted. The cupola metal has the composition

C	Si	Mn	S	P
2.5-2.6	1.1	0.2-0.3	0.2	0.1

The final composition in the electric furnace is

C	Si	mn	S	P	Cr
2.4-2.6	1.3-1.45	0.4-0.55	0.2 max	0.1 max	0.05 max

Manufacture of Steel

Cementation Process

The pure wrought iron bars are arranged in the furnace between the layers of powdered charcoal and maintained at higher temperature (about 1500°C) for 5 to 15 days depending upon the quality of steel required. The wrought iron gets covered with blisters due to combination of carbon and thus the steel so produced is termed as 'blister steel.' Blister steel has fissures and cavities and also its structure is not homogeneous. It may be employed for machined parts and facing hammer but less suitable for edge tools.

Bessemer Process

This process makes use of pear shaped iron converter which is supplied with pig iron melted in a cupola. The converter is lined with fire bricks and can revolve about the horizontal trunions. The bottom is pierced by a number of tuyeres connecting with wind box underneath and made detachable since the wear on it is particular is very severe. It is usually changed after every 15-20 blows.

This stage of process is known as 'the boil' owing to the violent agitation caused by the evolution of carbon monoxide gas from the metal. As the carbon is eliminated the boil gradually subsides and large white flame finally drops after sometimes. The metal in the converter is now virtually pure iron in the liquid form. A Bessemer converter is furnished with an acidic lining (ganister) if the pig iron is free from sulphur and phosphorus, otherwise a basic lining of dolomite is employed.

For removal of sulphur, calcined lime is added to the charge and then heated to red heat. A portion of it burns out while a portion combines with lime to form slag. The basic lining is least affected by this slag containing phosphorus.

Open Hearth Process

The furnace used in this process resembles a reverberatory furnace. Here pig iron is melted in the furnace and large quantity of scrap iron or steel is dissolved in the liquid bath. The source of heat is heated air and coal gas. In open hearth furnace a great economy in fuel is obtained by the utilisation of heat of the hot gases of combustion.

These gases are made to pass through brick grating of two regenerators before leaving the chimney.

The air and gas on the other hand traverse through two other chambers. After an hour direction of flow is reversed. In this way, when the entering air and gas are being adequately heated in their passage through the heated gratings in the two regenerators, the other two regenerators get heated by the hot gases escaping into the chimney.

The voltage between steel and electrodes may be 40-145 volts: the longer the arc, higher the voltage required and the less the input of heat to the furnace. Electric power is supplied in bulk in the form of three phase alternating current at 6.6 or 10 kv. A transformer set up close to the furnace reduces the voltage down to that required for the arcs and its primary winding having tapings to allow for adjustments to the arc voltage. As the power supply is a three phase circuit, three electrodes are arranged in an equilateral triangle over the metal. Owing to low voltage required by the arc the current must be very high to obtain the desired output.

The hearth of an electric furnace may have acid and basic lining depending upon the process adopted. Basic process is used for making steel ingots and some castings while the acid process mostly for making steel casting.

The usual size of this furnace is between 5 to 10 tonnes through 50 and 100 tonnes furnaces have been produced. This type of furnace is used for making alloy steels such as stainless, high speed steel etc.

LD Process

This process originated in 1953 at Linz steel works in Austria. In India it is being used in the Hindustan steel plant at Rourkela (Orissa). It combines the high productivity of the acid bessemer process and the superior quality of the basic open hearth steel.

The furnace is a vessel similar to that of the Bessemer converter except that the capacity is between 30 to 40 tonnes (double that of bessemer) and there is no detachable bottom with its row of tuyers bricks. The vessel has a basic lining.

In this process a jet of pure oxygen (99%) is blown at a pressure of 7.0 to 10.5 bar and at a speed even greater than the sound to the molten bath of hot metal. The temperature thus produced is about 2550°C due to which the impurities like carbon, nitrogen, phosphorus and sulphur etc., are burnt.

Kaldo Process

Kaldo process was introduced by professor killing. The fundamental departure from the LD process is the rotation of the bath during oxygen injection whereby slag metal contact and reactions are affected.

In the Kaldo rotary oxygen process conversion of Pig iron into steel is carried out into a rotating converter into which oxygen is introduced through a central opening at one end, which simultaneously acts as outlet for the exhaust gases. The speed of the rotation can be varied upto 30 r.p.m. which is most suitable speed for main stage of the process. The furnace or converter is lined with ordinary tarred dolomite and has a life of 50 heats.

Principles of Steelmaking

Introduction

Steelmaking is a refining or a oxidation process with the exception of reducing conditions being specifically required to eliminate sulphur. The necessity to refine pig iron arises because it is quite improve.

Steelmaking can also be viewed as an attempt to rectify the inevitable mistake made by the iron producer earlier by producing such an impure material. Being an oxidation process steelmaking needs a source of oxidising agent. The obvious choice being the oxygen in the form of atmospheric air and/or iron oxide in the form of iron ore and mill scale (oxide produced during hot working of steels

Similarly in a basic process the slag contains excess basic oxide and the furnace lining should be basic in nature. If the lining is of opposite chemical character slag will readily react with the lining and cause damage to the furnace.

Carbon Reaction

The carbon oxygen reaction plays a dominant role in steelmaking.

The activity of carbon in liquid iron-carbon alloys shows a negative deviation from ideality. The presence of carbide forming elements like Nb, V, Cr, W, Mo, etc. decrease whereas the presence of non-carbide formers like Cu, Ni, Co etc.

Phosphorus Reaction

Although the boiling point of phosphorus is very low a considerable amount of it still remains dissolved in liquid iron because of its strong interaction with iron. It is experimentally difficult to determine the interaction parameters of phosphorus with other solutes and thus only a few of these values are known.

For effective removal of phosphorus basic steelmaking processes have to employ slags of high basicities. If the basicity falls, phosphorus may soon revert back to the metal phase. (In acid steelmaking processes since the slag is nearly saturated with silica phosphorus can not be eliminated at all.

Silicon Reaction

Silicon content decides the grade of pig iron. It strongly interacts with iron to produce appreciable negative deviation from ideality. The activity coefficient in the presence of other elements is given by:

$$\begin{aligned} \log f_{\text{Si}} &= 0.18 [\%C] + 0.11 [\%P] + 0.11 [\%Si] + 0.058 [\%Al] \\ &= 0.056 [\%S] + 0.025 [\%V] + 0.014 [\%Cu] \\ &\quad + 0.005 [\%Ni] + 0.002 [\%Mn] - 0.0023 [\%Co] \\ &\quad - 0.23 [\%O] \end{aligned}$$

Activity of silica in slags of interest in steelmaking are known to a large extent. Silica is invariably present in refining slags and as such is a very important factor in determining its basicity. Silica is a very stable oxide and hence once silicon is oxidised to silica the danger of its reversion does not usually arise in refining slags.

Kinetics of Refining

The partitioning of solute elements during refining of molten pig iron takes place at the slag metal and gas-metal interfaces. The structure of the interface is broadly described as:

Apparent activation energies upto 10-15 Kcal/g mole is a strong indication of metal boundary diffusion being the slowest step and in the range of 10-60 kcal/g mole is a strong indication of slag boundary diffusion being the slowest step in the overall steelmaking reactions. The apparent activation energy for chemically controlled processes is also in the range of 10 to 60 Kcal/g mole. Both the diffusion as well as chemically controlled processes improve their rates with rise in temperature. The two however can be differentiated by stirring the phases.

