

LECTURE NOTES

ON

**Sponge Iron & Ferro Alloys
(4th Semester Metallurgy)**

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Chapter – 1

Review of Sponge Iron Making Process

Historical Development:

Sponge iron was the main source of iron for many centuries before the blast furnace technology of iron making got developed. During that time sponge iron was developed in shallow hearths using charcoal which worked both as reductant and fuel.

Methods of producing low carbon wrought iron directly from the ore are known as direct reduction process. After the development of the blast furnace, the DR processes were nearly abandoned. However after 1980s DR processes find wide acceptance because here the iron ore is reduced at lower temperature using low grade coal. Many mega integrated steel plants in India like Jindal, Bhushan, Essar have adopted this route of steel making.

Reasons For Rapid Growth of DR Process

The main reasons for rapid growth of DR process are –

- 1- Worldwide shortage of metallurgical coal to operate B.F.
- 2- Huge financial resources required for B.F route of iron making.
- 3- B.F takes more times to make iron as compared to DR process.
- 4- Non availability of suitable steel scraps for the Electric Arc Furnace steel making.

Chronological Evolutions of the DRI Processes

Time	Main Method	Main Processes	Remarks
1930-1950s	Saggers in Tunnel Kilns- Small Shaft Furnace- Rotary Kilns-	Hogganas- Wiberg- Krupp & Lurgi-	Coal Based Coal Based Coal Based
1950-1960s	Static Reactors- Fluid bed Reactors- Shaft Furnaces-	HYL-I- Fior- Midrex and HYL-II-	Gas Based Gas Based Gas Based
Recent Processes	Rotary hearth F/C- Improved fluid bed- self-reforming processes-	Fastmet- Inmetco- HYL-III-	Coal Based Gas Based Gas Based

Conventional versus DRI steel making

Molten pig iron is used for steel making in a conventional B/F route. However, the conventional route requires metallurgical grade coke as primary fuel and reductant. The availability of such grade of coal from which metallurgical grade coke can be produced is not plentifully available worldwide. Hence the scarcity of coking coal has demanded the need of developing alternative routes of iron making. Therefore, during the last three decades, considerable attention has been paid to develop the DRI processes. At present the conventional blast furnace route produces about 70% of the world's total steel. However, the limitations of this route is becoming more critical in recent times due to the following reasons

- Huge capital investment requirement
- Non-availability of coking coal
- Higher degree of environmental pollution.

Iron Ore Reserves in India-

It is estimated that India has iron ore deposits of around 23000 million tons. Out of which 85% is hematite and 8% magnetite. Out of the total reserves 43% is in Odisha & Jharkhand and rest 57% is in Chattishgarh, Karnataka, Goa, Andhrapradesh & Maharashtra.

Major Direct Reduction Process –

The direct reduction process is divided into two types-

- 1- Coal based direct reduction process
- 2- Gas based direct reduction process

1- Coal based direct reduction process

The different coal based direct reduction process are

- a) KRUPP-RENN process
- b) KRUPP- CODIR process
- c) SL/RN process
- d) ACCAR process
- e) TDR Technology
- f) OSIL Technology
- g) POPURRI Engineering
- h) INMETCO Rotary Hearth
- i) JINDAL Technology
- j) SALEM Direct Reduction process

2- Gas based direct reduction process

The different processes are

- a) MIDREX process
- b) FLUIDISED BED process
- c) FIOR process
- d) HIB process
- e) HYL process
- f) FASTMET Technology
- g) FASTMELT Technology
- h) IT mark 3 process
- i) Rotary Hearth Furnace Technology

Direct Reduction of Iron Ore-

The term direct reduction of iron ore originates from the fact that the iron oxide (Fe_2O_3) is directly reduced by the reductant. The percentage of oxygen associated with iron ore as oxide removed from the particle is known as percentage reduction whereas the percent of iron as part of whole iron existing as metallic iron is called as degree of metallization in sponge iron technology.

Sponge Iron Making Process(Coal Based)

Krupp-Renn Process :

The Krupp-Renn process was developed in 1930. In this process high silica ore and lime stone is treated. In this process a mixture of -6.4mm ore and reducing agent like coke breeze or bituminous coal fines are fed into rotary kiln continuously. The temperature of the rotary kiln is kept in the range of 1230-1260°C. At this temperature the gangue materials of the ore is converted to very high silica viscous sludge and also it helps in coalescence of the reduced iron ore particles. The reduced iron particles embedded in the viscous sludge into nodules called **luppen**.

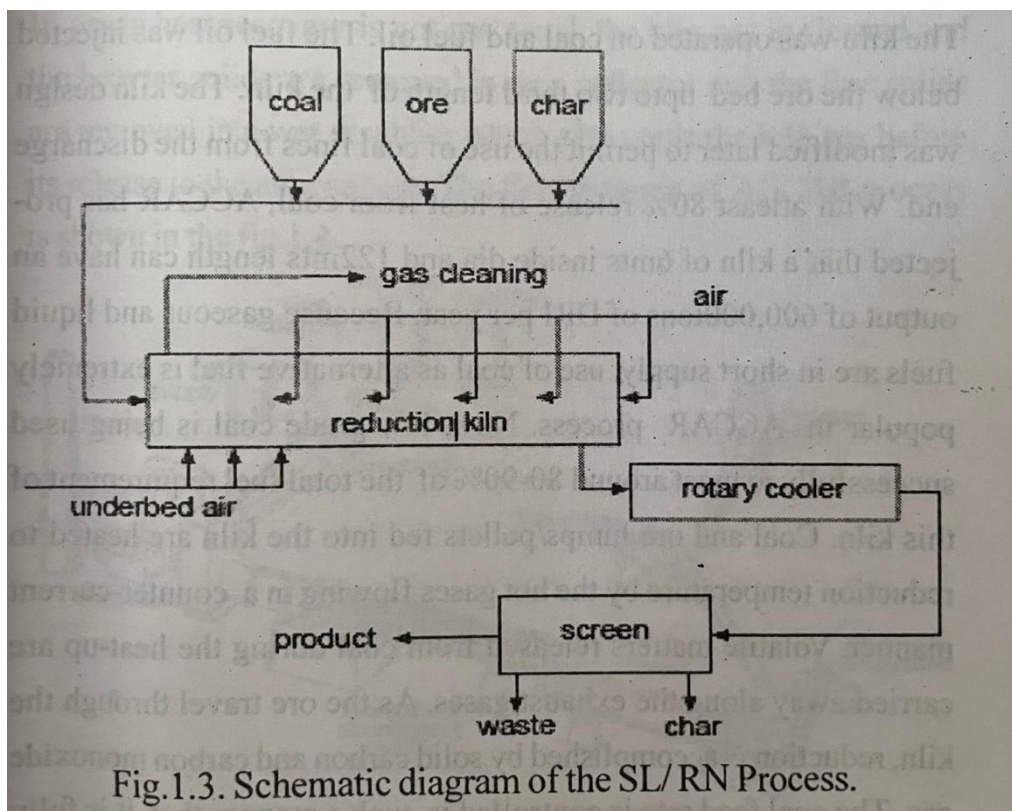
The product is discharged from the kiln and is cooled and crushed. The luppen are magnetically separated from the solidified sludge. The amount of iron in the luppen varies between 94-97.5%.

