

**INDIRA GANDHI INSTITUTE OF TECHNOLOGY
SARANG, DHENKANAL, ODISHA-759146**

(An Autonomous Institution of Govt. of Odisha)



**Lecture Note
On**

**Sub: FERROUS METALLURGY II (Th. 4)
Semester: 5th**

Prepared By

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Preamble

At the end of the course, a student will be familiar with different industrial steel making processes, identify and formulate problems, develop and apply analytical and experimental methods of investigation, identify contributing factors and generate, validate, and evaluate alternative solutions. This course also aims at familiarity and experience with modern techniques, instrumentation and other tools required for experimental and engineering design, data collection, and data analysis in the practice of steel making.

Before coming to steel making, one should be acquainted with the subjects of this programme such as Principles of Extractive Metallurgy, Transport Phenomena, Metallurgical Thermodynamics & Kinetics and Iron Making to make the teaching-learning process easier.

Syllabus

STEEL MAKING (3-0-0)

Module I (12 Hours)

Introduction: History of steel making, principles of steel making reactions viz decarburization, desulphurization, dephosphorisation, silicon and manganese reactions.

Slag theories: Molecular and ionic theories; interpretation of the above reactions in terms of ionic theory of slags.

Open Hearth steel making practices.

L.D. Process: Design of converter and lance; quality of raw materials charged, operation, control of bath and slag composition, chemical reactions involved, temperature and residual bath oxygen control, use of oxygen sensor; some characteristics of L.D blow viz. emulsion formation, slopping, maneuvering lance height for dephosphorisation and decarburization. Catch Carbon technique. Recovery of waste heat.

Module II (14 Hours)

OBM/Q-BOP process: Concept and operation of the process.

Mixed / Combined blowing processes: Oxygen top blowing with inert gas purging at bottom; oxygen top blowing with inert and oxidizing gases at bottom, oxygen top and bottom: status in India.

Electric arc furnace: Advantages, charging, melting and refining practices for plain carbon and alloy steel; uses of DRI in arc furnace and its effect on performance. UHP electric arc furnace with D.C supply, single graphite electrode, oxygen lancing, oxyfuel burner, water cooled panel and computer control. Combination of blast furnace: EAF. Duplex processes of stainless steel making using VOD, AOD and CLU.

Induction Furnace: Special features, advantages and limitation.

Module III (12 Hours)

Deoxidation of liquid steel: Requirements of deoxidizers, deoxidation practice, stoke's law, use of complex deoxidizers. Inclusions and their influence on quality of steel. Killed, semi-killed and rimming steel.

Secondary refining of steel: Objectives; principles of degassing different industrial process such as DH, RH, VAD, SD, LF, and ESR; limitations and specific applications.

Continuous Casting of steel: Advantages; types of machines; mould lubrication and reciprocation. Development in C.C. Technology with respect to productivity, quality and energy conservation; Near Net Shape Casting.

Pollutant emissions from steel making processes and their control. Management of wastes from steelmaking operations.

Books for reference:

1. Ironmaking and Steelmaking Theory and Practice by A. Ghosh and A. Chatterjee, PHI.
2. Steel Making by A.K.Chakravorty, PHI
3. Physical Chemistry of Iron and Steel Manufacture by C. Bodsworth, Longman Green & Co.
4. Physical Chemistry of Iron and Steel Making by R.G.Ward, ELBS and Edward Arnold 1962.
5. The Making Shaping and Treating of Steel (Steelmaking Volume), R.J.FruehN (ed.), The AISE Steel foundation.
6. Electric Furnace Steel Making: Design, Operation & Practice, Vol. I &II, by C.E.Sims (ed), Interscience.
7. Introduction to Modern Steel Making by R.H.Tupkary, Khanna Publishers, New Delhi1977.
8. Principles of Secondary Processing and Casting of Liquid Steel by A.Ghosh, Oxford &IBP 1990.
9. Electrometallurgy of Steel and Ferro-Alloys , Vol I, by F.P.Edneral, Mir Publishers.

Lesson Plan

Lectures	MODULE-I
Lecture-1	Introduction to Steel Making
Lecture-2	History of steel making
Lecture-3	Modern Steel Making-1
Lecture-4	Modern Steel Making-2
Lecture-5	Science Base of Steel Making
Lecture-6	Steel Making Slag
Lecture-7	Steel Making Reactions: Oxidation of Carbon
Lecture-8 Lecture-9	Steel Making Reactions: Oxidation of Fe, Si and Mn
Lecture-10	Steel Making Reactions: Desulphurization, Dephosphorisation
Lecture-11 Lecture-12	Open Hearth steel making furnace and practices
Lecture-13	Steel Making in LD
Lecture-14	Process Control in BOF
MODULE-II	
Lecture-15	Bottom Blowing process: OBM/Q-BOP
Lecture-16	Hybrid process of Steel Making
Lecture-17	Electric Arc Furnace Steel Making
Lecture-18	Developments in EAF
Lecture-19	Alternate Charge Materials in EAF
Lecture-20	Stainless steel making Technology
Lecture-21	Induction Furnace: Special features, advantages and limitation
Lecture-22	Material Balance in Steel Making
MODULE-III	
Lecture-23	Deoxidation of liquid steel: Requirements of deoxidizers, deoxidation practice, stoke's law, use of complex deoxidizers, Killed, semi-killed and rimming steel.
Lecture-24	Clean Steel and Inclusion Control
Lecture-25	Secondary steel Making: Ladle Metallurgy
Lecture-26	Secondary Steel Making-AOD, VOD, CLU, ESR & VAR
Lecture-27	Gases in Steel and Degassing Technology
Lecture-28	Degassing Practices
Lecture-29	Degassing Calculations
Lecture-30	Solidification of Steel : Ingot Casting
Lecture-31	Continuous Casting of steel: Advantages over Ingot Casting, Design of machines
Lecture-32	Developments in C.C. Technology with respect to productivity, quality and energy conservation; Near Net Shape Casting.
Lecture-33	Pollution Control & Waste Management.

LECTURE-1

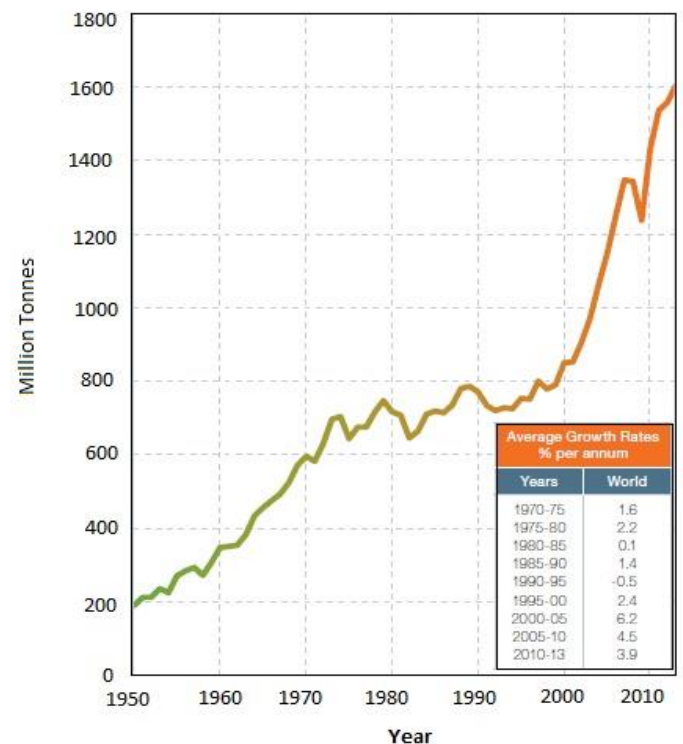
Introduction to Steel Making

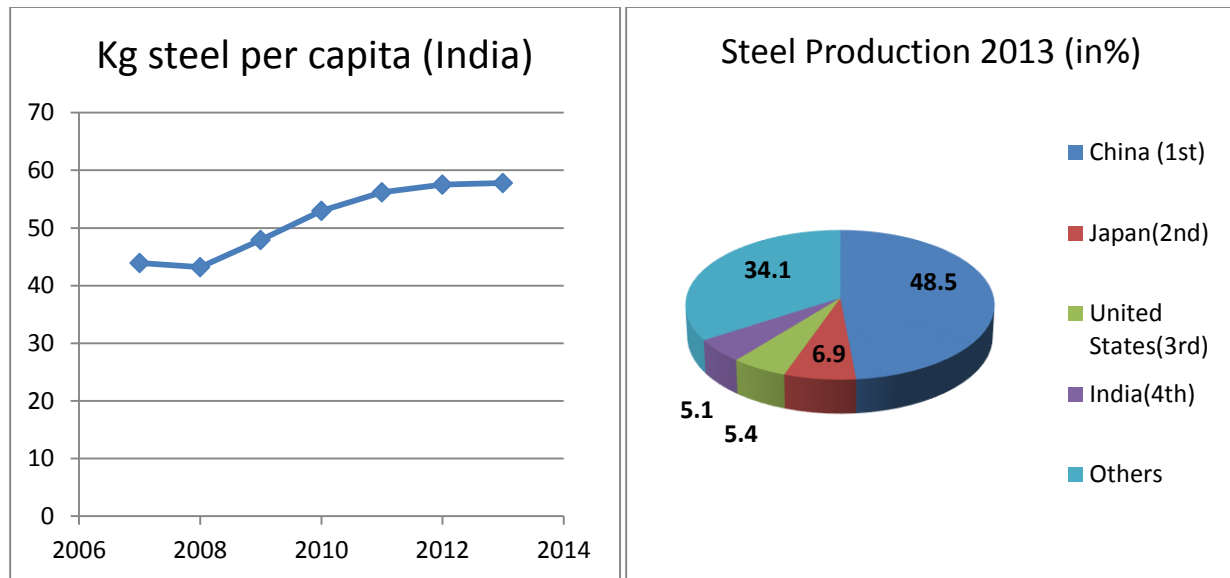
What is Steel?