Reactions at Slag-Metal Interface

In practice vigorous stirring is caused on Bessemer process by bottom blowing, in an open hearth and in an electric furnace by the carbon boil in Kaldo process by rotation of the vessel and, in LD and Rotor processes by the supersonic oxygen jet, stirring reduces the thickness of the slag-metal boundary and increases the interfacial area. In addition every attempt is made to keep the slag as fluid as possible by either raising the temperature of the furnace and/or by adding suitable fluxes to hasten mass transport in the slag phase.

Carbon Reaction

The decarburisation rate is controlled by the rates of diffusion of either carbon or oxygen to the gas metal interface. In the bottom blown Bessemer converters a continuous series of fresh air bubbles pass through the melt. It results in increasing the total area of gas metal interface enormously. The turbulence caused by the bottom blowing also favours mass transport. The net result is that decarburisation rates upto 10% per hour are observed in practice. In the basic oxygen furnace processes the formation of slag gas metal emulsion helps in providing an ever fresh gas metal interface and thereby decarburisation rates closer to those in Bessemer process are obtained. The carbon reaction is however very slow in a hearth process

wherein no gaseous refining medium is used.

Thermal Efficiency of Steelmaking Processes

During steelmaking the impurities are oxidised to their respective oxides as in all of which are exothermic reactions. Similarly the dissolution of oxides in each other in the formation of a slag are also exothermic processes. The actual amount of heat liberated during refining will have to be found out in relation to the compositions of the bath and the slag,

Conventional Open Hearth Process

Cold charge in an open hearth furnace needs to be melted using external fuel. The use of hot metal in the charge minimises the fuel requirements to the extent of heat required for melting and superheating the cold iron or steel scrap. But once the charge is molten what factors prevent it from becoming an autogeneous process like the Bessemer process?

Mechanism of Deoxidation

The deoxidation process is a very complex one. It can broadly be described in the form of four consecutive steps.

- (1) Dissolution and homogenization of the deoxidiser in the steel melt so as to make the deoxidation reaction move in the direction of oxide formation.
- (2) Formation of critical nuclei of the deoxidation product in a homogeneous medium since it involves formation of a new phase.
- (3) Progress of deoxidation resulting in growth of the reaction products.
- (4) Separation of the product of the deoxidation reaction by way of their flotation from the steel melt to improve cleanliness.

Deoxidation Practice

At the end of refining steel bath can be deoxidised either inside the furnace or while being tapped in a ladle. In the former case it is called furnace deoxidation and in the latter case it is called ladle deoxidation. A small part of the total deoxidation may be carried out in the ingot moulds if fine grained steel is to be produced or if earlier deoxidation has not been adequate. The extent of deoxidation carried out each of the possible stages is governed by the nature of the process and the end product required.

Control of Refining

From a given mix of charge of scrap and iron a given steel is to be produced by refining the charge to the desired chemical specifications. The refining process has to be properly controlled to achieve this within shortest possible time and with minimum consumption of reagents and additions. In general in slow processes like hearth processes there is little more time available to assess the state of the refining during refining.

Carbon reaction is therefore the crux of refining. In all processes decarburisation rates as affected by various parameters of steelmaking have been and are being established to whatever extent possible to establish the kinetics of decarburisation. This information is fully made use of in the development of refining control strategies.

Modern Steelmaking

- (1) Steelmaking involves removal of impurities as their respective oxides (except sulphur which is reduced).
- (2) The oxides are eliminated either as gas (carbon as carbon monoxide) or as liquid oxide product of suitable chemical character known as slag.
- (3) Steel can be produced efficiently only if refining is adequate right quality slag is made and clean slag and metal separation is brought about.
- (4) Except sulphur, all the rest (carbon, silicon, manganese, phosphorus) are removed through oxidation process and are favoured under oxidizing conditions of steelmaking.

Modern Steelmaking-History

(1) Modern steelmaking is supposed to have begun with the advent of the Bessemer process of steelmaking in the 1860s in the UK.

(2) This was followed by open hearth processes, but its productivity could not exceed beyond 35 tons/hour as against that of 500 tons/hour from LD, OBM or hybrid processes.

Modern Steelmaking-Bofild Steel Making

(1) In an LD refining is complete in about 20-25 minutes of oxygen blowing and a tap to tap time of 40 to 60 minutes is needed.

(2) The oxidizing conditions in LD are not conducive to desulphurisation, external desulphurisation of molten iron in transfer ladles is the answer. Major steel plants around the world have adopted this process to achieve a sulphur level below 0.001%.

(3) Use of multihole lances (4 to 7 hole lances) in larger converters has cut down blowing time, improved the yield and increased lining life.

Modern Steelmaking-Induction Furnace Steelmaking

(1) For steelmaking, medium and high frequency induction furnaces are universally adopted.

(2) It is essentially a process of melting and hardly any refining take place, a process wherein what goes in must come out.

(3) Thin layer of dry slag (works as insulating cover) does not take part in refining.

(4) Limited holding capacity and inability to control the composition of the melt except through careful selection of scrap appear as the chief draw backs of the induction furnace from metallurgical and commercial view points.

(5) In spite of inherent inadequacies as a melting unit for making quality steel, growth in mild steel capacity through induction furnace melting in India has been a phenomenal 26% in 2005-06 over 2004-05 as against 7% through EAF melting. During 2006-07 mini steel plants contributed 25.20 million tonnes out of a total of 50.85 million tonnes produced in India. EAFS share was 9.8 million tons. The rest of 15.40 million tons being from induction furnace.

Open Hearth Shop

The basic open hearth practice using hot metal charge is most popularly adopted in commercial practice. The Dulpex practice and the acid open hearth practice are relatively less common. Furnaces with hot metal practice, is described below.

In general such as shop may have anything upto 12 furnaces located lengthwise in a row. The main columns supporting the roof of the shop shed and the overhead cranes are located between every two consecutive furnaces. The stripper yard may be located in a separate building parallel to the furnace bay or at the end of the pitside bay. The calcining plant is suitably located. The ladle lining pit, oil storage tanks, hot-top storage, tartank, laboratories, Ferro-alloy storage and its weighing equipments, etc. may also be suitably located. A typical vertical section of the shop is shown.

Several overhead cranes are provided in the shop, i.e. in the furnace bay, pitside, stock yard, mould yard, etc. most of which run in the direction parallel to the furnace line.

Reaction Chamber

The furnace is referred to as a stationary furnace if the reaction chamber is fixed (or stationery) and as a tilting or rocking furnace if this chamber is capable of movements.

The details of the tilting furnace will be described in the present discussion is confined to fixed furnaces only. The stationary furnace chamber is mounted on rigid and massive concrete foundation and 1-beams as shown. The chamber is rigidly connected with other parts of the furnace.

(i) Hearth: This is a steel Pan made from 15-30 mm thick steel plate, rectangular in shape with the length about twice as much as the width. At each end of the Pan chill boxes are provided to facilitate cooling of

these parts. The Pan is lined from inside with a layer of insulating or fire-bricks and then at least three layers of acid or basic bricks as the case may be, to approximately shape the hearth contour such that it is sloping from all sides towards the tap hole located in the centre of the back wall. For the same capacity the size of the bath increases with increasing shallowness of the bath and it results in increased refractory consumption. For a given capacity, the length, the width and the depth are chosen in such a way that the flame should cross over the bath in less than 2 seconds since its temperature falls at the rate of about 200°C/seconds while flowing over the bath.

(ii) Walls: The strength and rigidity of the furnace super-structure should be adequate. The walls are; therefore, heavily, braced with vertical heavy steel sections (bulk strays) and are tied across the roof by tie beams to take up the stresses of expansion of the chamber on heating. The front wall of the furnace is vertical and the back wall, at least in the low or part is inclined to gradually make it a part of the hearth banks.