Krupp-Codir Process:

Codir stands for coal, ore direct reduction. It is very similar to Krupp-Renn process but operates comparatively at a much lower temperature. Here limestone or dolomites are

charged into the kiln. The first Codir plant started its operation in 1973 in South Africa. The size of the kiln is 74 mtr long and 4 mtr inside diameter. In this process low volatile anthracite coal is used as reductant. Primary heat is generated in the kiln by combustion of pulverized coal injected by burning the kiln gas with the injected air in the tubes spaced along the entire length of the kiln. Temperature generated is between 950-1050°C. The char, coal ash and spent fluxes are discharged via an enclosed chute extending from the kiln burner hood into the shield rotary cooler where cooling is accomplished. Initially the cooled solids are discharged over a 5mm screen. All the fractions of screening undergo magnetic separation to separate the direct reduced iron from the recycled char, coal ash and spent flux. Char is separated by gravity separation and returned to the kiln feed and the spent fluxes are disposed off.

SL/RN Process:



SL/RN stands for,

S = Steel company of Canada

L = Lurgi chemicals

R = Republic steel company

N = National lead corporation

This process is the oldest process and most widely applied coal based direct reduction process. Here the reductants used are coal, coke breeze and bituminous coal. The important features of this process are,

- a) This is a flexible process
- b) It can use large iron ore and pellets
- c) The length of the kiln is 125mtr inside diameter is 6mtr.
- d) This process uses lumpy ore, coal and recycled char.

In this process the charge is heated to the reduction atmosphere of about 900-1050°C. To maintain uniform temperature in the reduction zone, the combustible released from the bed are burnt by blowing air. The product is discharged from the kiln and is transported through a discharge hood containing a chute to a rotary cooler. It is then magnetically separated to collect metalized iron. In 1991 out of total coal based process the SL/RN process constitutes 56% of the total direct reduced iron.

ACCAR Process:

(Allis Chalmers controlled Atmosphere Reactor)

This produces highly metalized direct reduced iron using rotary kiln. Here solid, liquid and gaseous fuels are used directly in the kiln. The ACCAR process started in late 1960 and it is based on hydrocarbon gasses and liquid fuels. The first commercial ACCAR plant was developed in Canada in the year 1976.

OSIL Process:

The OSIL stands for Orissa Sponge Iron Limited. This plant was set up in the year 1983 at Palaspanga, keonjhar, Odisha. It is based on the ACCAR technology with under bed injection of diesel from discharge end. Later on OSIL used coal as fuel. In the year 1995 OSIL supplied the technology to Llyods India for their sponge iron production plant at Chandrapur, Maharastra. The OSIL process uses a rotary kiln of 3.5mtr diameter and 84mtr long. The output of this plant is 300 tons per day. The rotary kiln product is discharged into a rotary cooler at a temperature of 1050°C and subsequently cooled by spraying water on the cooler. The product is discharged from the cooler at a temperature of 100°C and undergoes magnetic separation. This technology achieves a metallization of around 90%.

TDR Process:

It stands for TISCO Direct Reduction. The TISCO plant is also known as TATA Steel. TATA steel established a sponge iron plant in Keonjhar Dist. Of Odisha. The TDR technology uses a rotary kiln of 4.2mtr internal diameter and 72mtr long. The temperature of this kiln is maintained from 800-1000°C. The feed size of iron ore varies from 5-20mm and up to 15mm for coal. In order to increase the productivity, a counter-current coal fines injection system of 2.5tons/hr was installed. This technology has been utilized by different plants.

Popurri Engineering:

Mr. popurri Ankineedu was one of the engineers associated with the sponge Iron India Limited project, who later on left the project and started marketing this process under the name of Popurri Engineering. Today there are over 50 small DRI plants all over India based on this process.

INMETCO Rotary Hearth Process:

The INMETCO process is currently operated by the International Metal Reclamation Co, Pennsylvania, USA. This process recovers iron from waste iron dust. This process utilizes oxide pellets as feed material and it is feed into a rotary hearth furnace. Here oil or natural gas is used as fuel through the burners provided above the bed. In the year 1980 this process has given 80,000 tons of feed per year.

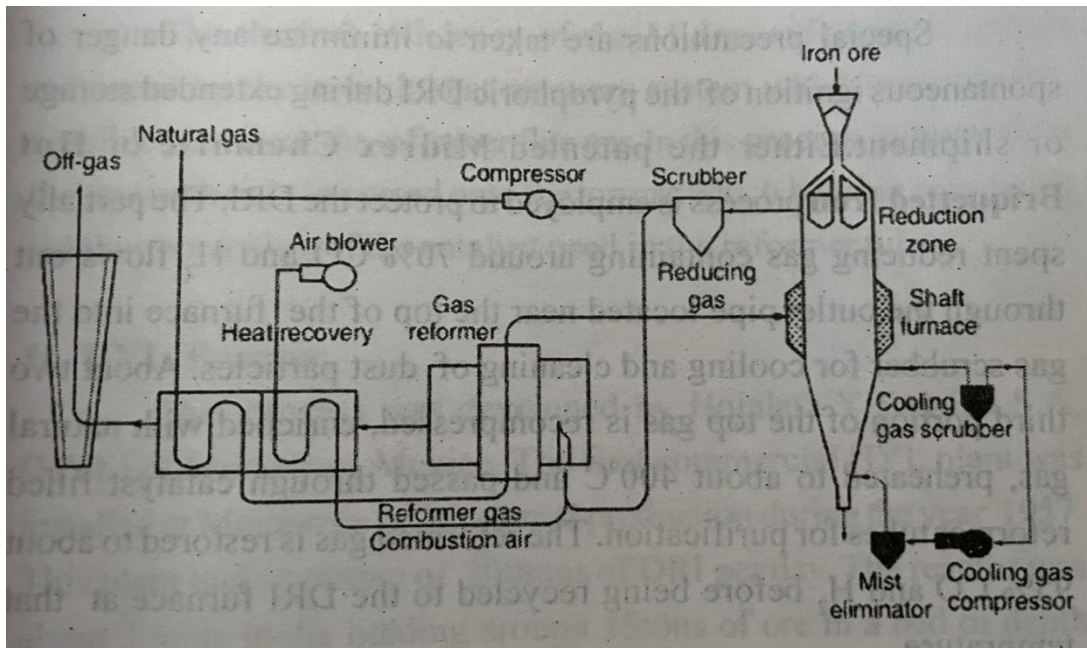
Gas Based Direct Reduction Process**Midrex Process:**

The Midrex process was developed by Midland Rose Corporation of Cleveland(USA). This plant started production in the year 1969 and by the year 1983 more than 20 plants are being established all over the world using Midrex technology. This plant includes two shaft furnaces of 3.4mts inside diameter. The main components of this process are

- a) The DRI shaft furnace.
- b) The reformer.
- c) The gas cooling system.

The process consists of reducing the ore by natural gas in a vertical shaft furnace. Here natural gas, light oil, coal gasification can be used as reducing gas which contains 55% H₂, 32% CO. In Midrex process these gasses reduces the iron oxide to 92% metallization.

In Midrex process reform gasses entering the reduction furnace at around 800-870°C. The product of Midrex process is very strong. This process can access high sulphur natural gas and it can produce good quality of sponge iron. Midrex process is most widely adopted process in the world for making direct reduced iron.