Steel has been called the world's most useful and inexpensive Ferrous Alloy. It is useful in the way that it shows polymorphism and has good response to various heat treatment processes with excellent properties. It has low temperature α -ferrite(BCC), medium temperature austenite (γ)(FCC) and high temperature δ -ferrite(BCC) phases. Further it is 100% recyclable, hence is a "green material".

Steel production in 2013

Countries	%	Million Tonne
China (1st)	48.5	779
Japan (2nd)	6.9	110.6
United States (3rd)	5.4	86.9
India (4th)	5.1	81.2
Rest of world	34.1	548.3
Total	100	1606





From: worldsteel.org

Steel is an alloy that consists mostly of iron and has carbon content up to 2.11% by weight for plain carbon grade. There are as many as two thousand odd varieties of steels in use. These specifically differ in their chemical composition. However, a couple of hundred varieties are predominantly in use. The chemical composition of steels broadly divide them into two major groups, viz. (i) plain carbon steels and (ii) alloy steels.

The plain carbon steels are essentially alloys of iron and carbon only whereas, if one or more of elements other than carbon are added to steel in significant amounts to ensure specific better properties such as better mechanical strength, ductility, electrical and magnetic properties, corrosion resistance and so on it is known as an alloy steel. These specifically added elements are known as alloying additions in steels.

Plain carbon steels are broadly sub-divided into four major types based on their carbon contents. These are not strict divisions based on carbon contents but are generally broad divisions as a basis of classification. This division is definitely useful. These are:

- (i) Soft or low carbon steels up to 0.15% C
- (ii) Mild steels in the range 0.15-0.35% C
- (iii) Medium carbon steels in the range 0.35-0.65% C
- (iv) High carbon steels in the range 0.65-1.75% C

The alloy steels are broadly sub-divided into three groups on the basis of the total alloying elements present. This division is also only a broad division and not a rigid one. This is :

(i) Low alloy steels up to 5% total alloying contents

(ii) Medium alloy steels 5-10% total alloying

(iii) High alloy steels above 10% total alloying

Steels may contain many other elements such as Al, Si, Mn, S, P, etc. which are not added specifically for any specific purpose but are inevitably present because of their association in the process of iron and steel making and cannot be totally eliminated during the known process of iron and steel making. These are known as impurities in steel.

Every attempt is made to minimize them during the process of steelmaking but such efforts are costly and special techniques are required for decreasing their contents below a certain level in the case of each element.

For cheaper variety of steels therefore their contents at high levels are tolerated. These high levels are however such that the properties of steels are not significantly adversely affected. These tolerable limits of impurities are considered as 'safe limits' and the impurity levels are maintained below these safe limits.

For example, for ordinary steels sulphur contents up to 0.05% are tolerable, whereas for several special steels the limit goes on decreasing to as low as 0.005% or even lower.

What is steel making?

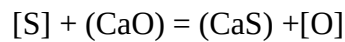
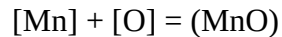
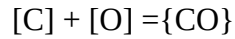
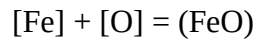
Steel making may be considered as the reverse of iron making i.e. an oxidation process. Impurities are oxidized to their respective oxides and remain within safe limits looking at less iron loss. That's why it is sometimes called the selective oxidation process. The overall process includes charge preparation, melting & refining, tapping, deoxidation, recarburisation, alloying, teeming, casting etc. and all these could not have been covered by any other more appropriate term than "steel making".

Raw materials for steel making:

1. Iron feed (Hot metal/molten metal/ molten pig iron, cold pig, scrap, sponge iron)
2. Flux (limestone, dolomite, lime)

3. Oxidizing agent (Fe_2O_3 , Air, Pure oxygen)

The reactions taking place during steel making can be simply written as follows:



[] for metal, () for slag and { } for gas phase.

- The products in the above reactions are only those which are stable at steelmaking temperatures. The oxides which are not thermodynamically stable at steelmaking temperatures need not be considered here.
- Except the sulphur reaction all the rest are oxidation processes and are favoured under the oxidizing condition of steelmaking.
- In the case of oxidation of carbon the product, being a gas, passes off into the atmosphere but the rest of the oxide products shall remain in contact with the iron melt in the form of a slag phase.

Slag = Gangue + Flux

The molten oxide by-product of smelting and refining process is called as slag. Slag may be acidic or basic in nature depending upon its basicity (B).

$$\text{Basicity} = \frac{\sum \text{All Basic Oxides}}{\sum \text{All Acid Oxides}}$$

Basic oxide: CaO , MgO , FeO , MnO

Acid Oxides: SiO_2 , P_2O_5

Based on the slag type steel making can be of two types: Acid Steel making and Basic steel making.

<u>Acid steel making process</u>	<u>Basic steel making process</u>
1. It is self fluxing (No additional flux required) 2. Slag type : FeO- MnO –SiO_2 3. Slag is acidic. 4. Lining is acidic. 5. Chief impurity is “Si” 6. This process is limited to foundries.	1. Flux is added, to increase basicity of slag. 2. Slag type: CaO- FeO- P_2O_5 3. Slag is basic. 4. Lining is basic. 5. Chief impurity is “P” along with Si,Mn can be removed. 6. It has vast use.

Steel making is carried out in different furnaces. Depending upon the type of furnace used it can be categorized as Pneumatic process (LD) and Hearth process (Open Hearth).

Some furnaces where steel is produced

1. Bessemer Processes
 - a. Acid Bessemer Process
 - b. Basic Bessemer/ Thomas Process
2. Open Hearth Process
3. Electric Arc Furnace Process
4. Basic Oxygen Furnace Processes
 - a. LD Process
 - b. Kaldo Process
 - c. LDAC/OLP Process
 - d. Q-BOP/ OBM Process
5. Hybrid Processes

2013 TOP 30 STEEL MAKING COMPANIES IN THE WORLD

(million tonnes crude steel production)

COMPANY	HQ	Tonnage 2013	Tonnage 2012	Rank in 2013	Rank in 2012	Rank Δ 2013/2012
ArcelorMittal (*)	Luxembourg	96.1	93.6	1	1	=
Nippon Steel & Sumitomo Metal Corporation (*)	Japan	50.1	47.9	2	2	=
Hebei Steel Group (**)	China	45.8	42.8	3	3	=
Baosteel Group (*)	China	43.9	42.7	4	4	=
Wuhan Steel Group (*)	China	39.3	36.4	5	6	↑
POSCO (*)	South Korea	38.4	39.9	6	5	↓
Shagang Group	China	35.1	32.3	7	7	=
Ansteel Group (*)	China	33.7	30.2	8	10	↑
Shougang Group (*)	China	31.5	31.4	9	8	↓
JFE (*)	Japan	31.2	30.4	10	9	↓
Tata Steel Group (*)	India	25.3	23.0	11	11	=
Shandong Steel Group	China	22.8	23.0	12	11	↓
US Steel Corporation (*)	USA	20.4	21.4	13	12	↓
Nucor Corporation (*)	USA	20.2	20.1	14	13	↓
Tianjin Bohai Steel (1)	China	19.3		15		
Gerdau (*)	Brazil	19.0	19.8	16	14	↓
Maanshan Steel	China	18.8	17.3	17	15	↓
Hyundai Steel (*)	South Korea	17.2	17.1	18	16	↓
Benxi Steel	China	16.8	15.1	19	19	=
Evrast Group (*)	Russia	16.1	15.9	20	18	↓
ThyssenKrupp (*)	Germany	15.9	15.1	21	19	↓
Severstal (*)	Russia	15.7	15.1	22	19	↓
NLMK (*)	Russia	15.5	14.9	23	20	↓
Valin Group	China	15.0	14.1	24	21	↓
Metinvest (*)	Ukraine	14.3	12.5	25	28	↑
Jianlong Group	China	14.3	13.8	25	22	↓
IMIDRO (*)	Iran	14.3	13.6	25	23	↓
China Steel Corporation (*)	Taiwan, China	14.3	12.7	25	27	↑
SAIL (*)	India	13.5	13.5	26	24	↓
Fangda Steel (2)	China	13.2	3.3	27	59	↑
Rizhao Steel	China	12.7	13.2	28	25	↓
MMK (*)	Russia	11.9	13.0	29	26	↓
JSW Steel Limited (*)	India	11.8	8.5	30	33	↑

LECTURE-2

History of Steel Making

Introduction

Steel making can be defined as the refining or removal of unwanted elements or other impurities from hot metal produced in a blast furnace.

Most of the hot metal produced in the world is refined by Oxygen steel making process.

The major element removed in OSM is carbon which is removed by oxidation to carbon monoxide.

Routes of Steel Making

1. Ancient Route:- Here molten iron is purified to produce first wrought iron & it is then carburised in solid state to produce steel.

Wrought iron + C = Steel (Blister)

This process is also known as 'Cementation processes.

2. Convectional Route:- Here iron ore is reduced by carbon in a vertical shaft furnace to produce molten iron. Molten iron thus produce is refined using iron ore & O₂ to produce steel in open condition.