(iii) Roof: The roof is a most vulnerable part of an open hearth furnace and it decides the life of a furnace since it cannot be repaired readily during the campaign while the rest of the parts could be. A proper design of the roof and choice of refractory is bound to improve life of the roof, and there by the furnace availability, for the Production of steel

The usual rise of one in eight in silica roof can thus be increased up to one in four in the case of basic roofs. A basic furnace with a basic roof can be operated at much higher roof temperatures.

(iv) Ports: These are the openings through which the air and the gaseous fuel enter the furnace chamber. The earlier open hearth furnaces used gaseous fuels only and hence had independent ports for air and fuel. Many of the modern open hearth furnaces are fired with oil alone and hence have only the airport through which the oil burner is inserted in.

Gas and air UPTAKES (DOWNTAKES)

These are the vertical passages connecting the ports to the regenerators. These alternately act as a uptake (to carry fuel and air up) and a down takes (to carry furnace exhaust gases down). These are designed in relation to the design of the port. Twin air uptake is required to match twin airport. They should be so designed that no pressure drop occurs during the passage of the gases through them.

These are a silica brick construction but for fast driven furnaces a basic brick construction with a backing layer of fire bricks is recommended.

SLAG POCKET

The slag is removed from the Pocket in solid state. The use of even explosives have been recommended. If needed, to break the accumulated slag. This is a silica brick construction but for faster driven basic furnaces basic bricks are also being used. The slag pocket is connected to the regenerator by what is known as a fantail flue.

GAS AND AIR CHECKERS

Sensible heat of the furnace gases is stored in the checkers of a heat regenerator. There are two regenerators, One on each side, to preheat air blast and a similar pair to pre-heat gaseous fuel. The furnace is fired alternately from each end. The checkers on the same side of the furnace Preheat the air and the gaseous fuel and those on the otherside store sensible heat of the exhaust gases every 20-25 minutes it is reversed.

TILTING OPEN HEARTH FURNACE

Tilting open hearth furnace was used for steel making for the first time in UK in 1902. Tilting furnaces differ from the fixed furnaces in the design of the reaction chamber and Ports. The massive concrete and steel structure of the foundation is replaced by rollers or rockers on which the furnace is able to rotate. The details are shown in. A tiling furnace rotates concentrically with the furnace ports where as rocking furnace rotates escentrically to the ports. The gas need not, therefore, be put off to tilt atilting furnace.

FURNACE INSTRUMENTATION AND CONTROL

Open hearth furnace should always be operated for obtaining a maximum rate of production at a minimum of overall cost of production. This is achieved in the design by presuming a certain set of operating conditions of the furnace using a certain type of raw materials.

THERMAL EFFICIENCY OF THE PROCESS

The average temperature being around 15500-15800C which is called the critical temperature of the furnace. Since the maximum exist gas temperature is dictated by the refractories that are, the minimum level shall be decided by the time of the reversal so as to obtain the desired level of critical temperature. If the cycle is prolonged the critical temperature decrease and if the reversal is quick the critical temperature increases. A optimum cycle of reversion is fixed for a furnace depending upon its use.

It has been found to vary from 15-20% to 70-75%. The smaller is the checker system and higher is the percentage cold air leakage in the system, the lower is the efficiency. The efficiency value can be increased by designing a big enough checker system and sealing the furnace tightly to keep the cold air leakage to be low 5%.

During refining carbon oxidises to Co which can further be oxidised with oxygen supplied in the form of an additional preheated air or cold oxygen. The heat so produced is nearly all useful energy (released above the critical temperature). Even if cold air leakage is directed to the slag surface about 55% of the Co to CO₂ reaction heat is available inside the chamber.

OXYGEN LANCING PRACTICE

Study of plant and laboratory investigations have clearly indicated that the rate of supply of oxygen is apparently the rate determining step in the oxidation reactions in all steel making processes. The oxygen requirement of the bath in a basic open hearth is determined by the quantity of hot metal or pigs in the charge for a typical 60/40 charge hot metal practice, about 60kg of oxygen is required to refine a tonne of charge and additional 303-400kg of oxygen is required for combustion of fuel.

WATER COOLED LANCE

The arrangement is found quite satisfactory and can be installed on existing furnace without much of alterations in the roof structure. Usually two or three lances are used and are evenly located on the long axis of the furnace roof as the arrangement does not interfere with any other usual movements in the shop. The position, condition and operation of the oxygen jet can be observed through an open door from a safe proximity on the floor. The lance is raised and lowered by an electrically operated winch and, the movement and oxygen flow rate are controlled from the furnace control cabin.

The safety arrangements usually provided for lances in LD, Kaldo and similar processes are provided for the open hearth lances as well. A water cooled box or a refractory ring is fitted in the roof to allow in certain of the lance in the furnace.

As the lance is progressively lowered the amount of splashing increases until a point and then decreases to a point of least splashing when the tip is just below the slag surface. This is the correct position of the lance. It usually supplies oxygen at the rate of 12-15 m³/minute to keep fuming and splashing of slag to a minimum excessive fuming tends to clog to checkers and excessive splashing of oxidising slag causes the roof and the walls to wear rapidly. Some of the furnaces do blow oxygen at the rate of as high as 40m³/min. It has not been possible to design a lance to blow more than 50m³ per minute without the splash becoming a serious problem.

MODERN STEEL MAKING TECHNOLOGY

Introduction

World crude steel production in 1979 and 1995 was almost similar with 750 million tons. During this period world steel consumption increased by about 60 million tons, which became possible due to the fact that the ratio of continuously cast steel with its higher yield of finished products increased from 20 to 73%. Also the

substitution of the open hearth steelmaking by oxygen steelmaking or electric arc furnaces resulted in an economical improvement. Thus the increase in efficiency of steel production has enabled world demand for more steel to be met without having to increase the amount of steel produced.

But it is not only the economy of steel making which has improved in recent years, the requirements on steel products have also increased steadily. These requirements include higher strength in order to reduce the weight of a construction, better toughness to allow for its safe application particularly at subzero temperatures, better cold formability and surface quality especially for the automotive industry and better weldability allowing for more economic high heat input welding processing. Furthermore, steel users demand reproducible properties from batch to batch, since further processing of steel products is carried out predominantly in automated processes. In order to guarantee such demands major changes in steelmaking technology have been necessary in addition to improvements in rolling mill technology.

Analytical Requirements

A term often used is "cleansteel", which originally described a steel product with a low level of oxide and sulfide inclusions. The term now also relates to demands to low levels of Phosphorus, hydrogen, nitrogen, and sometimes even carbon. The table below shows some of the lowest levels, which are actually demanded in certain specifications or internal standards.

By consequent use of available processes, the production of clean steel exhibiting max. 60 PPM miles the sum of all the above mentioned elements is possible.

Besides limitations in these metalloids there are often internal standards, which require low levels of metallic elements, e.g of those elements, which may have a negative influence on the surface quality of steel. One example is a company, which limits the sum of the elements Cu+Cr+Ni+Sn to max. 0.07% in about 50% of their production.

Desulfurization and Sulfide Shape Control

In order to remove sulfur from the liquid metal. It is necessary to use a sulfide-forming agent such as a calcium compound. The sulfide-forming reaction is promoted in a reducing atmosphere, therefore, it is most economical to desulphurize already the pig iron. The most important agent used to be calcium carbide with additives, owing to its favorable costs. But a better desulphurization ratio is achieved by using agents based on magnesium and the joint injection of both elements results in the most economic process as with modern practice the pig iron charged to the converter has typically a sulfur content below 0.010%.