FIOR Process:

The full form of FIOR process is Fluid Iron Ore Reduction process. In this process the reduction is carried out in a series of four fluidized bed reactor. This process continuously convert iron ore fines into a highly reduced product, usually in the form of briquettes. The first of the reactor preheats the ore and reduction is started in the second reactor and it continues in the third reactor and completed in the fourth reactor. All the reactors are operated at 10 atmospheric pressure. This process reduces iron oxides by using gasses such as natural gas and reformed gas as reductant. The entire process of reduction takes place at around 850°C. The reduced iron ore fines are discharged through pressure reducing device and enter an insulated tank from where direct reduced iron is discharged at 650°C. It is compacted in the hot condition in a briquetting machine into briquettes for further use.

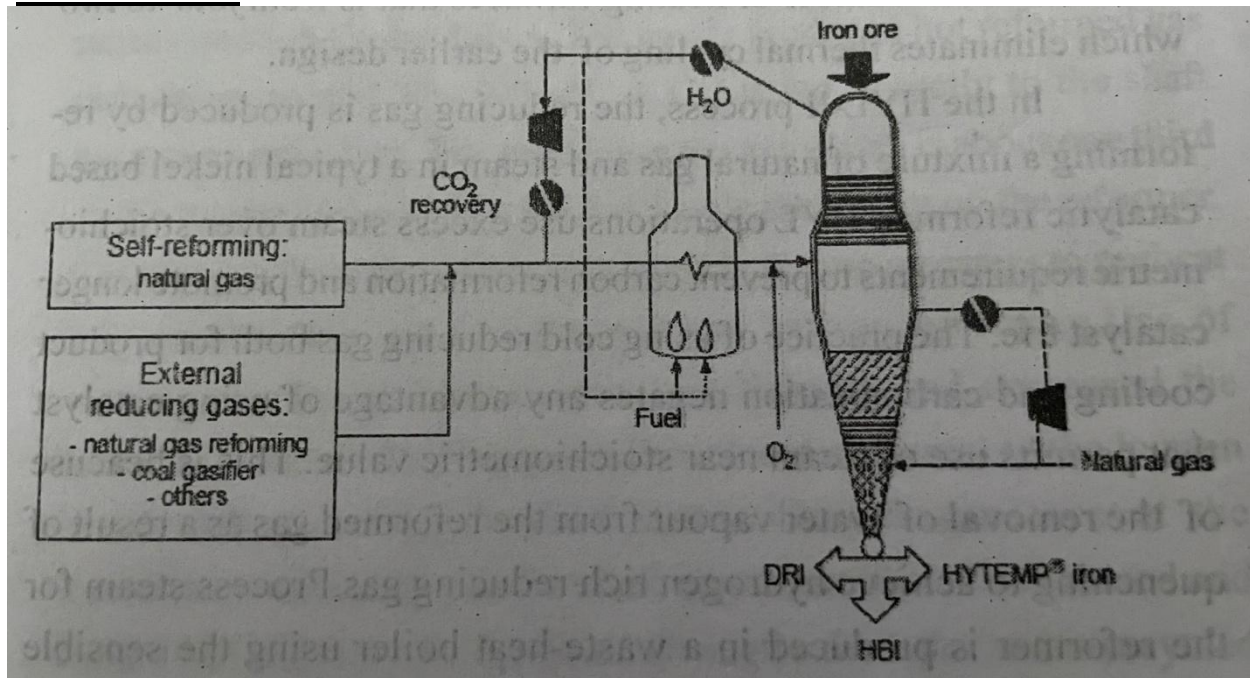
HIB Process:

The full form of this process is High Iron Briquette process. This process is quite similar to FIOR process in its design and operation. Here natural gas, reformed gas are used as reductant. In this process iron oxide fines are reduced in a fluidized bed

reactor by reformed natural gas. In the HIB process two different types of products are produced –

- 75% reduced high iron briquette which can be consumed in the B.F as a part of the burden.
- 92% metalized high iron briquette are produced that can substitute scrap in electric arc furnace steel making. In HIB process the reduction is started at 700°C and completed at 870°C.

HYL Process:



This process was developed by Hojalata Y Lamina S.A (HYL) of monterrey, Mexico. The first commercial HYL plant was installed in the year 1957. This plant had an output of 200 tons of DRI per day. The reactor was about 2.5mtr diameter holding around 15tons of ore in a bed of depth 1.5mtr. The most recent reactor of this process has a diameter of 5.4mtr and a height of 15mts. The capacity of such a reactor is about 1900 tons of DRI per day at an average reduction of 90%. HYL technology is now upgraded to HYL-II and HYL-III. These designs includes-

- High temperature alloy tubes in the gas reheating furnace.
- Reduced the number of heating furnaces from 4-2.

The HYL process is known as HYL-I

HYL-II Process:

In the HYL-II process the reducing gas is produced by reforming a mixture of natural gas and steam in a typical nickel based catalytic reformer. HYL operations use

excess steam over stoichiometric requirements to prevent carbon reformation and promote longer catalyst life.

HYL-III Process:

This process is evolved from the HYL-I by retaining the catalytic reformer, gas reheater and the off gas handling system. In this process a single shaft furnace with a moving bed is used in place of four fired bed reactors as used in HYL-I. The HYL-III plant is operated on iron ore, pellets or mixture of both. The equipments of this process are –

- 1) Shaft furnace
- 2) Gas reformer
- 3) Gas reheater

The process operates on principles similar to the Midrex process. This process operates at 950°C and at a pressure of 5 atmosphere.

Rotary Hearth Furnace Technology:

This process consists of –

- a) FASTMET Technology
- b) FASTMELT Technology
- c) IT mark 3 Process
- d) TUNNEL KILN Process
- e) HOGANAS Process
- f) KINGLOR-METOR Process

a) FASTMET Technology:

This is a rotary hearth furnace technology method. The concept of coal based direct reduction of iron ore is also utilized in the rotary hearth furnace for production of sponge iron. The rotary furnace consists of a flat refractory hearth rotating inside a stationary circular tunnel kiln. Direct reduction of iron ores occurs inside the rotary hearth furnace using coal as a reductant. Rotary hearth furnace process uses ore and coal fines either in pellet or briquette form for production of sponge iron.

b) FASTMELT Technology:

This process uses simultaneously a rotary hearth furnace and a melting furnace to produce hot metal. The input materials are iron ore and carbon either contained in the feed or added separately as coal, charcoal or other carbon bearing materials in solid state. After reduction the DRI plates or briquettes are

discharged into the melting furnace for steel making. The product from Fastmelt is comparable to pig iron from the B.F. The product quality can be very good as compared to other process.

c) **IT MK 3 Process:**

This process uses similar rotary hearth furnace technology as that of FASTMET. The primary feed materials are iron ore and coal. This process producing iron ore particles containing carbon but without any oxygen and slag. The small iron particles are known as **nuggets**. The carbon level can be controlled by different technology different heating pattern. The iron particles or nuggets have a maximum carbon content of around 3%. The silicon, manganese and phosphorus content of the product depends on the input raw materials. This process is flexible, economical and environmental friendly.

d) **TUNNEL KILN Process:**

This process uses a mixture of ore, coal and dolomite fines. The major advantage of this process is the decrease in coal consumption as compared to any other DRI process. The process requires around 650 kg of coal per ton of DRI product and as coal is entirely consumed only as reductant. The charge mix has 3% dolomite.

e) **HOGANAS Process:**

This process was developed in the year 1910 at Hoganas in Sweden. In this process alternate layers of iron ore, coke and limestone are charged into cylindrical ceramic containers called saggars and the saggars are heated to a maximum temperature of 1260°C in Tunnel Kiln type furnace by burning producer gas. The CO generated in the saggars helps the reduction of ore. The total retention time of the saggars in the Tunnel Kiln is about 80hrs including cooling. Most of the DRI produced by this process is solid as iron powder.

f) **KINGLOR METOR Process:**

This process is based on the concept of producing DRI continuously by heating a mixture of iron ore and coal in an externally fired rectangular shaft or retort furnace. There are certain limitations of this process –

- 1) The reduction reactions are highly endothermic and required higher heat flow into the charge in the retort.
- 2) Restricted heat transfer into the charge through the retort walls made from fire bricks.