Pig iron + O₂ = Steel

3. Alternative Route:- In this method sponge iron is produced & it invariably melted in an electric arc or induction furnace to produce steel.

Sponge Iron → Steel

4. Secondary Route:- Steel can also made by remelting of scrap, as a secondary source.

Scrap → Steel (Green Material)

❖ Based upon furnace steel making process is of 2 types.

1. Hearth Process
2. Pneumatic Process

<u>Hearth Process</u>	<u>Pneumatic Process</u>
- Hearth is shallow, where maximum area is provided for slag-metal interaction. - It is a slower process. - Ex.- Open Hearth furnace.	- Hearth is deep, & also gas pressure is provided. - It is a faster process. - Ex.- L.D.Converter.

Historical Development of Modern Steel Making:-

Year	Developments
1856	The father of steel making is, Sir Henry Bessemer, a British engineer developed a process for bulk steel production called Acid Bessemer Process.
1878	S.G.Thomas and Gilchrist developed basic Bessemer process.
1868	Siemens's and Martins developed Open Hearth Process.
1900	Paul Heroult showed use of electricity for steel production.
1928	Bulk oxygen production technology was developed.
1950	Oxygen was used to produce steel at Linz and Donawitz and process was termed LD Converter steelmaking.
1960	Continuous casting was developed. Today most of the steel plants use continuous casting to produce billet/bloom/slab
1950 and till date	Major developments took place in the following areas - Multi-hole lances for blowing of oxygen in LD Converter - Hot metal pre-treatment to control S and P - Simultaneous blowing of oxygen from top and inert gas/oxygen through the bottom. Industrially the process is known as combined blown steelmaking or hybrid blowing - Refractory lining materials and refractory maintenance and repairing procedures - Usage of ladles to perform refining,

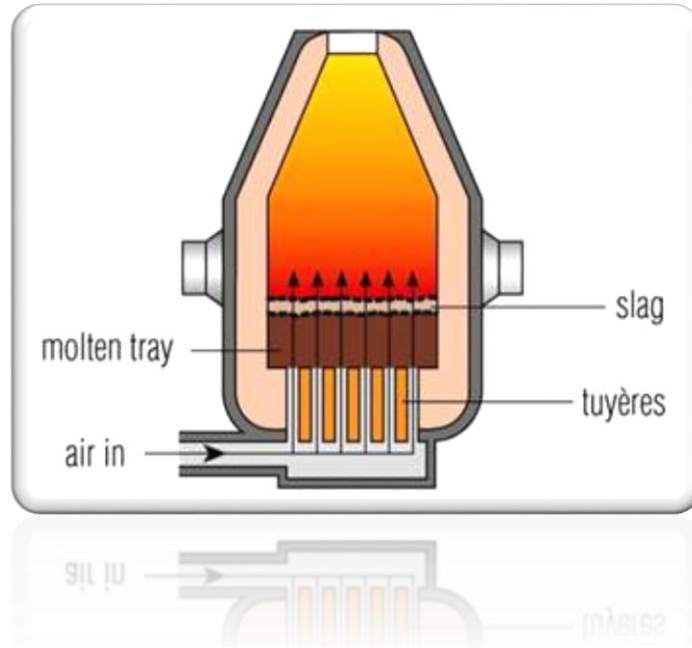
Acid Bessemer process

- This pneumatic process was developed by Henry Bessemer in 1856 .
- Here no heat was supplied from outside because most of the refining reaction are exothermic in nature.

- This process consists of pear shape vessel lined with acid refractory & air is blown through bottom of the vessel .

Demerits:-

- Because of acid lining , it was not possible to remove phosphorous .
- Also oxygen content of steel was very high.



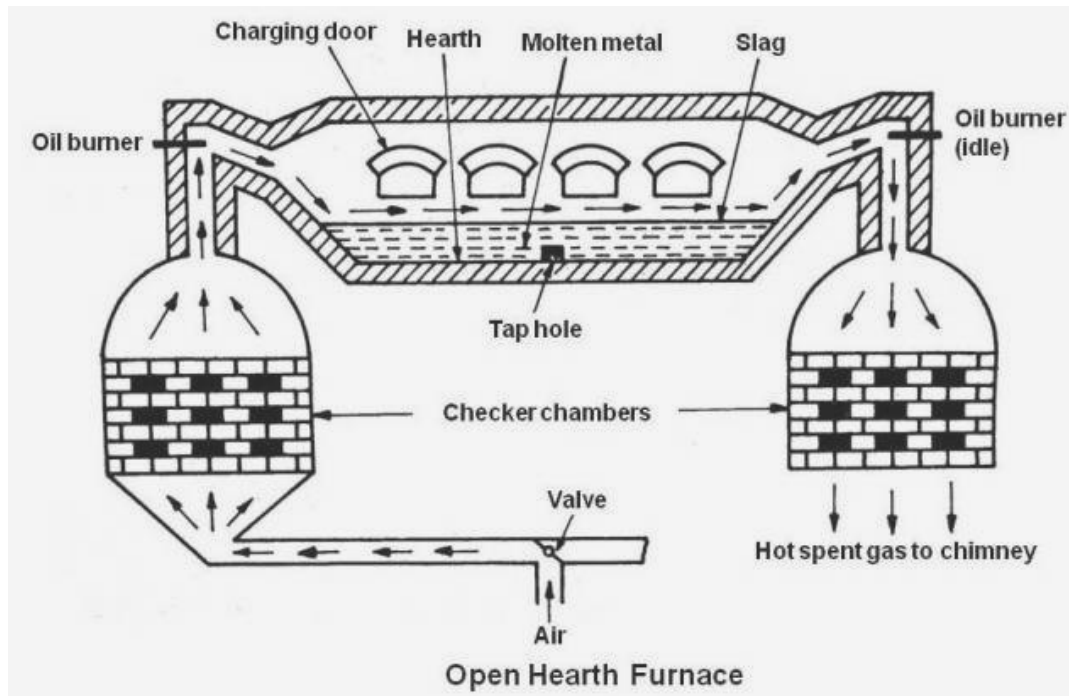
In around 1864, Mushed had developed iron-manganese alloy, with this development, it did become possible to reduce the oxygen content of steel.

Basic Bessemer Process:-

- This process was developed in 1878 .
- Here shape of the vessel was same as the Bessemer process.
- The basic difference between the two process was the use of basic lining instead of acid lining.
- Due to the basic lining, it was possible to remove Phosphorous from the hot metal which was not possible in Acid Bessemer process.
- High nitrogen content of steel, no usage of scrap and plugging of bottom blown tuyeres were the problems.

Open Hearth Process:-

- The hearth furnace in this process is fairly shallow basic lined vessel. It is heated either by liquid and /or gaseous fuel using heat regeneration principle to attain temp 1600-1700° c and enabling them to use steel scrap in addition to other charge materials..
- Atmosphere in this process always oxidising.



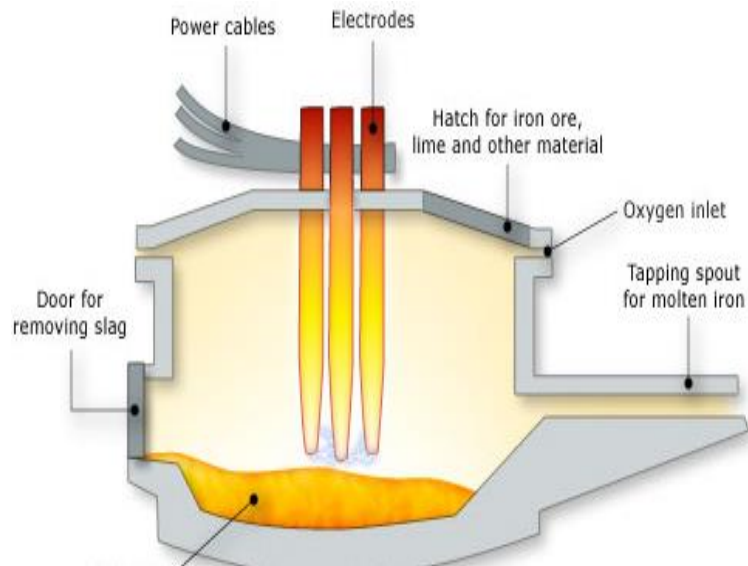
Open Hearth Process for steelmaking has dominated the steel production for over approximately a century.

Disadvantage:

- The process is very slow.
- The process is not autogenous.
- Thermal efficiency is less.

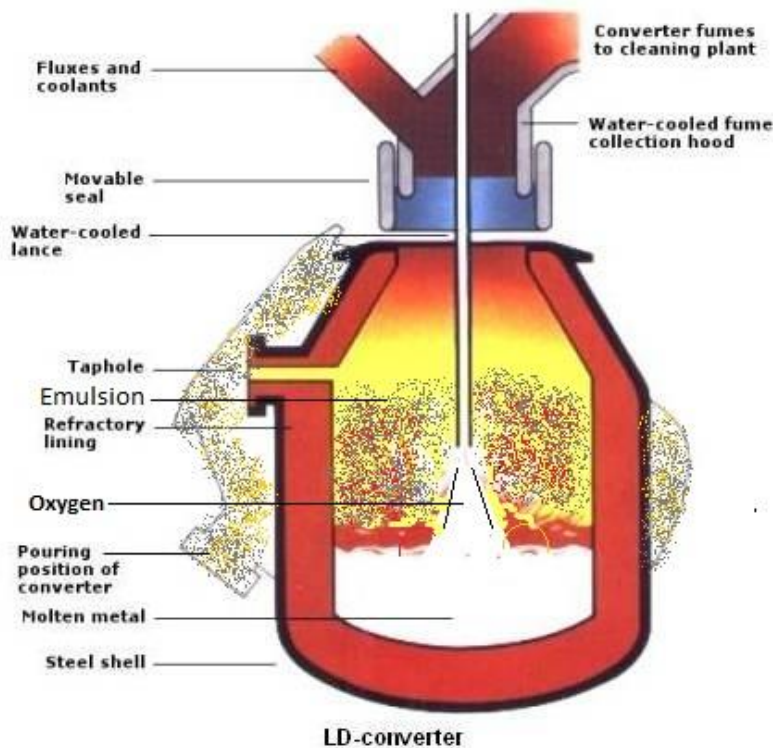
Electric Arc Furnace:-

- The steelmaking temp is maintained by an electric arc struck between the electrodes & the metallic charge.
- This is the only process wherein either oxidising or reducing condition can be maintained as desired. So, different slag types can be carried out.
- The high cost of electrical energy makes this process costly.
- It is well suited for making alloy steels.