Owing to the high oxidation potential any desulfurization during the oxygen steelmaking process is rather low. When starting with a very low sulphur content in the pig iron, an increases in sulfur can be observed deriving from the scrap. Typically the sulfur content after tapping is also around 0.010% and a further lowering is made via ladle metallurgy.

HOMOGENIZATION

The described standard technology of slag free taping, the use of an active slag and inert gas bubbling in the ladle also improve the cleanliness of the steel with regard to oxide inclusions. Furthermore, this technology also allows a high recovery of the alloying elements when they are added after deoxidation, a homogenization of the melt and the possibility of fine tuning the chemical composition at a later stage of secondary steel making. Therefore, tight chemical composition control from heat to heat is obtained.

Summarizes the various possibilities of secondary steelmaking by a schematic model reactor for multifunctional steel refining.

Vaccum Treatment

In a low pressure environment, all chemical reactions resulting in a gaseous product are enhanced. Such a vaccum treatment can for example be combined with the other options of secondary steelmaking in a tank degasser, as indicated already in addition to the above discussed improvements, the low pressure causes a remarkable reduction in hydrogen and also the nitrogen content.

Besides the low pressure, the amount of stirring gas in the treatment vessel also favors the degassing process. That a low hydrogen level below PPM is obtained almost independently of the hydrogen level before the vacuum treatment. But this is different for nitrogen. Where, besides the initial nitrogen content elements with high activity to nitrogen such as titanium or aluminum influence the final result.

This is not the only way to achieve low carbon contents. A number of companies rely on oxygen blowing into the RH degassing vessel which reduces the reaction time and allows the effective treatment of steel with initially higher carbon levels, thus reducing the heat losses during the vacuum treatment.

CONTINUOUS CASTING

In order to avoid nozzle clogging by solid alumina particles which are the most important deoxidation product. Low sulfur steels are often treated with calcium, which promotes the of CaO-Al₂O₃ inclusions being liquid at the steel casting temperature. Furthermore in the processing steps following secondary steelmaking, major care is taken to further reduce the oxide inclusions.

There is also a tendency to improve the tundish metallurgy further with the objective of more complete removal of inclusions. Dams, filters or porous plugs are helpful tools in this regard.

The submerged entry nozzle to the mould is constructed to allow an upflow of inclusions followed by their absorption in the mould powder. Major care has to be taken in the mould not to contaminate the steel by exogenous inclusions originated by inadequate casting conditions.

Modern Open Hearth Practice

BOH furnace capacity steadily increased from a mere stone in 1890 to a more popular size of 200-250 tonnes by the end of the second world war. Several of the furnaces have now each 400-600 tonnes capacity. Even 800 tonne capacity furnaces were designed in USSR by 1955 but were not constructed because it was realized that even the most modern design of BOH could not compete with the newly developed a LD process of steelmaking in terms of capital and operational costs. The existing BOH shops however had to be modified to successfully compete with the new and fast BOF processes.

The BOH process, therefore, particularly in the last 4-5 decades has, developed considerably to decrease its tap to tap time from earlier 16-20 to 8-12 hours. Some of the more efficient furnaces have attained even much less tap to tap time than this.

Materials Handling

Many of the shops have modified their transport system to a little more than adequate to avoid or minimize any unforeseen delay. The following example illustrates the problem.

The same is true with other material handling facilities. The problem is more acute in old shops wherein the usual tap-to-tap time is 12-16 hours. Similarly the production rate can be improved by improving the operation of general repairs to decrease the down-time and increase furnace availability. Furnace availability has been improved to 92-93% in some of the most mechanised and modern shops as against the usual figure of around 70-85% in old shops.

REFRACTORIES

A heavy scale wash is given to the sub-hearth to close all the cracks and joints in the brick work. The entire layer of 250-300mm thick magnesite is then laid on the brick work and fritted into a monolithic mass only the top 100-150 mm thick layer gets fritted well. The remaining gets fritted during actual steelmaking. The time consumed in making such a working hearth is less than 10 hours for a 500 tonne furnace. The grain size of magnesite is 0-2 mm. This operation is readily accomplished in a furnace with a basic roof since hearth surface temperature of 1680-1720°C is reached. Such a hearth is fettled with 0-1 mm size magnesite fines.

The net effect has been that the furnace campaign is no longer limited by the roof life but by the wear on other parts of the furnace, filling of slag pocket, and so on. Since combustion practice affects refractory performance, the problem is being controlled by using waste-gas analysers for oxygen for combustion

control.

The initial applications of roof lances were on furnaces with a silica roof. The time saved in accelerating the refining however was generally lost in additional repairs required due to severe corroding action of fumes and splash generated by lancing as a result basic roof and end walls were adopted as a matter of routine practice for adopting roof lances.

FASTER WORKING

The production rate of an open hearth shop can be increased by increasing the rate of working of the furnace, faster melting by way of increased rate of heat input in the furnace.

In an open hearth, heat available below 1600°C can be used for melting the cold charges in the early part of the heat (at a severe penalty in heating rates). Heat available below 700°C cannot even be recovered in the regenerators. It, therefore, hardly needs to emphasise the importance of high flame temperatures in an open hearth. Roof lances have also been used as an additional oxy-fuel burner to assist melting. The lance is invariably a multi-nozzle lance to increase effective area of heating. It is however yet to be conclusively proved that this method is better than supplying the fuel and oxygen through the ports. In any case it may only be useful if scrap proportion is very high in the charge.

In either of the above cases if the lance is used to accelerate melting, the same lance is later on used to blow oxygen for decarburisation of the bath. The number and locations of the lances should be decided in the modified design from the point of view of their dual use.

Light and bulky scrap take longer time for charging than heavy scrap. A heavy piece may get melted on the surface leaving the core still solid and the heat transfer to the core is slow. A suitable combination of heavy, medium and light scrap in proper proportion is made by an experienced steelmaker. Heavy scrap, pieces are charged at the top above the light scrap, so that the liquid steel drips down and heat transfer to the core is hastened.

REFINING

In the modified open hearth hot metal practices oxygen lancing is commenced immediately after the charging of the hot metal without waiting for the scrap to entirely melt giving a proper meltout.

As the lance is progressively lowered the amount of splashing increases until a point and then decreases to a point of least splashing when the tip is just below the slag surface.

The flushing should be over before the carbon monoxide formation is vigorous or else high basicity also would be flushed out which is not desirable. The composition of the flushed slag is already shown in earlier section.

If oxygen is not available at the required pressure of 5-6 atmosphere spraying of low pressure oxygen on the slag surface is also quite beneficial during refining. It increases the supply of oxygen to the slag is eliminating the nitrogen blanket on the slag which hinders the oxygen flow in a conventional practice. The spraying of oxygen can burn evolved during the boil to CO₂ and keep the process nearly autogeneous during refining.

In small furnaces oxygen lancing is carried out at low pressure only. There are not much of fumes and hence no gas cleaning is necessary. Oxygen fed through the roof lance is also being used to accelerate combustion in the flame. Usually two (or two pairs) are used, only at each end and, one is used, at a time from that end from which fuel and air are being admitted in.

Refining is controlled by the control of decarburization reaction and the carbon-oxygen relationship in a BOH heat. It shows that the furnaces operates away from C-O equilibrium and hence the bath will have to over oxidized to obtain the required carbon at the end of refining. On the whole the evolution of impurities during the total heat time charging melting and refining times are shown in. It clearly shows that the bath has to be oxidized more to obtain the desired end-carbon.

Blocking

At the end of the refining the oxygen pressure is reduced to decrease the vigour of carbon oxidation and then it is completely stopped to block the heat, if rimming steel is not being made. For blocking the heat lumpy Fe-Mn and/ or Fe-Si are added to the bath. It raises the manganese content of the bath by about 0.2% and silicon content by about 0.50-0.20%. If fuel is on, it is also shut off and a sample is with drawn for analysis.