Kinglor Metor overcome these limitations by replacing the fire bricks with highly conducting silicon carbide bricks for the retort walls and by incorporating a preheating zone in the upper part of the retort.

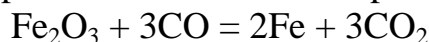
Chapter - 2**THERMODYNAMICS OF SPONGE IRON MAKING****Introduction :**

The principle of thermodynamics is essential to understand the fundamentals of process reaction. Thermodynamic explains the reason why a particular reaction occurs while another does not. In short it predicts the feasibility of a process under certain condition of temperature and pressure. The limitations of thermodynamics is that it does not tells anything regarding the rate at which it proceeds. The rate of a chemical reaction can only be explained with the principle of kinetics.

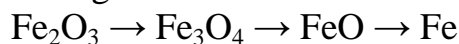
Principles of Direct Reduction Reaction:

As we know DR is the conversion of iron oxide(Fe_3O_4) to the metallic iron entirely in solid state.

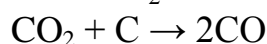
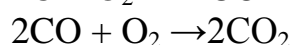
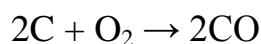
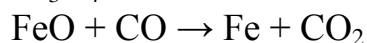
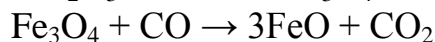
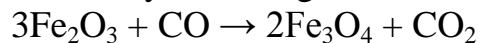
- Direct reduction uses hematite(Fe_2O_3) as a raw material and coal as a reductant.
- The carbon in coal gets converted to CO which subsequently reacts with hematite to produce metallic iron as per the reaction



- The reduction process proceeds in several steps and Fe_2O_3 reduced to metallic iron according to the reaction-



- The degree of reduction on each step of the progressive reduction shown above varies widely involving several complex reaction as –

**Reaction between Coal, Oxygen and CO_2 :**

Carbon from the coal reacts with oxygen to form CO_2 and heat released. The heat released increases and maintains the operating temperature inside the kiln and the CO_2 reacts with fresh carbon to form CO. This CO is responsible for reduction of iron ore.

Reaction between Iron Ore and CO:

Each ore particle may be considered to be porous as it contains micro pores. The reaction between the ore particles and the gaseous reductant occurs in five successive steps –

Step 1 – Diffusion of the gaseous reactants

Step 2 – Penetration and diffusion of reactants

Step 3 – Reaction at the reduced, unreduced interface

Step 4 – Diffusion of gaseous product through the reacted layer

Step 5 – Diffusion of gaseous product through the gaseous film.

Reaction Mechanism in Coal Based DRI:

Different reduction mechanism operates in coal based process are –

Iron ore reduction by coal begins only at the point of contact between them and stops once metallic iron is formed in the outer layer of the particle. Thereafter the reduction can proceed only by diffusion of carbon atoms through the metallic iron layer. For substantial reduction solid coal must get converted to CO. CO is produced by the reaction between carbon in the coal and CO₂ produced by the reduction of iron ore according to the Boudouard reaction. This reaction is endothermic and occurs above 1000°C and the reduction of iron oxide is not feasible below 600°C. Therefore in a coal based DRI process, the reduction of iron ore and Boudouard reaction takes place simultaneously.

Reaction Mechanism In Gas Based DRI:

The gas based process is more popular because of the following reasons –

- 1) Natural gas is available plentifully in the world.
- 2) It is economical and pollution free to use.
- 3) Reformed natural gas is a better reductant as compared to coal.
- 4) The reaction mechanism using natural gas is essential which has to be studied properly.
- 5) The mechanism may change depending on physical characteristics of iron ore. At 700°C, the reduction of hematite(Fe₂O₃) with pure CO stops at around 40% . While at 800°C the reduction is extended upto 85%.

Reduction by CO:

The reduction reaction of iron oxide by CO can be represented as

- 1) $3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO}_2$
- 2) $\text{Fe}_3\text{O}_4 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2$
- 3) $\text{FeO} + \text{CO} \rightarrow \text{Fe} + \text{CO}_2$

Reduction by Hydrogen:

The reduction reaction of iron oxide by hydrogen can be represented as

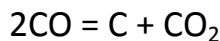
- 1) $3\text{Fe}_2\text{O}_3 + \text{H}_2 = 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$
- 2) $\text{Fe}_3\text{O}_4 + \text{H}_2 = 3\text{FeO} + \text{H}_2\text{O}$
- 3) $\text{FeO} + \text{H}_2 = \text{Fe} + \text{H}_2\text{O}$

Boudouard Reaction and Reduction by carbon:

The reaction, $\text{CO}_2 + \text{C} = 2\text{CO}$ is known as Boudouard reaction. It is also called as carbon loss reaction. This reaction is faster than, $\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$ which causes reduction of iron ore. Therefore a little amount of reduction occurs by direct contact between the solid carbon and iron ore particles. Initially iron ore is reduced by CO gas, which is produced by Boudouard reaction.

Carbon deposition:

In any DRI process it is not possible to achieve complete thermodynamic equilibrium. This is due to the fact that CO decomposes according to reverse Boudouard reaction i.e.,



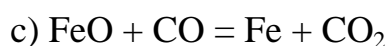
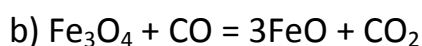
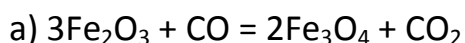
At 600°C , $P_{\text{CO}_2}/P_{\text{CO}} = 10$

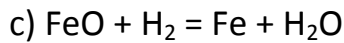
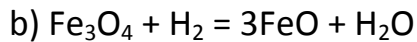
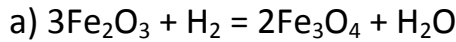
This implies that $P_{\text{CO}_2}/P_{\text{CO}}$ is greater than the equilibrium constant K for Boudouard reaction. Boudouard reaction will continue to proceed from right to left with deposition of solid carbon till $P_{\text{CO}_2}/P_{\text{CO}}$ ratio decreases to its equilibrium value which is $10^{0.5}$ at 600°C .

Reaction Kinetics in DRI:

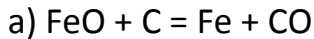
Reaction kinetics of iron ore deals with the rate at which the iron oxides are converted to metallic iron with the removal of oxygen. The reductions can be performed by CO, H₂ and C, as per the following reactions-

1) Reaction with CO:



2) Reaction with H₂:

3) Reaction with Carbon:



The evaluation of reduction kinetics for iron ore is very complex as the oxides undergoes a series of changes till the conversion is completed. However the slowest of the steps in the process determines the overall reduction rate and is known as rate controlling step. The ease at which the oxygen can be removed from the ore by the reductant is defined as reducibility.