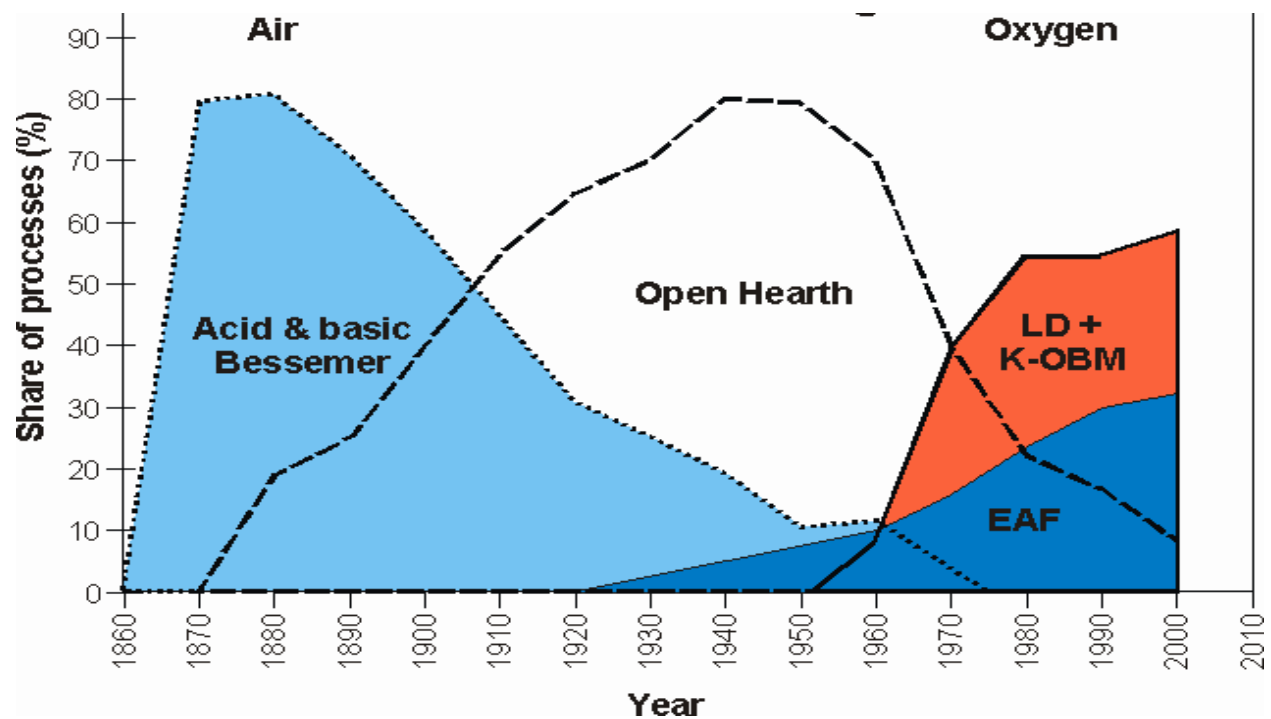


L.D. Converter:-

- The furnace is similar in design to that of bessemer converter except that the bottom is solid & oxygen is blown vertically from top.
- This process is autogeneous & need molten pig iron as a charge material(75%).
- Steel scrap(25%) is used as coolant since excess heat is available.
- Refining is complete in 20- 25 min of oxygen blowing & tap to tap time 40 -60 min is needed.
- Emulsion phase reaction makes the process so fast that there is no time for Sulphur removal
- Pure oxygen (99.5+) enhances the oxidation of impurities.



Share of various processes in total steel production on global basis:



Indian steel industry is organised in three sectors as shown in the following:

Sectors			
Integrated steel plants		Mini steel plants	Induction furnaces.
Public sector		Private sector	
• Rourkela • Bhilai • Durgapur • Bokaro • Salem • Alloy steel plant Durgapur • Indian iron and steel company • Visvesyary a iron and steel • RINKL, Vishakhapatnam	• TISCO • ESSAR • ISPAT • JSW	• Uttam steels • Kalyani steels • Lloyd steel • Usha martin • Tata Metalics • Mukand ltd. (Reader may add more).	Dispersed In various Parts of the country

LECTURE-3

Modern steelmaking-1

Introduction

Steel is a very old material and known to mankind for a long time. For a metallurgist it is a solution of carbon in iron with certain amount of trace elements may be sometimes silicon, sometimes other alloying additions like manganese and occasionally, we have some impurities also present in steel, which we are unable to drive off completely. Steel is a material that has diverse engineering properties like high toughness, high tensile strength, good strength to weight ratio, superior high temperature properties immense recycling potential. After iron making steel making is carried out and through different refining and mechanical working processes final steel product is obtained. The objective of this lecture is to acquire adequate knowledge of fundamentals of modern steel making, get familiar with the modern steel making processes, difficulties experienced and to know how difficult it is to be overcome by further advanced technologies. When we talk of modern steelmaking process, we are talking of the era of oxygen steel making that means we are talking of the post 1950 years and we are talking of steelmaking that is mostly oxygen steel making processes. Steel making has been improved in terms of productivity, cleanliness and environmental context since last decade.

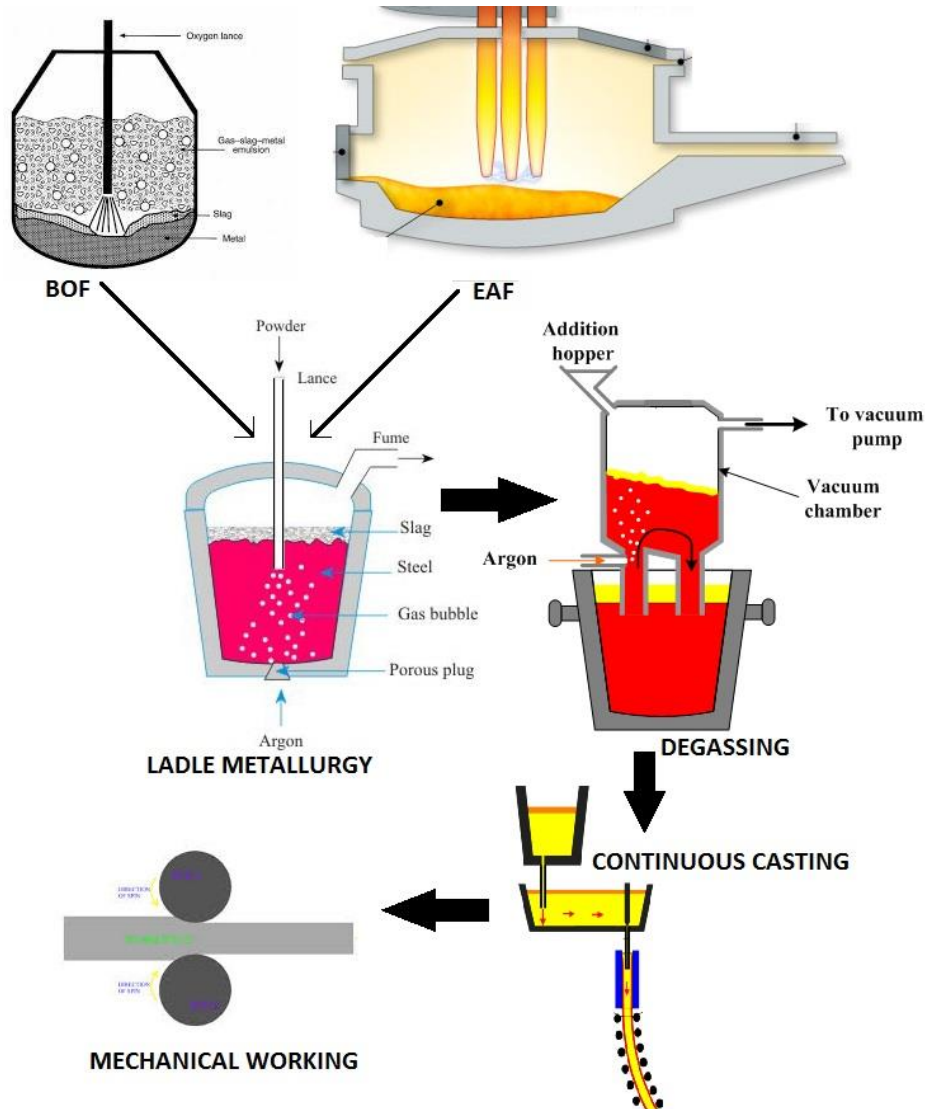
To obtain steel the following steps are operative