Deoxidation and Finishing

Once it is found that the carbon analysis is correct the heat may be deoxidized further and alloying additions are made in predetermined lot, if required, to complete the heat. Completion of heat means obtaining correct chemistry and temperature before the heat is ready for tapping.

In a BOH process deoxidation inside the furnace has to be carried out very carefully since phosphorus is likely to revert to the bath if dissolved oxygen level falls to low. Deoxidation inside the furnace can be more safely carried out without the danger of phosphorus reversion if basicity is high (V ratio of) under these conditions a small amount of even oxidisable alloying additions can be made inside the furnace. The bath is usually deoxidized and alloyed further in the ladle during tapping.

Concluding Remarks

Out of the economic and technological necessities the open hearth furnace design and practice are continuously being modified to stand competition from the BOF processes, one of the important asset of an hearth which is otherwise matched only by an electric arc furnace alone, is its ability to consume a much higher proportion of scrap in the charge, even hundred percent scrap if it comes to that. It can also operate on any scrap to hot metal charge ratio. Since the BOF processes are unable to offer these advantages some of the existing open hearth shops will continue to be used for quite sometime to come.

Due credit must be given to the open hearth process since the problems it posed led to the development of basic thermo-chemical principles of steel making and which were equally applicable in general for any process of steelmaking. In way the understanding of BOH process was responsible for the development of superior process of steelmaking using oxygen for refining. But with all this understanding the productivity of basic open hearth type process could not exceed 35t/ hr as against the productivity of almost 500t/ hr from LD and OBM or hybrid processes individual furnace.

BOH Process Products

The BOH produced all varieties of rimming, balanced and killed steels as well as low alloy steels. In the early days the open hearth steels wee characterized by their low nitrogen and hydrogen contents and better cleanliness. The nitrogen averaged 0.004-0.006% as against 0.01-0.18% in Thomas steels. Similarly the hydrogen range was between 4.0-6.0 ppm. The electric furnace steels produced by use of double slag would be nearly double this concentration.

ELECTRIC ARC FURNACE PROCESS

ELECTRIC ARC FURNACE

The furnace proper looks more like a saucepan covered from top with an inverted saucer as shown. The electrodes are inserted through the cover from top. Arc furnaces are of two different designs:-

- (i) The roof along with the electrodes swing clearly off the body to facilitate charging from top.
- (ii) The roof is lifted a little and the furnace body moves to one side clearly off the roof to facilitate charging.

Gears for Furnace Body Movements

The furnace body needs to be tilted nearly through 45° on the tapping side and 15° on the slagging side. The tilting gear is either hydraulic or electrical. In electrical a motor actuates the rear of the furnace as shown. Guide rails are used to ensure true movements. Some locking arrangement is necessary for the horizontal positioning of the furnaces.

Electrode support:- The furnace is provided with a vertical column or mast to which horizontal arms are

attached and the electrode is held by the arm of position. The mast are of two types. In one design the mast is fixed and the electrode are travels up and down the fixed mast. In the other, the mast itself rises and falls: the electrode arm is rigidly attached to the most. The later design is more popular because it allows easy tilting of the furnace.

In general the possibility of parts in the furnace superstructure being heated by eddy currents, induced due to the heavy secondary currents, is minimized by using non-magnetic type of metallic material, i.e, austenitic stainless steels.

Transformer

Large transformers are required to run electric arc furnaces. The primary voltage may be 33 KV more and the secondary with a series of tappings from 60 to 300 volts. Simplified circuit arrangement is shown in during melting more power is required than during refining. The transformer capacity is designed to suit melting requirements. The capacity is therefore, under-utilized during refining. It is economical to have at least two furnaces operating side by side to improve the overall electrical power factor. Since high current densities are involved special circuit breakers are used.

The capacity of the transformer is usually 470-650 KVA per tonne of furnace capacity.

Plain Lay-Out

Layout of an electric arc furnace steelmaking shop varies considerably from plant to plant. The difference is essentially due to the difference in the quality of the product and the scale of production. Several plants have just one are furnace. Some may have two, but shops with more than two furnaces are, definitely uncommon. The variation is also due to whether the shop is provided with oxygen lancing facilities, gas cleaning equipments, a vacuum treatment unit, continuous casting unit and so on. The shop design to produce finished castings is different from the one meant to produce ingots.

Modern Electric Arc Furnace

The factors like small size of the furnace and the high cost of electric power restricted the use of electric arc furnaces for the production of only the costly alloy steels until recently. The cost pattern of electric power vis-a-vis chemical fuels has steadily used in favour of the former because the cost of chemical fuels has gone up considerably whereas that of electricity has in fact, if at all, decreased a little coupled with this favorable factor were the advances in general and more specially in electrical engineering aspects of design and construction of electric arc furnaces that steadily led to bigger and bigger furnaces for use in practice.

Prospects of DRI-EAF Combination

A sponge iron and electric arc Furnace combination for producing steel is estimated to be 30-40% cheaper than an equivalent blast furnace and oxygen steel making combination in the lower range of steel Production capacity. such a plant as shown in 1.5 million tonnes capacity has been in operation. Several such plants have been or are being set up in India recently and they contribute a substantial Fraction in the overall steel Production. The degree of consistency in terms of metallurgical properties of sponge iron is far better than that of scrap, and hence, extensive automation of arc furnace operation has become readily possible with the use of sponge iron. This was rather difficult earlier because of variable nature of steel scrap.

Modern Arc Furnace Practice

The existing arc furnace plants are being rejuvenated with respect to the above Mentioned innovations to improve upon their economy to the extent possible interms of captial investment required vis-a-vis economic advantages accurable.

A green field arc furnace installation however will have to adopt the modern furnace design, sponge iron charge and Modified practice to obtain desired economy of production even in the case of bulk steels.

The rates of oxidation of Cr, Mn and Fe increases with increase in blowing rate upto nearly 30 NM³/hr and

thereafter it remains nearly constant. The higher is the initial chromium content the more is the final temperature of the bath at the end of refining.

This Method of raising the bath temperature is much more efficient than oxidising the chromium by excess iron oxide as in the Rustless process, because the iron oxide takes part of the exothermic heat of chromium oxidation for its own dissociation. The bath can be decarburised to 0.06%C and whatever chromium is oxidised, is reduced by Fe-Si and / or Cr-Si addition during the reducing Period.

This is almost a universal practice which successfully takes any proportion of stainless steel scrap in the charge and for this reason the demand for this scrap exceeds its supply.

INDUCTION FURNACE

The Modern furnaces use currents of high frequency in excess of 10 KC/sec. upto the level of radio frequency. High frequency furnaces do not require the core type design. Now-a-days even mains frequency furnaces are also being used. For steel melting Medium, and high frequency induction furnaces are universally adopted and hence are only described below. These units use either multi-conductors, Motor generators sets, spark gap converters or oscillators. The output may be at upto several thousands volts and 100 MC/sec. with a total power output of upto 100KW. In general high frequency furnaces are costly but are more efficient in melting than low frequency furnaces.

The furnace is consists of a crucible of usually a magnesite Monolithic construction with a spout for pouring. The charge is placed in this crucible and it acts as the secondary winding.

The process is equally suited to produce any type of alloy steels on a small scale. In fact it is practically the only commercial process for making steels on a small scale. It is commonly used in alloy steel foundries.

The crucible can be enclosed in a vacuum chamber and thereby better quality steels of wide specifications can be produced on a small scale. This is known as vacuum induction melting.