Factors Affecting Reducibility of Iron Ore:

The reducibility of iron ore in a direct reduction process is affected by the following factors-

- 1) Size, shape and size distribution of ore particles
- 2) Average density, porosity and crystal structure of ore particles.
- 3) Percentage gangue and its distribution in the ore.

1) Size, shape and size distribution:

While selecting iron ore for sponge iron making, special attention should be given to the reducibility of ore, also size of ore plays an important role. It is found that 5-18mm size ore is good for sponge iron production. Also ore preparation should be carried out in such a manner to provide maximum possible surface area. The particle size distribution is also an important parameter which controls the reducibility of iron ore.

2) Average density, porosity and crystal structure:

The importance of porosity can be analyzed by microscopic examination of cross-section of a partially reduced dense iron ore particle. The cross-section of a dense iron ore particle shows a hematite core surrounded by three concentric layers as

- An inner layer of magnetite
- An intermediate layer of wustite.
- An outer porous layer of metallic iron.

Rate Controlling Theories:

There are several rate controlling theories which affect the rate of iron ore reduction-

- a) Boundary layer control
- b) Phase boundary reaction control.
- c) Gaseous diffusion control.
- d) Mixed control

Chapter - 3

Parameters of Sponge Iron Making

Raw materials of sponge iron making:

The basic raw materials for this are iron ore, coal and flux.

A) Iron Ore:

It is very much important raw material which is required for making sponge iron. The important iron ore is hematite(Fe_2O_3). This ore is used for sponge iron making. While selecting iron ore for sponge iron making the following factors are considered -

- a) The ore should be suitable for getting good quality of sponge iron.
- b) The ore should not have any negative effect on the life of rotary kiln.

The following important factors are considered for selecting iron ore for production of sponge iron -

- a) Chemical composition of ore.
- b) Reducibility of ore.
- c) Physical characteristics of ore.

Physical and chemical test on iron ore:

1) Chemical Composition:

The chemical composition of iron ore plays an important role in the production of sponge iron. The chemical composition of iron ore should be such that the minimum iron content of the ore is 65%. The phosphorous content of the ore is less than 0.05%. The composition of Indian ore i.e., Fe_2O_3 should be-

Fe – 65%(minimum)

$\text{SiO}_2 + \text{Al}_2\text{O}_3$ – 4.5%(max.)

P – 0.03%(max)

Tumbling Index – 88%(min)

2) Reducibility:

The reducibility of iron ore determines the ease at which the oxygen can be removed from iron ore by the reducing gasses. The parameters which affect the reducibility are -

- a) Particle size and its distribution.
- b) Strength of the ore.
- c) Density of the ore.
- d) Porosity of the ore.
- e) Composition of the ore.
- f) Crystal structure of the ore.

It is therefore concluded that the iron present in the ore is in the form of hematite, as this ore has a better reducibility as compared to magnetite.

3) **Strength:**

The strength of the ore indicates its resistance to degradation. Higher the strength, lesser is the generation of fines during handling and reduction. The strength property is represented in terms of Tumbler Index, shatter Index, Abrasion Index and thermal Degradation Index.

Tumbler Index:

The iron ore during reduction in rotary kiln is subjected to tumbling action in a reducing atmosphere. The ore should have high tumbling index. For efficient kiln operation the tumbling index should be at least 88%. Tumbling index test uses a cylindrical steel drum whose diameter is 1000mm and width is 500mm.

Abrasion Index:

The iron ore during reduction in rotary kiln is subjected to abrasive action. The ore should have low abrasive index to minimize the generation of fines during sponge iron production. For efficient kiln operation the abrasion index should be less than 5%.

Shatter Index:

This index measures the resistance of the material to free fall from a particular height and is defined as the quantity of material those retains the size range over a specified dimension.

Thermal Degradation Index:

This is defined as the fragmentation of ore, producing fines when it is subjected to heating either in a reducing or oxidizing atmosphere. Iron ore is susceptible to thermal degradation when heated above 400°C. This characteristic of the ore is expressed in terms of an index. The ore having less than 4.5% T.D.I is suitable for sponge iron production.

Porosity:

It is an another important parameter which affects the reducibility of ore. As the degree of reduction is dependent on time, the ore having different porosity would require different time period for same degree of reduction. High porosity ore may give rise better reducibility. For better productivity a porosity of 3-5% is recommended.

Bulk density:

The bulk density can be determined by knowing the mass and volume of the material including voids. The mass per unit volume is calculated to express the bulk density of the material.

B) Non-coking Coal:

The coal plays an important role in sponge iron making. It provides the heat to the furnace to sustain the process and gives the reductant to reduce the ore.

Tests on non-coking coal:

The important tests on coal should be carried out to find its application for sponge iron making. They are -

- 1) Proximate Analysis.
- 2) Ultimate Analysis.
- 3) Reactivity.
- 4) Calorific value.
- 5) Caking Index.
- 6) Swelling Index.
- 7) Ash Fusion test.
- 8) Bulk density.

1) Proximate Analysis:

This analyses moisture content, volatile matter, fixed carbon and ash content of the coal in terms of percentage by weight. The proximate analysis is very significant as it evaluates the fixed carbon content of the fuel, which is the main source of reductant.

a) Moisture content:

If the moisture content of the coal is high, the consumption of coal will increase. Therefore the moisture content evaluation helps in ascending the heat i.e., going to be wasted along with the flue gas during burning of the coal.

b) Ash content:

The ash indicates the inert load on the kiln. Ash is an impurity in coal and should be as low as possible.

c) Volatile Matter:

Volatile matter contributes to the calorific value of the coal and it helps in the reduction of the reaction.

d) Fixed Carbon:

The fixed carbon which when gasified behaves as reductant in direct reduction.

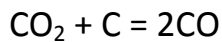
2) Ultimate analysis:

It evaluates the constituents like carbon, hydrogen, oxygen and sulphur in

the coal in terms of percentage by weight of elements free from moisture and inorganic constituents.

3) **Reactivity:**

The reactivity of coal is its ability to react with CO₂ and to produce CO at a given temperature as per the Boudouard reaction.



4) **Calorific Value:**

It is the amount of heat produced by burning 1 kg of coal. The calorific value of coal should be around 5600 kcal/kg.

5) **Caking Index:**

It is a measure of binding property of coal undergoing carbonization. It is observed that the coal having higher caking index has low reactivity.

6) **Swelling Index:**

Caking and swelling index are related to each other. The coal swells up when heated to release the volatile matter. Low swelling index is preferred for sponge iron making.

7) **Ash Fusion Temperature:**

The ash fusion temperature of coal should be as high as possible. It should be atleast 200°C more than the operating temperature, which is around 1100°C.

8) **Bulk Density:**

Bulk density of coal plays an important role in the productivity performance of DRI kiln. The experience in DRI production indicates that bulk density of sized coal should be 800 kg/m³.

Effect of Iron Ore Size on Reduction:

The rate of reduction depends on the size of ore particles. The time require for reduction is dependent on the longest path along which an oxygen atom travels to reach a gas-solid interface. It indicates that there is an inverse relationship between particle size and reduction rate. The size range of iron ore should be 5-18 mm.