1. Primary steel Making (BOF/EAF)
2. Secondary steel making(ladle metallurgy)
3. Casting (95% CC+5% ingot casting)
4. Mechanical working/Finishing

Primary Steel Making can be:

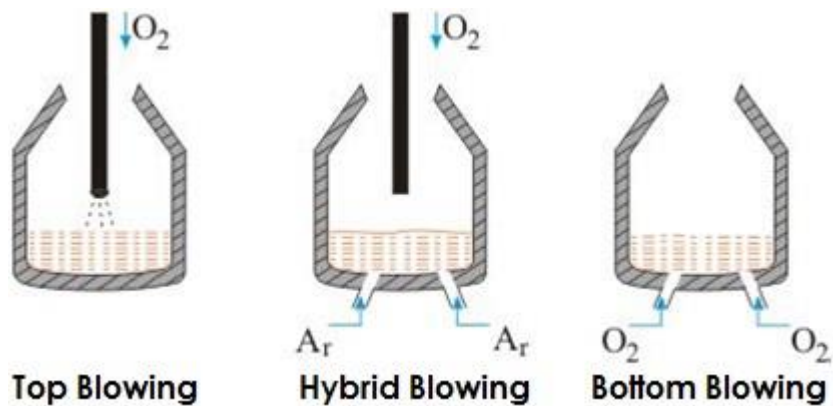
1. Basic Oxygen Steel making
2. Electric Steel Making

	Basic Oxygen Steel Making	Electric Steel Making
Raw Materials	Molten pig iron, scrap	Sponge Iron/Direct Reduced Iron (DRI), Scrap, Solid pig iron
Furnace	BOF (LD)	Electric Arc F/c
Share	60% world crude steel	34%
Atmosphere	Oxidizing	Oxidizing/Reducing
Process	Pneumatic	Hearth



BOF:

It is generally a pneumatic process. In basic steel making processes we have slag basicity more than 1, so we can afford to have a lining of the reactor also as basic; if we make the lining acidic then the slag is going to eat up the lining.



Today acid steel making process no more in practice; steel making process are all basic, whether it is electric arc furnace steel making process (ESP) or whether it is BOS, it is always basic oxygen steel making process, because by making a slag with high basicity more than 2, 2.5, 2.8 etc. it is possible to simultaneously eliminate both phosphorus and silicon when we particularly inject oxygen to the system. Raw materials are generally: Molten pig iron+ scrap, lime and oxygen. Oxygen is provided in supersonic speed through a water cooled top lance fitted with multi hole nozzle which distributes oxygen from the gas phase to the liquid iron: $\{O_2\}=2[O]$ and oxidation is carried out. The pig iron enters the f/c at a temperature of about $1300^{\circ}C$. as the oxidation of impurities in it are exothermic in nature, provides heat for steel making at $1600^{\circ}C$ along with compensating other endothermic steps like lime dissolution, slag formation, deoxidation, alloy addition and tapping without requiring external fuel. That's why this process is called autogenous process of steel making. Therefore a threshold amount of carbon, a threshold amount of silicon is necessary to produce that desired level of heat. Often in steelmaking, we will see that the level of impurities is such that the temperature gets even more than $1600^{\circ}C$ and that is why when such a scenario is experienced; we add coolant into steel, which is nothing but the plant generated solid scrap and that solid scrap when you put into the steel making reactor the temperature goes down.

Top lancing of oxygen provides stirring effect of the bath. Lancing of oxygen generally forms tiny particles of slag-metal-gas system which increases the interfacial area in turn enhances the reactions as they depend upon mass transfer rate with a heat time as low as 30-60mins. For more stirring oxygen / argon can be introduced from the bottom. OBM process is a bottom blowing process which provides oxygen from the bottom through inner most space of the cocentric tube

of the tuyere along with hydrocarbon through the annular space. In hybrid processes oxygen top and argon bottom may be used for effective stirring.

In Bessemer process, when air was used, some threshold amount of oxygen was required to get into that, to react with molten metal to produce molten steel. So more amount of air had to be supplied, because, air contains only 21 percentage of oxygen.

Therefore, it is understood that more volume of air is going to be introduced; that means, more heat is going to be consumed by the cold air as we are introducing more amount of nitrogen and this nitrogen, without doing anything goes out of the steel converter taking away heat.

A critical amount of phosphorus, a critical amount of silicon is required to fulfill the thermal requirement of the process. Otherwise, so much of heat is going to be lost because of the high volume of air injected, that the steel may not be at the desirable temperature.

It is now clear that air is not a good oxidizing agent. Soft steel of a very low level of carbon cannot be produced with air. So, steel makers always wanted in the beginning to produce or to make steel through an oxygen steel making route, which was not possible since late 1950s, when the Henry steel making process was encountered.

The campaign of a BOF may be as long as 20-30 thousand heats with an average of 30 heats a day. So, the converter lining is lost in 1000 days, this means a converter is required to be relined only after 3 years of time.

Campaign: Lining to relining of the furnace. Often called life time of the furnace.

Heat: Tap to next tap time.

Tapping: Collection of metal or slag

EAF

The EAF steel bath is shallow so it called a **hearth process**. The furnace consists of a steel shell, lined with suitable (generally basic) refractory materials and is mounted on the tilting mechanism. **Three graphite electrodes** enter through the roof. In indirect arc f/c, arc is struck between two carbon electrodes & heat is transferred to the charge by radiation. In direct arc f/c current flows from the electrode to the charge & heat is transferred from the arc to the charge primarily by radiation but a part of the heat is also generated in the charge itself. A three

electrode EAF is used where one phase connected to each electrode and charge is the neutral point. Heat is generated by the hot area formed between the electrodes and the charge. As we are not using pig iron here we are using DRI and scrap, It is **not an autogenous process**. It has no atmosphere of its own. We can make it oxidising as well as reducing up to our requirement.

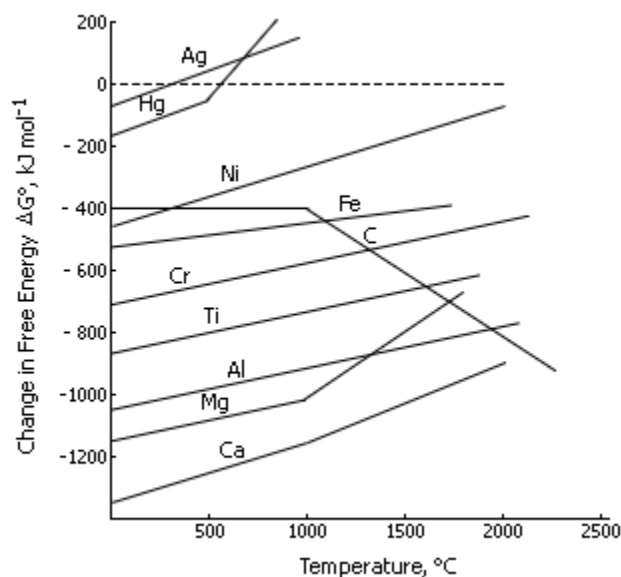
LECTURE-4

Modern Steel Making-2

After bulk steel making either through BOF or EAF the steel is subjected to deoxidation or ladle metallurgy. The arc furnace or oxygen steelmaking furnace is emptied into the steel ladle- this process is called tapping. The steel ladle is dolomitic lined vessel basically a cylindrical shaped, marginally tapered cylindrical vessel. When the ladle becomes completely filled, it contains lot of oxygen and this is to be eliminated. The first very step beyond the primary steelmaking is de-oxidation and then comes the ladle metallurgy or the secondary steelmaking and we must note here, that we do not want to carry out de-oxidation operation in the BOF or EAF, because we would like this furnace to be used not for de-oxidation, but for making of steel.

A) Deoxidation

These deoxidizers are basically elements having greater affinity towards oxygen. We require an element which has greater affinity towards oxygen than iron has and in this context, aluminium, silicon, manganese can be used as deoxidisers. For example, we can say aluminium has very high efficiency or affinity towards oxygen, how do we know that? If we remember the Ellingham diagram lower is the position of the line of a metal oxide, greater its stability and greater is its



affinity towards oxygen. So, we refer to the oxide Ellingham diagram and then, we can find out which are the elements. So, these materials deoxidizers will react with oxygen form some oxides; they will react with siliceous materials, spar, etcetera and produce a slag layer basically silicates and that silicates are going to float at the free surface and prevent any preferential heat loss through the free surface, because the oxide layers here will provide some barrier for the escape of the heat to the surrounding; otherwise, the metal is going to get a really chill.

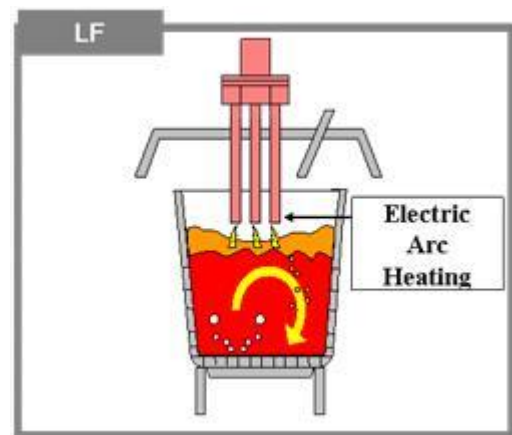
In a steel plant, we will see that deoxidisers are projected in the vicinity of the jet impact zone, because deoxidizer elements are lighter, and the flow is downward and this try to downward flow try to catch the particles and take them down; as a result of which the deoxidizer elements very go deep into the bath and then, reacted dissolve melt and react with dissolve oxygen. Otherwise, if they are projected other than in this particular region, they will immediately come up to the surface and here they will come in contact with atmospheric oxygen giving rise to very low yield or low efficiency of utilization of the deoxidizer.