It has been estimated that nearly 60% of the energy input is usefully used in an induction furnace as against 65-70% in an arc furnace. The power consumption varies from 900 kwh/t for a 0.5t furnace to 650 Kwh/t for a 5 to furnace. Although it is costlier than an arc furnace its flexibility to produce different steels in small lot is unsurpassed even by an arc furnace and that is why it still stands competition from an arc furnace.

ARC FURNACE PRACTICE FOR CARBON AND LOW ALLOY INGOT STEELS

The Proportion should be such that charging is over in the beginning itself. If this is not possible Minimum of back charging is adopted. The power and the electrode consumption are maximum during melting and hence this period should be bare Minimum. Many operators prefer to charge lime and ore only after 2/3rd of the charge is Molten. Other add it Party with the charge and the remainder later. The lime consumption varies from 3-5% of the charge weight. The lime addition should not be delayed other wise the acidic impurities may attack the lining.

During oxidising refining impurities such as P, Si, Ca, Mn are oxidised. Any oxidisable alloying elements in the scrap are also lost to the slag. Initially the temperature of the bath is low and dephosphorisation is possible even by a low basicity slag. As the refining continues and the bath temperatures rises, iron oxide content of the slag decreases (supply of oxygen is limited) and sufficient lime is added to retain Phosphorus in the slag.

ARC FURNACE PRACTICE FOR CARBON AND LOW-ALLOY STEELS FOR CASTING

Use of acid lined arc furnaces is popular for steel foundries. The acid lining is better for intermittent operation of the furnace than basic lining. Acid furnace is cheaper to construct and operate than basic furnace. The only limitation being that good quality scrap, low in Phosphorus and sulphur contents, is required as a charge in an acid furnace.

Conventional Arc Furnace Practice of Stainless Steel making

By 1931 a process was developed wherein carbon was oxidised and whatever chromium oxidised

concurrently was later on reduced back to the Metal phase. The process soon came to be known as the Rustless process which is still being used when oxygen gas is not available for refining. The furnace bottom and side walls to a height just above the slag line were made of chrome bricks to withstand the chemical action of super heated iron oxide rich slags. Chrome are used for fettling the walls soon become a major source of chromium.

Typically the charge consisted of such ingredients that one third of the specification chromium was obtained from high carbon ferro-chrome, one third from chrome ore and the remaining one third from the stainless steel scrap. Chrome ore is evenly charged on the bottom and along the banks. Light scrap is charged first on the charge-chrome ore and then the heavy scrap followed by iron ore, anything upto 15-25% of the heat weight. High carbon Fe-Cr is charged above the iron ore followed by a little of light scrap. The reason for adding a large excess of iron are will be clear from the following:-

In basic slags the activity of silica is very low and hence the chromium distribution is favoured in the direction of the Metal bath. Kinetically chromium transfer across slag Metal interface is quite rapid and hence much of the chromium from the slag is reduced back to the metal phase. Fe-si addition is very effective in case of basic slags. In acid slags it has hardly any effect and hence a stranger deoxidiser, like AL is used when slag is acidic in Nature.

In Practice it is aimed at obtaining the desired carbon content of the bath by the time the charge is melted down. Rapid melting and liberal iron oxide in the charge are useful in this regard.

This is a very cheap process as compared to the early method of making stainless steel because cheaper sources of chromium are used for obtaining the necessary alloying content.

SCOPE OF THE PROCESS

Electric furnace, both the arc and the induction types are best suited for the production of medium and high alloy steels from any quality of all solid charges. These are the most economical methods of utilizing the alloy steels scrap. In steel foundries electric furnaces are practically the only choice for making varieties of plain carbon or alloy steels in small or large Quantities for founding.

Steelmaking by Basic Oxygen Furnace

Steelmaking by Kaldo Process

The process was developed at the Domnarfvet works of Stora Kopparbergs Bergslags AB. swedon, by a team lead by Prof. B. Kalling and hence the name. Early experiments were tried on a 3t rotany furnace and then on a 15t pilot plant. The largest vessel has 135t capacity. Although the process was originally designed to refine. Thomas grade iron it can refine any quality of basic iron.

Kaldo Plant

In the Kaldo process refining is carried out in a vessel which is similar in shape and about the same size as that of the concentric LD vessel with a solid bottom. It is lined much in the same way as the LD vessel. The vessel is placed in a cradle and is rotated therein, around its long axis, at any desired speed upto a maximum of about 30 rpm during refining. The cradle is mounted on trunions so that the vessel can be tilted in various positions to permit charging, tapping, slagging, etc.

Heat

The hot vessel, containing some slag from the Previous heat, is rotated into vertical position and it receives lime, ore and other fluxing material, scrap is charged after making the vessel nearly horizontal. Scrap is literally poured in the vessel.

Hot Metal is charged immediately after the scrap. The vessel is tilted to blowing angle of 16-20° to the horizontal. The hood is swung in and held firmly against the nose of the vessel. The lance is inserted through the hood at a proper angle. The rate of oxygen supply and the speed of rotation of the vessel are varied during blowing. Blowing commences at oxygen flow rate nearly. Both of them are increased progressively and they attain their respective maximum values in about 5-7 minutes.

At the end of 18-20 minutes of blowing all the solids are completely Molten. The oxygen flow rate is then decreased by nearly 50% and the speed of rotation is reduced to about 10-12 RPM. The lance angle is also decreased. This is a dephosphorisation period. The blow is stopped after nearly 25 minutes of blowing and the Phosphoric slag is removed as completely as possible.

PROCESS CONTROL

The process is controlled by varying the speed of rotation of the vessel, the flow rate and pressure of oxygen, and the lance angle.

Rotating the vessel at a very slow speed is good enough to cool down the lining heated by the combustion of co inside the vessel. High speed of rotation is made use of as a major tool to control refining

Steelmaking by Rotor Process

The process was developed at oberhausen in Germany in 1952. A rotary melting furnace was used for early trials where in the burner was replaced by the oxygen lance.

The original idea was just to prerefine the blast furnace metal to subsequently refine it in an open hearth.

The trials however indicated that it could by itself refine the hot metal plus scrap change to finished steel. A 60t rotary furnace was, therefore, designed and installed on the blast furnace casting bed.

OPERATION

Some or all the final slag from the Previous heat is retained for the next heat. The heat commences with hot repairs followed by charging some lime. The vessel is rotated to spread it all over the lining. The remainder of lime, scrap, ore and hot metal are then charged. If scrap Proportion is more it is charged from both ends.

The vessel is moved to blowing position. The lances are inserted and blowing started. Simultaneously the vessel is also rotated. The Primary oxygen flow is nearly constant throughout the blow at about 70-85 m³/min. The secondary lance is put on a little after the Primary is put on and it blows air, enriched air or pure oxygen as per the design. It is also equipped to feed lime powder if required.

Steelmaking by oxygen bottom blowing processes

OBM Process

The relative feed rates of these two fluids are adjusted to obtain optimum temperature at the tuyere tip and there by ensure its reasonable life as well as speed of refining. The deposition of carbon, which is a product of cracking, also helps to product the bottom from heat generated due to the refining reactions at the tips of tuyers.

But even so, these steels end up with high hydrogen contents as compared with Thomas steels. The distinct advantage of this situation is that nearly 50% of the hydrozen burns with dissolved oxygen and there by generates heat.

The tuyere arrangement is such and coupled with the provision by hydrocarbon and oxygen for usual blowing, it can be used for preheating the scrap. The scrap proportion in the charge is thus rendered flexible to run the process with equal ease.

The tuyeres are generally made of stainless steel pipes embedded in magnesite bottom. Longitudinal ribs in the annular part maintain the dimensional accuracy till the end of its useful life. This is essential for consistent operation of the converter during its entire compaign. During blowing the pressure of the protective gas is about 20-50% below that of the oxygen.