Carbon Enrichment of Sponge Iron:

An appropriate quantity of carbon would react with the iron oxide and gaseous oxygen to maintain a strong carbon bonding relation. Therefore the

industries can take advantage of the presence of residual unreduced iron oxide and excess carbon in the DRI during steel making.

How carbon enrichment of sponge iron is performed:

The sponge iron from the rotary kiln is discharged to cooler where the temperature is decreased from 1050°C-900°C within 105 hours with the help of liquid hydrocarbons. The hydrocarbon forms a dense carbon monoxide around a sponge iron and helps in carbon deposition on sponge iron.

Flow of solids in the reaction:

The important factors such as temperature, furnace atmosphere are to be controlled for the sponge iron production. The atmosphere should be reducing. The duration of time that is required for controlling atmosphere at specified temperature is dependent on heat and the solid.

Process parameters of sponge iron production:

1) Raw Materials:

To produce 1 ton of sponge iron, the raw materials required are -

Iron Ore = 1.7 ton

Coal = 1.4 ton

Dolomite = 30 kg

Air = 2200mtr³/hr

2) Iron ore feed rate:

To produce 500 tons of sponge iron per day in a sponge iron plant the iron ore feed rate is maintained at 31tons/hr.

3) Coal feed rate:

Around 390 kg of fixed carbon is required to produce 1 ton of DRI.

4) C/Fe (carbon/ Iron) ratio:

The C/Fe ratio is 0.4-0.46 which indicates that the quantity of carbon feed to the kiln. The higher the C/Fe ratio indicates excess coal consumption and lower C/Fe ratio indicates lower coal consumption.

5) Dolomite feed rate:

Dolomite feed rate is monitored according to the percentage of sulphur in the coal and its feed rate. Around 26-28 kg of dolomite requires for 1 ton of sponge iron.

6) Reduction coal to blow coal ratio:

Normally this ratio is maintained at 60:40. However it changes when coal feed rate is changed to achieve a particular C/Fe ratio.

7) Ratio of coarse and fines in blow coal:

The coal particles having -5 mm size in the blow coal is generally treated as fines.

Normally a ratio of 2:1 is maintained between coarse and fines in the blow coal.

8) Blow coal pressure:

The maintenance of blow coal pressure is required to get uniform throw of the blow coal. The blow coal pressure is so maintained that the coal particles should react atleast 80% of the total length of the kiln measured from the discharged end.

9) Temperature profile:

It is the outcome of the air profile, fuel availability and enthalpy of various reactions taking place in the kiln. Further the temperature inside the kiln is also influenced by the filling degree of charged burden. Higher the degree of filling less is the heat loss and higher is the temperature in the kiln.

10) Kiln speed:

The rotating speed of the kiln influences followings-

- a) Filling degree.
- b) Retention time of feed material.
- c) Heat transformed from the kiln.

11) Cooler discharge end pressure:

This is always maintained positive compared to the atmospheric pressure throughout the kiln operation to avoid any false air getting into the kiln. It may re-oxidize the product affecting its quality.

Non Magnetic Percentage in Kiln Discharge:

The percentage of non magnetic separated from the sponge iron with its carbon content indicates the manner in which the kiln has been operated. The carbon percentage of the non magnetic depends on C/Fe ratio, reduction coal to blow coal ratio, temperature profile and nature of coal used in the kiln. The normal range of non magnetic in the sponge iron is around 18-22% with a carbon content of around 32-38%.

Properties of Refractories Used in Plant:

Refractory's plays an important role in DRI plant operation. The term refractory means hard to fuse. These materials also have good insulating properties. Before selecting a specific refractory it is necessary to analyze its properties. The maximum temperature of a sponge iron rotary kiln is 1200°C. Both oxidizing and reducing atmosphere prevails inside the kiln. The function of the refractory lining of the kiln is to protect the kiln shell from the influence of flame and reduce heat losses due to radiation. The refractory selected should have the following properties –

- 1) Good refractoriness.
- 2) High resistance to thermal shock.
- 3) Good resistance to kiln atmosphere.
- 4) High abrasion resistance.

Chapter-4

Plant Operating Parameter

Daily operating parameter of DRi kiln:

On a daily basis the critical parameters are to be maintained perfectly for smooth operation of the plant. The major operational problems are –

- 1) Ore feed rate.
- 2) Coal feed rate.
- 3) Ratio of feed coal to blow coal.
- 4) Temperature maintenance at different zone of the reactor.
- 5) Reactor exit gas temperature.
- 6) Reactor discharge end pressure.
- 7) Burner temperature.
- 8) Reactor speed.
- 9) Cooler speed.
- 10) Air feed rate.
- 11) Raw material characteristics.
- 12) After burn temperature.
- 13) Boiler inlet temperature.
- 14) Cooler discharge end temperature.
- 15) Boiler inlet and outlet pressure.
- 16) Kiln inlet and outlet pressure.
- 17) Injection coal pressure.
- 18) Plant compressed air pressure.
- 19) Boiler steam pressure.
- 20) Percentage magnetic and non-magnetic in the cooler discharge.
- 21) Total gas flow.
- 22) Amount of dust coming from dust settling chamber and E.S.P.

Operational Abnormalities:

The common process abnormalities found during plant operation are –

- 1) Process pressure fluctuations.
- 2) Temperature deviation.
- 3) Back spill.
- 4) Loss of process fan.
- 5) High temperature of cooler discharge.
- 6) Loss of quality.

1) Process pressure fluctuations:

During normal operation the reactor discharge end pressure should be maintained around 0.5 milibar and the cooler discharge end pressure should steady and positive.

2) Temperature deviation:

There should be at least two different temperature recorders for DRI kiln. One is the original thermocouple fitted into the kiln and other is quick response thermocouple (Q.R.T) which is inserted into the reactor as when required to record the temperature.

3) Back spill:

Back spill is that material which spills out at the feed end of the reactor due to over feeding. Due to over feeding and accretion formation the inside volume of the kiln decreases and excess feed material comes out as back spill. During normal operation there is a small amount of back spill at the reactor. If excessive back spill is noticed then –

- a) Check the feed rate.
- b) Check the reactors speed.
- c) Check the feed pipe.
- d) Check the pressure.

4) Loss of process fan:

It can be detected from the sudden reduction in the ID fan opening. Even if this goes unnoticed, fall in temperature in those zones served by fan indicates loss of fan. In such cases the fan loosed or stopped are identified and either replaced or repaired immediately.

5) High temperature of cooler discharge:

If the cooler discharge temperature exceeds 130°C it is considered to be hot. Special attention on product temperature is necessary.

6) Loss of product quality:

For getting consistent product quality it is important to maintain following parameters consistently –

- a) Feed rate.
- b) FC/FeT ratio(fixed carbon/total iron).
- c) Kiln speed.
- d) Quantity of air.

Major operational problems in a DRI Kiln

Major problems of DRI kiln operations are

- 1) Injection coal jam
- 2) Feed pipe jam
- 3) Transfer chute jam
- 4) Main drive problem
- 5) Refractory failure

1) **Injection coal jam-** This means the stoppage of coal thrown from discharge end

Causes-

- a) Jamming of rotary feeder.
- b) Empty raw material bin or chute jam.
- c) Injection coal pipe leakage.