If we visit a steel plant, we will see that the bottom of the ladle is connected through a host pipe when the ladle is lifted from the tapping area that pipe basically is the argon feeding pipe through the porous plug. This essentially helps in stirring the metal for homogenization.

B) Ladle metallurgy

The objective of ladle metallurgy is composition adjustment, composition control, temperature control and cleanliness control; these are the three primary objectives of ladle metallurgy steelmaking.

Steel may contain lot of alumina particles still within the melt itself; not that each and every alumina particle has floated up; it may contain lot of dissolved nitrogen; it may contain some amount of sulphur, which is not acceptable to the customer.



Though we have deoxidized steel, but the composition is not right, we have to have further composition adjustment and of course, when we are making an alloyed steel, obviously different grades of steel has been made in steel plants, so we have to make some alloying additions and so on. So, we will have to adjust now the composition of the steel as per the requirement of the customer.

In the process of composition control, we must know that, if we want to add alloying additions, we will add in cold additions. So, with the cold additions, there is going to be some drop in temperature, because of the melting; there may be some heat of mixing, heat may be produced.

So, a thermal readjustment may be necessary. There may be a temperature drop in most of the cases and therefore, we have to over-win that loss in temperature somehow, such that as the material is fluid enough. Ladle metallurgy ensures the correct temperature of the material as it goes to the continuous casting or the casting bay.

The final stage of steelmaking which is the continuous casting today, and when the ladle brought to the turret, turret means, which is the place, where the ladle is kept about the tundish and where from material is fed into the tundish and from the tundish into the mold.

So, during the ladle metallurgy steelmaking itself, we will not only do composition adjustment; or do get to the right temperature, but we will also control the inclusion counts in the material such that, when steel is brought to the turret, it has absolutely no question regarding any of the three issues. And that is why it so important for us to control the secondary steelmaking or ladle metallurgy steelmaking processes.

Now, the first thing to note about secondary steelmaking or ladle metallurgy steelmaking is that the duration of ladle metallurgy steelmaking could often be more than the duration of primary steelmaking. The size of the ladle is same as the capacity of the electric arc furnace or capacity of the BOF.

So, the gas stirring essentially enhances the temperature and composition homogeneity, it enhances mixing in the system itself. So, this is all the time in most of the steel plants, in ladle metallurgy, this is a common process which is going to be used in ladle metallurgy steelmaking process. Now, this is the essential component inert gas stirring and then, ladle furnace, after this ladle furnace you can continue to put in the gas, then you can lift the ladle and take it to the turret.

Degassing:

Now, one such process is the degassing process. We have various types of degassing processes, which will study in detail when you talk about secondary steelmaking or we know ladle metallurgy techniques.

Now, this degassing process - the basic objective of the degassing process is that we want the dissolved gasses like nitrogen, hydrogen to be removed. And we know that this sort of a reaction- the degassing reaction- are going to be facilitated under lower pressure, because lower

the pressure, more will be the tendency to go in the forward direction. Therefore, the degassing process is carried out under vacuum and therefore, most often we say that these are vacuum degassing process.

In the degassing station an air tight cover is fitted to LF and the suction started and as a result of which, the vessel becomes depressurized and it is continued to inject argon and we must remember that, here we have a slag layer over the metal we want some opening in the slag layer . This opening is created by the gas injection or the inert gas stirring. So, the argon gas rises; it pushes the slag and brings the molten metal in contact with the vacuum and through this, the nitrogen, hydrogen will go into the gas phase. So, more is the argon flow rate, more bigger is the opening; better is the contact of the melt with the ambient atmosphere and therefore, more is the transfer of the dissolved gases from the melt into the atmosphere.

Injection Metallurgy:

After Vacuum Degassing, we can have injection metallurgy and the purpose of injection metallurgy is to control the inclusion morphologies, to fine-tune the chemical composition. Calcium injection is very popular; it has a low vaporizing temperature. Calcium in the form of wire is injected deep inside the melt and this calcium becomes gas under steelmaking conditions; it can react with sulphur to form complex compounds with alumina inclusions and so on and thereby, help to produce clean steel after separation of these liquid inclusions with modified composition of the inclusions. Calcium is a very expensive element to add into steel, so this also going to add to the cost of steel to a significant extent.

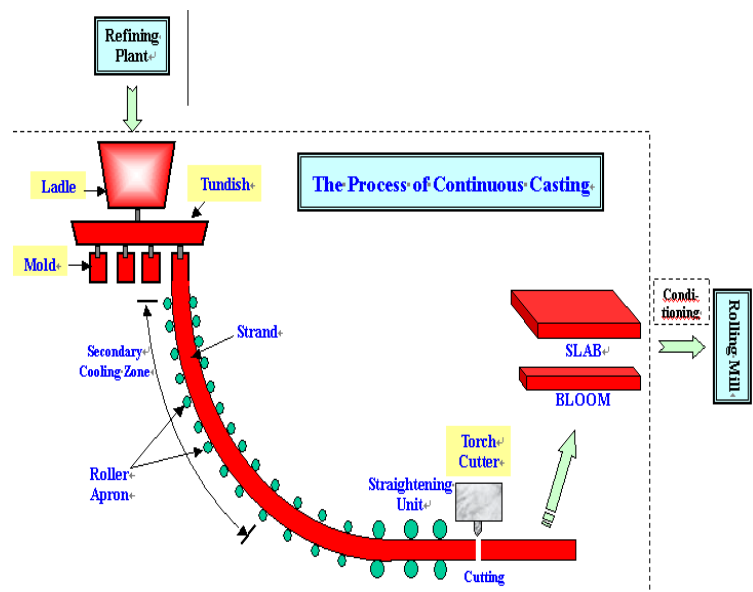
There may be subsequent operations. Degassing process, for example, there may be injection metallurgy processes for another 20 minutes; degassing processes could be about 30 minutes and again in this 30 minutes and subsequent 20 minutes of injection process, the temperature will be dropped because of radiation losses. It can drop often if the ladle is covered about 0.5 degree centigrade per minute. So, some engineering calculations are necessary for the temperature drop. Here for example, If we just go to the casting bay immediately from the LF, we would say may be 5 degrees more than what is required by the custom operator. If it has to go through the vacuum degassing process, if it has to go through injection metallurgy processes, then we may say 30 degree is more or may be after vacuum degassing processes, we have to bring it that to the LF, because there may be significant amount of temperature drop itself. These to and fro

movement may also be there and all these are going to consume time and that is why it is mentioned, that ladle metallurgy techniques can actually take more than the duration of the primary steel making process.

A series of operations can be carried out to achieve entire objective of ladle metallurgy viz: the composition control, the temperature control and to control in the cleanliness.

Continuous casting:

Continuous casting machines perform vital roles. The mold is water cooled; so some materials solidify here and then, the solidification is completed in the secondary cooling zone where we have spray of water, as the result of which steel becomes completely solidified and as it comes down, as it drawn at some point through a shearing machine to cut into sizes and then, it is subsequently taken into heat treatment furnace for further mechanical treatment and final operations



Lecture-5

Science Base of Steelmaking

Introduction

In order to be a good steel making engineer we have to acquire sound knowledge in the field of Iron and steel making processes. Science based fundamentals of steel making let us know about the process to build models and enable us to make meaningful measurements in turn which is helpful in optimizing the process with respect to yield, new technologies and also new products. In steelmaking, the impurities like carbon, silicon, manganese, phosphorus and sulphur are removed from hot metal through a combination of metal-slag, Metal-gas and slag-gas reactions so as to produce steel of desired chemistry and cleanliness (cleanliness refers to the inclusions). Science of steelmaking involves: Metallurgical Thermodynamics and Metallurgical Kinetics which includes chemical reactions and rate phenomena like heat transfer, mass transfer and fluid flow.

Equilibrium between the phases:

The phases in steelmaking are hot metal, molten slag and gas. Hot metal is a multi-component solution in which impurities like carbon, silicon, manganese, phosphorus and sulphur are dissolved in very low amount (total concentration of all the impurities is approximately 5% to 6%) in iron. Slag is a solution of predominantly oxides with small amounts of sulphides, phosphides, silicates etc. Composition of the solutions in steelmaking is conveniently expressed either as Wt% or mole fraction(N). The mole fraction of the i^{th} component in a solution of n components is

$$N_i = X_i / \sum X_i$$

where X_i is the number of moles of i^{th} component. The equilibrium of a component between the liquid phases is expressed in terms of integral molar free energy. Integral molar free energy of solution

$$G^m = \sum G_i^m N_i = \sum G_i N_i - \sum G_i^0 N_i = RT \sum N_i \ln a_i$$

$G_i N_i$ represents free energy of solution and $G_i^0 N_i$ is the free energy of pure components before entering into the solution. The quantity G_i^m is the partial molar free energy of mixing of

component i and represent the change of energy or work which a mole of pure component i can make available.

- Chemical potential is a useful concept to describe chemical equilibrium between liquid phases. At chemical equilibrium the chemical potential of any component is identical in all phases. Knowledge of chemical potential is important in steelmaking because an impurity can transfer in the gaseous or slag phase only when its chemical potential is lower than in hot metal.
- The criterion for equilibrium at constant temperature and pressure is the change in the integral molar free energy of the solution, $(dG)_{T,P}$ i.e.
 $(dG)_{T,P}=0$ for an infinitesimal process and
 $(\Delta G)_{T,P}=0$ for a finite process

Where $(dG)_P$ is change in integral molar free energy

At constant temperature and pressure when $(dG)_{T,P}<0$, a process occurs spontaneously.