Operation of OBM Process

This is described by illustrating the process at sulzbach rosen berd plant of maximillianshuttle iron and steel co. The shop previously had 6x25 tonne Thomas converters and produce 0.7 million tonne of steel per annum. These were converted to 6x30 tonne OBM vessels and produced 1.0 million tonne of steel per annum. The bottom life of 50 heats in Thomas increased to 200 heats in OBM.

Future Prospects of OBM

None of the secondary refining techniques permit simultaneous desulphurization and dephosphorisation. In

bottom blown converter desulphurisation under oxidizing conditions can be achieved by obtaining highly dispersed slag with a high lime content by the injection of lime powder with argon. In the after blow period of about a minute nearly 90% dephosphorisation and 50% desulphurisation has thus been achieved. For example by injecting 20kg lime/t of steel the sulphur was reduced from 0.032 to 0.018% and phosphorus from 0.010 to 0.001% in about a minute of blowing.

Applicability Under Indian Conditions

Specific trials have been carried out on hot metal with typical composition under Indian conditions (high silicon and phosphorus 0.3%) at the IRSID petrot plant in France using the LW & bottom blown design. The metal temperature was 13300-13500°C. Flux mixture with 70% CaO and 14% CaF₂ was injected from bottom trials where taken with and without intermediate slagging. The results without intermediate deslagging were superior to those for intermediate deslagging. The phosphorus content of around 0.03% for carbon level of 0.3% was achieved.

STEELMAKING BY LD PROCESS

The Charge Materials

The charge consists of molten metals, cold pig iron, steel scrap, lime/limestone, dolomite, Fluorspar, bauxite, iron ore, mill scale, gaseous oxygen, etc.

HOT METAL

The classical LD or the modified LD process, both because of oxygen refining, are often used to make soft steels for flat products. This coupled with general requirements for extra low sulphur specification & has necessitated a constant reduction in sulphur contents of the Final steel products. The adoption of continuous casting also need that the sulphur should be below 0.02% to produce transverse-crack-free product. In special steel plates, the normal sulphur specification is 0.01% and there is demand for extra low sulphur steels with as low as 0.001% (10 ppm) coupled with very low carbon, for example the pipe line steels.

A certain minimum manganese content was considered necessary for hot metal charge in BOH practices. It results in enough manganese in the bath to prevent over oxidation of the bath. In a LD process however, particularly for producing soft steels, the manganese has to be removed to very low level and at times even by adopting slag flushing which unnecessarily Prolongs the blow and reduces the yield. A high manganese in slag also tends to retard dephosphorisation of the bath. Manganese content in the range of 0.5-1.1% are tolerated but 0.7% is considered better.

OXYGEN

It has been observed that nitrogen content of the bath increases with decreasing purity of oxygen. During the decarburisation of bath from 3.0% to nearly 0.12% C, the nitrogen-level remains the same for a given purity of gas. But below 0.12% C the nitrogen level increases if oxygen purity is less than 97%, whereas it decreases if purity is above 99% hence oxygen of 99.5% purity is always desirable to keep nitrogen level of finished steel below 0.0016%. It finally gives nitrogen content below 0.003% in the steel ingots.

OUTPUT

The blowing times in LD vessels are kept nearly the same irrespective of the sizes of the vessels. The tap-to-tap time, therefore, increase with vessel size due to the increased time of charging tapping etc. One of the fastest vessel of 150 t capacity has a tap-to-tap time of just 30 minutes in which lancing time is 16 minutes.

STEELMAKING BY HYBRID PROCESSES

INTRODUCTION

The LD process was developed more from the point of view of thermodynamic advantages of using oxygen for refining. The study of Physics of interaction of oxygen jet with molten metal however revealed the severe limitations of this process in achieving the desired metallurgical results. In spite of impinging the

molten bath with supersonic oxygen jet from top the kinetic energy of the jet does not get converted into a desired effect in stirring the bath. This gives rise to concentration and temperature gradients within the bath and the attendant problems of getting the correct chemistry and temperature at the turndown.

Bottom Gas Purging Design

Being the easiest to fit and operate the bottom gas purging came in operation early. A variety of devices have been developed to introduce inert gas from bottom in an otherwise classical LD vessel and these are shown. These devices are simple and rugged to last for almost the life of the rest of the wall lining of the vessel during refining. They allow to vary the stirring times and its extent by controlling the gas flow. Even in emergency if it fails to operate, the vessel can still be operated in the form of classical LD style to continue steel production. The supporting pressure required to purge gas through them is usually in the range of 2-3 bars only.

Hybrid Blowing Design Considerations

In hybrid processes the top and the bottom blowing have to be so adjusted as to obtain maximum stirring without any adverse effect on the refining reactions and yield. The top and the bottom blowing are designed to obtain optimum conditions of overall blowing.

FUTURE OF HYBRID PROCESSES

It can be said with certainty that the last OBM and classical LD vessels have definitely been built and no one is going to install them in their classical form hereafter, one or the other hybrid process will only be choice for a new Greenfield installations.

Steels could also be produced by catch-carbon technique without any adverse effect on desulphurisation and dephosphorisation. Ferro-alloys consumption reduced by 1kg/ tonne because of lower oxygen potential of the bath. The lime consumption also was decreased because of improved partitioning of phosphorous between slag and metal.

LD KG Process

In order to improve bath agitation in LD the Kawasaki steel corporation developed this process of inert gas purging. The flow rate of gas was very low, 0.02 N-m³/t/ min, Encouraged by the results of preliminary trials they adopted this technology to 3 out of 6, 180t LD converters at its mizushima works and 3 out of 5, 150 t LD converters at its Chiba works.

The new technology has resulted in decrease in oxygen consumption by about 1.7m³/t and increased the yield by about 0.5 to 0.7%. Except manganese other distributions such as of P and S were altered favourably.

LD-HC Process

The original LD-AC, using lime-powder with oxygen blown from top, was converted to combined blowing process at haine utsambre in collaboration with CRM. The vessel was provided with 4-6 bottom tuyeres using CO₂ or natural gas as protective media. The proportion of oxygen blown from the bottom varied from 5 to 43% of the total. It was observed that total blowing rate which was 2.6 Nm³ per min. Per t in original 40t LD vessel increased to 4.0 N-m³ per min. Per t in this LD-HC process.

K-BOP Process

The Kawasaki steel converted one of its 250t BOP vessel into combined blowing with much higher flow rates from the bottom. Oxygen flow rate of 1.5 N-m³ per minute per tonne was employed and lime powder was fed along with oxygen from the bottom as in OBM. The high oxygen flow rate from bottom was required to feed lime flux from the bottom. This combination did not result in spitting even through high flow rate was used from the bottom. The results on the whole were quite encouraging.

Hybrid Process at Tata Steel

Tata steel installed their first LD steel making shop in early 1982 and the second one in 1993 and thereby replaced most of their open hearths, except perhaps two.

As usual their LD blowing strategy was result of consideration of many a variable such as si, mn and p content of the molten iron, the desulphurization aimed at during refining, the final p content at turn down, final mn and c at turndown and soon. With nearly 1.6-2.0% si and more than 1.0% mn in the hot metal, as conditioned by the compulsions of blast furnace operation in those days, early fluid slag formation within 2-3 min of blowing was aimed at.

The frequent earlier slopping came almost to nil in 1996. The lining life increased from around 275 heats in 1984 to over/200 heats now in 1997.

The blow profiles of hybrid process using a six hole lance for hot metal charge above 0.8% Si and that below 0.8% Si are illustrate the way the blowings are carried out and how the lance height is adjusted during the blow. This operation has been found to be much smoother when compared with that using three-hole lance earlier.