Remedies-

- a) Clean and restart the coal blowing equipment
- b) Adjust coal feed from other beans, clean the chute and start.
- c) Change the pipe and check the alignment of pipe.

2) **Feed pipe jam-**

Causes-

Feed pipe jam occurs due to wet feed and foreign materials.

Remedies-

The feed pipe is cleaned and then feeding restarts to the kiln.

3) **Transfer chute jam**

Causes-

Large accretion pieces falling from kiln wall into the charge do not pass through the transfer chute and causes jamming.

Remedies-

Clean the transfer chute when required.

4) **Main drive problem**

Causes-

This may be either due to problem in electrically driven motors or due to other mechanical problem.

Remedies-

After solving the problem the main drive may be restarted.

5) Refractory failure**Causes-**

- a) It may be due to improper selection, preparation and maintenance of refractory lining.
- b) It may be due to thermal shock produced by the water spray.

Remedies-

Always cool the shell with compressed air. If there is a major refractory failure a kiln shutdown is taken.

Kiln shutdown procedure

The following considerations must be made during the shutdown of a DRI kiln-

- 1- Maintain uniform reactor rotation to avoid shell distortion.
- 2- The reactor should be cooled at such a rate so as to avoid damage to the refractory due to thermal shock.
- 3- All the partially reduced and unreduced material should be flushed out from the reactor.

Normal kiln shutdown schedule

- 1- Stop feeding coal, iron ore and desulphurizer from the feed end side.
- 2- Gradually reduce air from the feed end side.
- 3- The injection coal quantity may be reduced gradually.
- 4- Rotate the reactor at a higher r.p.m to flush out material from the kiln
- 5- When the kiln temperature reaches around 100°C, its rotation may be stopped.

Kiln start-up procedure

Starting the kiln is known as start-up. The start-up will commence at the completion of the following pre-operational activities

- 1- Check-out the utilities such as power, water, compressed air etc.
- 2- Check-out the starting of ore and coal crushing system.

- 3- Check-out the coal slinging system.
- 4- Check-out the reactor.
- 5- Check-out the off gas system.
- 6- Check-out the auxiliary stack cap.

Heating of Reactor Refractory

- 1- Before starting the heating of the kiln, it is to be ensured that all the foreign materials are removed from the kiln and from the door manholes.
- 2- During the heating-up the refractory, the drying and heating schedule provided by the refractory manufacturers is strictly mentioned. Initially, temperature should be raised at a rate of 30 °C per hour till it reaches 110 °C followed by an isothermal holding of at least 6 hours at the same temperature to remove the moisture from the refractory lining completely. Then the temperature is raised at a rate of 30 °C per hour upto 260 °C followed by isothermal holding of 5 hours for the refractory to develop uniform temperature throughout. Then temperature may be raised at a rate of 30 °C/hr upto 550 °C followed by an isothermal holding of 5 hrs. After this stage the temperature is raised at a rate of 40 °C/hr till 850 °C followed by another isothermal holding of 5 hrs. Then the temperature is raised at a rate of 50 °C/hr till it reaches 1100 °C. During the entire process, air is introduced and proper draft is maintained to draw the heat towards the feed end of the kiln.

Accretion Formation in DRI kiln

After the shutdown of the DRI kiln accretion samples are collected from different zones of the kiln. From the analysis it is found that –

- 1- SiO₂, Al₂O₃, FeO and Fe₂O₃ are the major constituents of accretion.
- 2- Higher amounts of Fe₂O₃ in all zones are due to sticking of this oxide on low melting compounds.
- 3- The presence of higher silica and alumina in accretion indicates that these compounds must have come from coal ash.
- 4- The percentage of silica is 25-44%, Al₂O₃ is 4-10%, Fe₂O₃ is 25-54% and FeO is 9-30%.

Control of Accretion Problem

- 1- Maintain the raw material quality and quantity as per specification.
- 2- Use coal with high ash fusion temperature.
- 3- Minimize the use of dolomite.
- 4- Maintain product quality with as minimum temperature as possible

Chapter - 5

ENVIRONMENTAL MANAGEMENT IN DRI PLANTS

1- Air pollution mitigation measures:

In the rotary kiln the DRI gases flows counter current to the flow of feed materials. The temperature at the discharge end of the rotary kiln is 950-1050 °C and the temperature at the feed end is 750-900 °C. The counter current flow of the hot DRI gases remove the moisture from the feed. The hot DRI gases contains poisonous CO, fine dust of oxides and unburnt carbon. Hence to be treated before discharged to the atmosphere.

The feed side end of the rotary kiln has a structure below the after Burn Chamber (A.B.C) which acts as Dust Settling Chamber (D.S.C). In the A.B.C the CO gas is converted to CO₂ gas. In D.S.C about 15-20% coarse particles settled down by means of gravity.

Different industries are using different types of pollution control equipments like bag filter, scrubber and electrostatic precipitator (E.S.P). The cleaned gas is passed to the atmosphere emitted through stacks of around 30 mtrs high.

2- Fugitive Dust Generation

The sources of fugitive dust generation in a DRI plant are-

- a) Raw material handling section.
- b) Product discharge system.
- c) Product handling system.

The dust at raw material handling system is controlled by using water spray.

3- Water pollution mitigation measures

In the coal based sponge iron plant water is used in these areas-

- a) Cooler.
- b) After burn chamber.

The water requirement is around 5000-6000 ltr/hr for 100ton/day of sponge iron. In after burn chamber water is sprayed through the nozzle in the form of fine spray. This controls the temperature of the gases. Some of the plants uses water for fugitive dust suppression in raw material handling section. Some of the plants are having wet scrubber as pollution control system for kiln off gas.

After A.B.C the gas is passed to scrubbers where the gas is scrubbed with plain water. The water from thickener is recirculated to scrubber unit. Underflow of the thickener is cleaned periodically for small plants and for big plants it is taken to sludge settling ponds. Most of plants are now using E.S.P system for water mitigation measures.

4- Solid waste generation and disposal

Char, flue dust, gas cleaning plant disposal and kiln accretion are the solid waste generated in the DRI plant. The char comprises un-burnt carbon, oxides and gangue materials. It is segregated from the product by magnetic separation. The metallic oxide deposited on the inner surface of the kiln is called accretion. Flue dust is generated from air pollution control system like dust settling chamber, electrostatic precipitator and bag filter. Sludge is generated from the G.C.P (Gas Cleaning Plant), if the plant is not using wet scrubber for dust treatment.

The flue dust and sludge collected from air pollution control equipment are non-hazardous non toxic oxides which are mainly dumped into nearby area. It can also be used for brick making.

5- Hazardous waste and chemicals

Coal based DRI plants do not handle any hazardous chemicals nor generates any hazardous solid waste. Spent oil and lubricants generated from moving equipments or machineries are collected in drums and given to authorized reprocessor for recycling. The volume of oil and lubricant is about 300 ltr/year/100 TDP DRI.

6- Occupational health and safety

At present no occupational health monitoring system is followed by most of the DRI plants. The occupational problems arises in the DRI plants are-

- a) Respiratory problem due to dust.
- b) Carbon monoxide poisoning.
- c) Accidental exposure to untreated DRI gases.
- d) Workers working in the area like raw material handling section and product house that generates dust particles.