For an isothermal chemical reaction:

Say **$aA + bB = cC + dD$**

$$\Delta G = \Delta G^0 + RT \ln J$$

where ΔG^0 is the standard free energy change and J is activity (a) quotient.

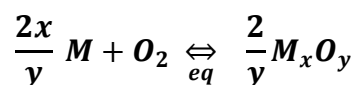
$$J = \frac{a_{[C]}^c \cdot a_{[D]}^d}{a_{[A]}^a \cdot a_{[B]}^b}$$

At equilibrium $\Delta G=0$

$$\Delta G^0 = -RT \ln (J)_{eq} = -RT \ln K, \text{ where } K \text{ is equilibrium constant.}$$

Standard free energy of formation ΔG^0

Consider an oxidation reaction



{For Example: Alumina Al_2O_3 X=2, y= 3}

$$K = \frac{a_{[M_xO_y]^{2/y}}}{a_{[M]^{2x/y}} \cdot a_{[O]^2}}$$
$$= \frac{a_{[M_xO_y]^{2/y}}}{a_{[M]^{2x/y}} \cdot p_{O_2}}$$

For standard state activity of pure metal and metal oxide is 1

$$K = \frac{1}{p_{O_2}}$$

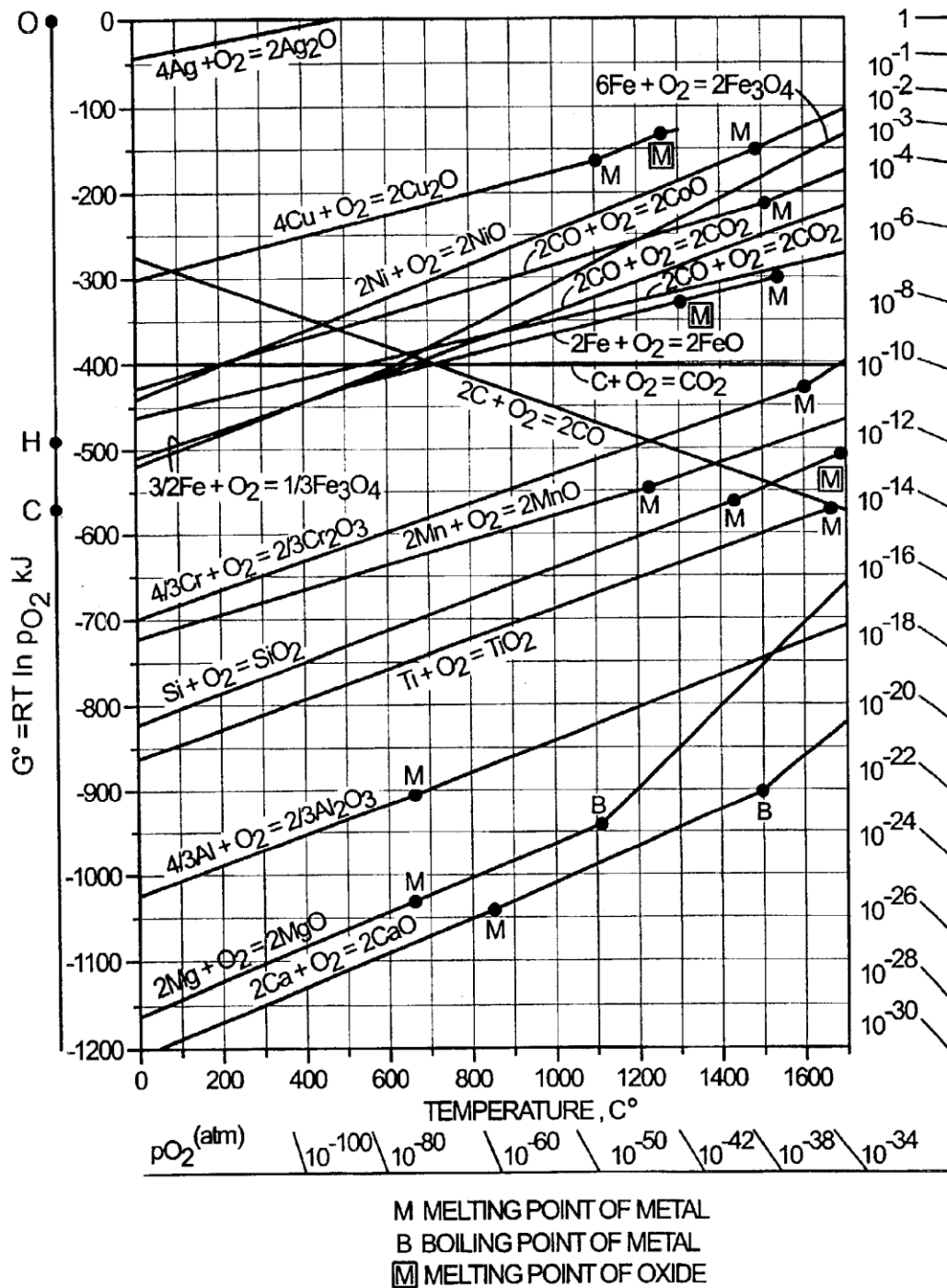
So, now we can write $\Delta G^0 = -RT \ln (1/p_{O_2}) = RT \ln (p_{O_2})$

And calculate the ΔG^0 value for any given temperature.

The plot between ΔG^0 at various temperatures gives the Ellingham diagram for oxides.

Gibb's Free Energy : $G = H + TS$ or $G^0 = H^0 + TS^0$

H=Enthalpy S=Entropy T=Absolute Temperature



- Phase change shows slope change
- Oxides at lower part are more stable than those above them i.e. a metal can reduce metal oxide that lies above it.

Activity of solution:

In dealing with chemical reactions in solution it is important to define the activity of a component. Activity of a component denotes its effective concentration. It is related to fugacity as

$$a_i = f_i / f_i^0$$

f_i is the fugacity of component i in solution and f_i^0 is the fugacity of a component in its standard state (standard state could be either pure element or compound at 1 atmospheric pressure) So at standard state activity equals 1. In an ideal gas activity of a component i is equal to its partial pressure.

Raoult's Law:

An ideal solution obeys Raoult's law, in which activity of a component a_i equals to its mole fraction N_i (somewhere written as X_i)

$$a_i = N_i$$

Real solutions exhibit either positive or negative deviation from Raoult's law for a binary solution.

Deviation from Raoult's law is taken care by activity coefficient γ_i

$$\gamma_i = a_i / N_i$$

The Fe-Mn forms an ideal solution, whereas the Fe-Cu exhibits strong positive deviation and the Fe-Si strong negative from Raoult's law. Physically it implies that in Fe-Cu solution copper has a strong tendency to segregate, and in Fe-Si solution silicon has a strong tendency to form chemical compound with iron.

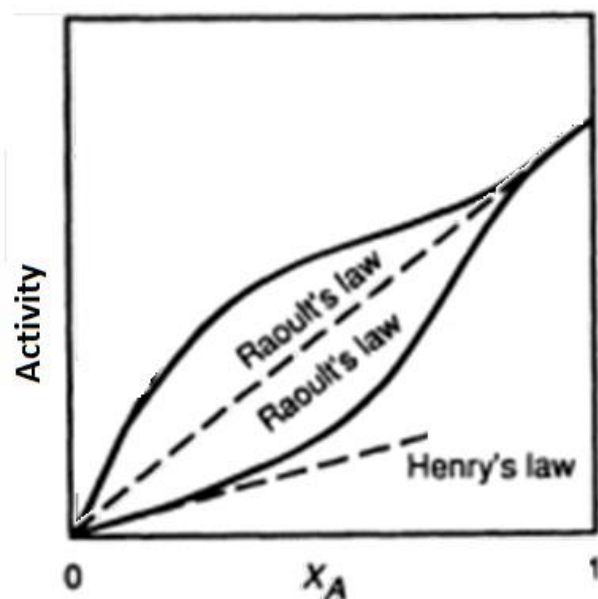
In binary liquid oxides, FeO-MnO behaves ideally, whereas most binary silicates i.e. CaO-SiO₂, FeO-SiO₂, MgO-SiO₂ show negative deviation from Raoult's law.

Henry's law:

Liquid steel, and to a reasonable extent hot metal primarily fall in the category of dilute solution. In a dilute binary solution activity of a solute obeys Henry's law, which is stated as

$$a_i = \gamma_i^0 N_i$$

where γ_i^0 is a constant (activity coefficient for the solute in dilute binary) and N_i is the mole fraction of the specie i. Solutes in all infinite dilute solutions obey Henry's law. Deviation from Henry's law occurs when the solute concentration increases.



1wt% standard state:

In steelmaking the concentration of solute in molten steel is expressed in weight percent.

It is frequently most convenient to choose the infinitely dilute solution expressed in terms of weight percent as the standard state. This is defined as

$$h_i / (\text{Wt\% } i) = 1 \text{ when wt\% } i \rightarrow 0$$

For weight percent i other than zero

$$h_i = f_i \text{ Wt\% } i$$

Interaction parameter:

Molten steel contains several dissolved solutes in dilute scale. For example, molten steel contains C, S, P, Si, Mn etc. This steel is a multi-component solution. In multi-component solution solutes interact with one another and thus influence activities of other solutes. If Fe is the solvent, and 1, 2....J are solutes in dilute state, then

$$\log f_i = e_i^1 \text{Wt \%} 1 + e_i^2 \text{Wt \%} 2 + e_i^3 \text{Wt \%} 3 + e_i^4 \text{Wt \%} 4 + \dots e_i^J \text{Wt \%} J$$

The term e_i^j is known as interaction parameter describing the influence of solute j on the activity coefficient of solute i . The value of interaction parameter can be found in any book on thermodynamics.