Secondary Process of SteelMaking

(A) Tundish Technology

Tundish Technology has developed substantially to improve strand quality and caster productivity of premium steel at a decreased cost.

Argon Bubbling in a Tundish

The inert gas/melt interface that is provided by gas bubbles injected into the steel melt has proved to be a favourable site for Al₂O₃ inclusions to adhere. The adhered inclusions instantly agglomerate into large clusters as revealed in situ by Y in et al. Stirring of the melt by inert gas bubbles also enhances collision and agglomeration of inclusions suspended in the melt. As shown by Okamura et al, the stirring also helps in transferring the inclusions to the bubble melt interfaces and subsequent flotation of the bubbles with the adhered inclusions to the surface of the melt. On the contrary, the Ar injection rate in a tundish needs to be limited to avoid emulsification of tundish slag and re-entrainment of surfaced inclusions near the slag/melt interface.

If small-sized Ar bubbling in a tundish becomes successful in the long run, it will be a promising way to produce ultra-clean steels. To make Ar bubbling and industrially viable technology, the durability of materials for Ar gas injection needs to be improved for long lasting sequence casting.

Also the structure of the injection unit should be simple and easy to exchange for a tundish hot cycle. As mentioned in section 8.2 for an H-shaped tundish, Ar bubbling was utilized for enhancing inclusion removal at the through hole. In plasma heating, it was also used for improving heat transfer in the plasma heating, chamber, where no tundish slag exists and the atmosphere is totally inert. In these cases, slag emulsification and open eye formation do not occur and are not problems. fine argon bubbles on the gas injector are required to minimize the risk of tundish flux entrainment.

Tundish Heaters

Tundish heaters have been developed, as mentioned in to compensate for the temperature drop of steel melt at the start, junctions, and at the end of heats in a sequential casting. The tundish heater minimizes variation of temperature over the entire heat sequence, and serves to reduce the tapping temperature of the Bof or LF. It also makes consistent low super-heat sequential casting possible, which increases equiated crystal fraction in the pool end in strands.

GASES IN STEEL

(A) Oxygen in Steel

The use of de-oxidizers, unless, it forms gaseous product of de-oxidation reaction, tends to decrease cleanliness of steel. Except where cleanliness is of supreme importance (ball bearing steels, die steels, tool steels, air and space craft steel, de-oxidation of liquid steel prior to teeming, in the usual manner, is however adequate to eliminate the deleterious effect of excess dissolved oxygen in steel.

Where cleanliness is of supreme importance and where oxygen is to be reduced to a level lower than that

attainable by normal de-oxidation practice, liquid steel has to be treated under vacuum prior to solidification.

(B) Nitrogen in Steel

Since steel making operation is carried out in furnaces open to atmospheric air a certain amount of nitrogen always finds its way in liquid steel. Nitrogen also comes from the raw materials charged in the furnace and, from the nitrogen that is directly brought in contact with the both along with oxygen during melting and/or refining.

In oxygen steel making processes a high nitrogen absorption can take place in the hot zone, where oxygen jet impinges on the metal, if the jet gas contained nitrogen. The purity of oxygen used is thus very important and it should not be below 99.5% to produce steels with less than 0.002% nitrogen, since these processes are meant to produce deep drawing type dead soft steels.

The amount of nitrogen thus picked up depends directly upon the height of furnace tap hole from the ladle. It also depends upon its own content in steel: the pickup is more if it is already low (e.g. in LD process) and is less if it is already high (e.g. in Bessemer process) LD process showed increase in nitrogen content during tapping as follows:

Rimming steels 0.0005-0.0006% nitrogen

Semi-killed steel 0.0003-0.0010% -do-

Killed steels 0.001-0.0015% -do-

Sulphur content of steel has often been found to be related to its nitrogen level. Low sulphur content is accompanied by high nitrogen content in Bessemer process whereas the reverse is true in case of electric arc process.

(C) Hydrogen in Steel

The solubility of hydrogen in solid iron at its melting point is nearly 10cc/100g. Liquid steel may contain as high as 20cc/100g in high alloy steels made under unfavourable conditions. It constitutes serious problem of hairline cracking in fully killed high alloy steels with large cross sectional area. In rimming steels it causes no problem because it is reduced well below the safe limit by the scavenging action of gases evolved during cooling. The ductility of steel is decreased with increasing hydrogen content and this effect becomes greater the higher is the tensile strength of steel.

DEFECTS AND REMEDIES OF STEEL

Blow Holes

The entrapment of gas evolved during solidification of steel produces cavities known as blow holes in all except killed steels. The blow holes are of two types. The primary blow holes are elongated or like honey comb and are located next to the ingot skin.

The secondary blow holes are more spherical and are located further in a formation of blow holes eliminate partially or fully the pipe and thereby increase the ingot yield during rolling, provided these are located at proper depth from the surface from all sides of the ingot. Deep seated blow holes do not open up and thus do not get oxidized during soaking (due to scaling) and rolling of the ingot. Such blow holes are welded up during rolling and do not leave any mark of theirs in the product. Blow holes that are closer to the surface often get oxidized during soaking or get first punctured and then oxidized during rolling. Oxidized blow holes do not heal up during rolling and leave surface defects (seams) on the product.

Gas evolution during solidification should therefore, be controlled to obtain these blow holes only after an ingot skin of adequate thickness is formed.

Columnar Structure or Ingotism

Steel is a crystalline solid. After the formation of initial chill layer further solidification results in the formation of dendrites which grow along their principal axis perpendicular to the mould walls. Their lateral growth is restricted due to the growth of adjoining dendrites giving rise to elongated crystals. If the length of these is appreciable it is known as columnar structure and in exaggerated form ingotism. Ingots possessing

ingotism tend to crack during rolling unless in the first few passes the reduction in cross-section (draft) is kept low.

Segregation

The initial chill layer of the ingot has practically the same composition as that of the steel poured in the mould i.e., there is no segregation in the chill layer because of very rapid rate of solidification. The progressive solidification there after results in solidification of purer phase (rich in iron) while the remaining liquid gets richer in impurity contents.

A killed ingot cast in wide-end-up mould shows are two types of segregation as shown. The impurity segregation at the top follows the shape of the pipe and is known as V segregation, side by side inverted V or A-shaped segregation is also observed at the top. It may be due to the sinking of purer crystals down and rising up of the impure liquid in the upper part. The impurities get entrapped in impure part at the end of solidification. This is the positive segregation. The negative segregation is confined to the lower central portion of the ingot. In the actual ingot these zones are not as sharp as are shown there are quite diffused.

Non-Metallic Inclusions

The term cleanliness is used to refer relative freedom from the entrapped non metallic particles of solid ingot. In some steels this is the most important criteria in judging their quality. The fact that it is non-metallic and, therefore, incongruent with the metal lattice, has often been considered as prima facie evidence of its undesirability. Inclusions are of two types: -

Indigenous-those arising in the course of steelmaking.

Exogenous-those arising from mechanical erosion of contacting refractory lining.

Indigenous inclusions comprise of de-oxidation products like oxides, oxy-sulphides or precipitates like sulphides, carbides, nitrides etc. Almost all sulphur is precipitated as iron or manganese sulphides. The best way is to keep sulphur as low as possible to avoid formation of inclusions. Oxide inclusions can be kept to a minimum by suitable de-oxidation practice. Enough time is allowed for them to rise to the surface in the ladle. Alternatively, if economically permissible, vacuum treatment may be adopted to decrease the oxygen content of steel. De-oxidation carried out in the furnace also helps to minimize them.

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