The safety requirements are-

- a) The worker should wear nose mask or dust filter.
- b) Carbon monoxide probe with electrochemical sensor should be installed.
- c) The first aid boxes with medicines should be kept.
- d) The employee should be subjected to regular health check-up.

7- Environmental monitoring

At present no structural environmental monitoring program is followed by most of

the DRI plants. Regular monitoring in a systematic and standardized manner helps in assessment of environment and provides information on operational performance of installed pollution control facilities. The DRI plant should conduct routine environmental monitoring such as

- a) Monitoring of air quality in plant boundary for fugitive emission. This should be carried out twice in a month.
- b) Monitoring of ground water quality in the surrounding area of dump yard.
- c) Monitoring of solid waste quantity.
- d) Noise monitoring near the kiln, product house and raw material handling system.
- e) Monitoring of emission gases.

8- **Environmental Standards**

The fugitive emissions of suspended particles should not exceed $2000\mu\text{g}/\text{m}^3$ at a distance of 10 mtr from the source area like feeder area, mixing area, screening plant, crushing plant, stop bin area and magnetic separation unit.

All efforts should be made to reuse and recirculate the water and to maintain zero effluent discharge. The effluent from the settling tank of the wet scrubber should be treated suitably conforming to the following standards

pH – 5.5-9

Total suspended solids - ≤ 100 mg/lit

Chemical oxygen demand - ≤ 250 gm/lit

Oil and grease - ≤ 10 mg/lit.

Chapter - 6**PRODUCTION OF FERRO-ALLOYS****Different Ferro-alloys**

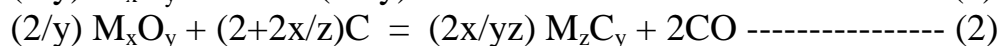
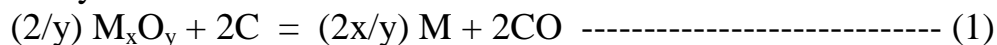
The different ferro-alloys are ferro-silicon, ferro-manganese, ferro-vanadium, ferro-titanium, ferro-chromium and ferro-zirconium.

General methods of producing ferro-alloys:

- 1) Carbothermic Reduction
- 2) Aluminothermic Reduction

1) Carbothermic Reduction:

The relevant reaction during carbothermic reduction of an oxide ore can be represent by –



Where,

M = Metal

X = Valency of oxygen

Y = valency of metal

Z = valency of carbon

In general, the free energy change associated with the reaction (1) and (2) indicates that it is impossible to obtain a ferro-alloy with low carbon content by using carbon as reducing agent because stable carbides are formed as per reaction (2).

The temperature required for carbothermic reduction smelting of a ferro-alloy is 1500 – 1800° C. Such high temperature are required because a molten ferro-alloy required as because the oxides such as SiO₂, TiO₂, MnO, Cr₂O₃ which are present in the ferro-alloy are highly stable and can be reduced by carbon only at high temperature. To do this operation an electric furnace is required.

Refining of Ferro-alloy

The main purpose of refining a ferroalloy produced by carbothermic reduction is to lower its carbon content. The methods employed are –

- 1) The removal by oxidation.
- 2) The removal by introduction of an element into the molten alloy in order to decrease the solubility of carbon in the alloy.

Production of Individual Ferro-Alloy :

1) Ferro-Manganese:

a) Raw material:

Manganese ore.

b) Composition:

Mn = 47 – 57%

Fe = 6%

SiO₂ = 1%

P = 0.14 – 0.18%

c) Process of production:

The manganese ore is smelted in an electric furnace with addition of 15 – 20% coke, also some amount of flux is added depending upon the ore composition. The flux is having CaO and this addition is necessary to control the silicon content of the ferroalloy. The high carbon ferromanganese is produced by the carbothermic reduction of high carbon manganese ore. At last high carbon ferro-manganese is produced having 74 – 80% Mn, 7.4%C and rest Fe. Similarly low carbon ferro-manganese is produced by a silicothermic reduction of the manganese ore in a electric furnace.

2) Ferro-Chrome :

a) Raw material:

Chromium ore

b) Composition:

Chromium = 68%

Carbon = 6%

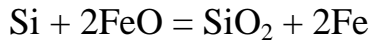
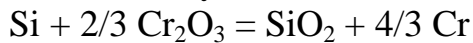
Silicon = 5-8%

Fe = rest

c) Process of production:

Ferro-chrome can be produced in an electric furnace. For example carbonized ferro-chrome is obtained by the carbothermic reduction of chromium ore at a temperature of 1600-1700°C. A basic slag is produced during reduction which gives the silica accurately in the system at a low level and allows the production

of ferro-chromium with low silica content i.e., 2-5%. Low carbon ferro-chrome is obtained by the reduction of chromium ore by silicon. The reactions are –



3) **Charged-Chrome:**

The ferro-chromium with chromium to iron ratio 1.5:2 (Cr:Fe) is known as charged chrome. The charge chrome is used in stainless steel industries.

4) **Ferro-Silicon:**

a) Raw material:

Quartzite

b) Composition:

$\text{SiO}_2 = 95-97\%$

c) Process of production:

The ferro-silicon is produced by carbothermic reduction of quartzite in an electric furnace. The normal grade of ferro-silicon contains 45% silicon or 75% silicon and rest is iron. During ferro-silicon production all the phosphorus present in the quartzite will be reduced. The raw material should contain low phosphorus.

5) **Ferro-Titanium:**

The most important method of ferro-titanium manufacture is by the aluminothermic reduction of Rutile(TiO_2) ore. During reduction the iron oxide is completely reduced and 80% silica and 70% Titanium oxide present in the ore is also reduced. It should be noted that the extend of Titanium recovery is directly related to the Aluminium content of the ferro-titanium produced.

6) **Ferro-Tungsten:**

It is produced by the reduction of tungsten oxide using carbon, silicon or aluminium as the reducing agent to obtain a ferro-tungsten that contains less than 1% carbon. Carbothermic reduction is carried out in an electric furnace lined with magnesite. The magnesite lining allows the use of highly basic slag which gives rise to high tungsten recovery and enable the production of low carbon ferro-tungsten which contains 82-85% Tungsten.

7) **Ferro-molybdenum:**

It is produced by silicothermic reduction of molybdenum ore. Here ferro-silicon is employed as reducing agent and lime is added to produce a slag which helps the separation of ferro-molybdenum from the slag.

8) **Ferro-Vanadium:**

It is produced by silicothermic reduction of Vanadium ore at high temperature in an electric furnace. The formation of lower oxide of vanadium during reduction and the reaction of V_2O_3 and VO with silica to form vanadium silicate which becomes more difficult. Therefore a two stage reduction operation becomes necessary. In the first stage V_2O_5 is reduced under basic condition to produce ferro-vanadium. In the second stage silicon is removed using fresh charges V_2O_5 . The overall recovery

rate is 75-85% Vanadium.

Uses of ferro-alloys:

1) Ferro-Chrome:

It is used in the stainless steel making and alloy steel making.

2) Ferro-Silicon:

It is used as a deoxidizer in steel industry. Also it is used to produce very good steel.

3) Ferro-Tungsten:

It is used in the manufacture of tungsten steel and high speed steel(18%W, 4%Cr, 1%V).

4) Ferro-Vanadium:

It is used for the production of tool steel.

5) Ferro-Titanium:

It is used as a carbide stabilizer and deoxidation of steel and alloy steel.