The concept of interaction parameter is very important in estimating the activity of a solute element in presence of other solute elements. For example we want to calculate the activity of sulphur in hot metal of composition C = 4%, Si = 1.5%, Mn = 1% and S = 0.04% at 1600 °C. By assuming infinite dilute solution as the standard state, the activity of sulphur is given by

$$h_s = f_s \text{ Wt\%S}$$

$$\log f_s = e_s^S \text{Wt \%S} + e_s^C \text{Wt \%C} + e_s^{\text{Si}} \text{Wt \%Si} + e_s^{\text{Mn}} \text{Wt \%Mn}$$

Substituting the value of $e_s^S = -0.028$, $+e_s^C = 0.24$, $e_s^{\text{Si}} = 0.066$ and $+e_s^{\text{Mn}} = -0.025$, we get $f_s = 10.78$ and activity of sulphur is 0.43.

LECTURE-6

Steel Making Slag

Introduction

A solution of molten oxides is called “Slag”. The purpose of slag in metal extraction and refining is to collect all the “gangue” waste products in the form of oxides (or sulphides in small quantities) and eliminate the impurities into a separate phase. Thus refining reactions are often studied in terms of the relevant “metal-slag equilibrium”. The thermodynamics of the refining behaviour of a slag phase with respect to a liquid metal is a function of temperature and of the composition of the two phases. Slag plays a very important role in steelmaking to the extent that it is said that “take care of slag and metal will take care of itself”. Slag is a generic name and in steelmaking it is mostly a solution of oxides and sulphides in the molten state and the multi-crystalline phases in the solid state.

Slag is a separate phase because:

- It is lighter than molten steel and
- It is immiscible in steel

Slag is formed during refining of hot metal in which Si oxidizes to SiO_2 , Mn to MnO , Fe to FeO , and P to P_2O_5 , and addition of oxides such as CaO , MgO , iron oxide, and others. The addition of oxides is done to obtain desired physico-chemical properties of slag like melting point, basicity, viscosity etc. All these oxides float on the surface of the molten steel. Synthetic slag is also used to absorb inclusions to produce clean steel for certain applications.

The role of slag in steelmaking:

- It acts as a sink for impurities during refining of steel
- It controls oxidizing and reducing potential during refining through FeO content. Higher FeO makes the slag oxidizing and lower FeO reducing
- It prevents passage of nitrogen and hydrogen from atmosphere to the molten steel
- It absorbs oxide/sulphide inclusions
- It acts as a thermal barrier to prevent heat transfer from molten steel to the surrounding

- It protects steel against re-oxidation
- It emulsifies hot metal and promotes carbon oxidation.
- In electric steelmaking slag prevents the radiation of heat of arc to the walls of the furnace and roof

The above functions require that slag should possess certain physical (density, melting point, viscosity) and chemical properties (basicity, oxidation potential). Both physical and chemical properties are controlled by composition and structure of slag. In steelmaking slag is predominantly a mixture of oxides with small amounts of sulphides and phosphides. The oxides are either acidic or basic in nature. We will first consider the structure of pure oxides and then we discuss what happens on addition of one type of oxide to the other.

Basic oxides: FeO, MnO, CaO, MgO. Na₂O etc.

Acid oxides: SiO₂, P₂O₅ etc.

$$\text{Slag Basicity } B = \frac{\Sigma(\text{wt}\% \text{ All Basic oxides})}{\Sigma(\text{wt}\% \text{ All Acid oxides})}$$

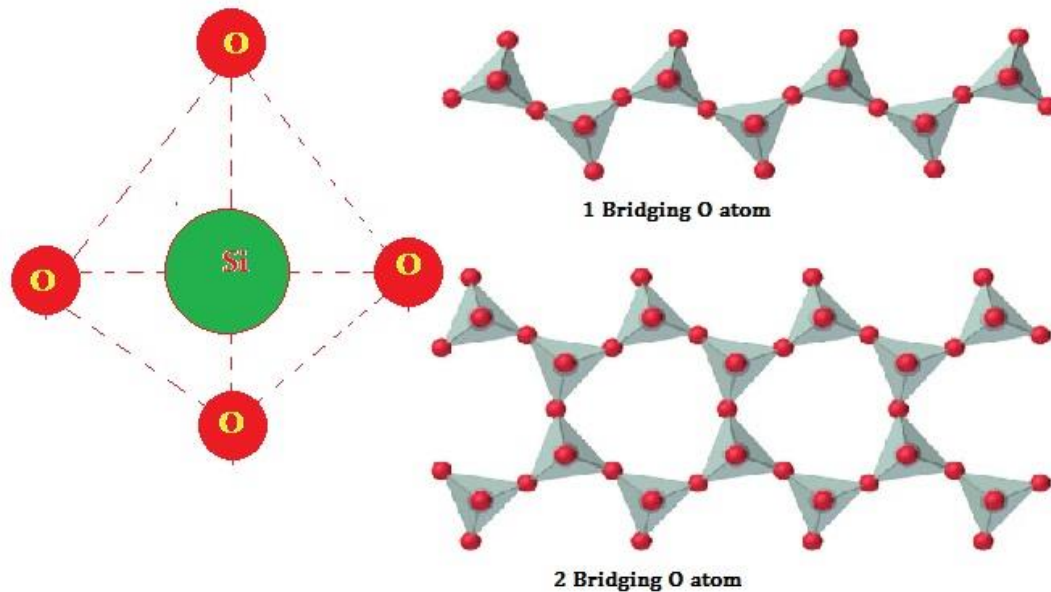
$$V \text{ ratio} = \frac{\text{wt}\% \text{ CaO}}{\text{wt}\% \text{ SiO}_2}$$

$$\text{Modified } V \text{ ratio} = \frac{\text{wt}\% \text{ CaO}}{(\text{wt}\% \text{ SiO}_2) + (\text{wt}\% \text{ Al}_2\text{O}_3) + (\text{wt}\% \text{ P}_2\text{O}_5)}$$

The basic oxides have octahedral and acidic oxides tetrahedral structure

Structure of pure silica

In silica, each atom of silicon is bonded with four oxygen atoms and each atom of oxygen is bonded with two silicon atoms. The elemental tetrahedral of silica are joined at the vertices to give the hexagonal network in three dimensions.



As seen in the figure each tetrahedron is joined at the vertex so as to obtain the three dimensional hexagonal network.

Network former and breaker oxides

It must also be understood that the bonding between cations and anions in acidic oxides like SiO_2 and P_2O_5 is strong, and these simple ions group to form complex ions as $(\text{SiO}_4)^{4-}$ and $(\text{PO}_4)^{3-}$. In slags, these tend to form hexagonal network. These oxides are, therefore, called network formers or acids. These acidic oxides can accept one or several oxygen ions.

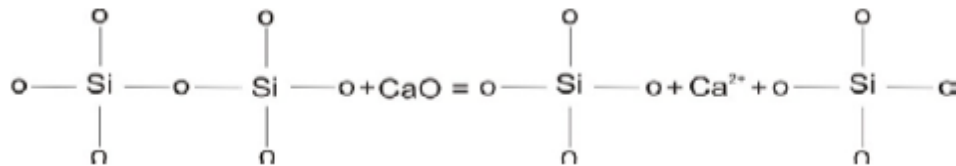
Basic oxides like CaO , MgO , Na_2O , FeO dissociate and form simple ions like Ca^{2+} and O^{2-} . All basic oxides are donors of oxygen ions. These oxides are called network breakers, since they destroy the hexagonal network of silica by reacting with it.

Structure of slag

Most slags are silicates. Pure silica has very high viscosity at the melting point. Addition of basic oxides decreases the viscosity by breaking the hexagonal network of silica. Consider the addition of CaO to molten silica. Calcium oxide dissociates to

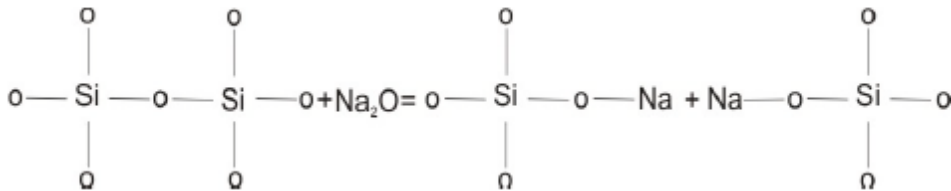
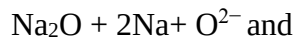


Each mole of CaO introduces one mole of oxygen ions in the hexagonal network of silica and can break two vertices of the hexagonal structure of silica. By adding 2 moles of O^{2-} for every mole of silica all the four vertices are broken and we simply have Ca^{2+} and $(SiO_4)^{4-}$ as shown below



Note that Ca^{2+} can combine with two tetrahedrons

The reaction between alkaline base oxides, e.g. Na_2O and SiO_2 is as follows:



Since Na has one charge, each tetrahedron of silica will have Na ion attached to oxygen ion. As a result one should expect more decrease in viscosity of silica on addition of alkaline base oxides as compared with basic oxides.

A slag of CaO , SiO_2 and Al_2O_3 , having mole fraction of alumina as 0.1, has $Si_2O_7^{6-}$, AlO_4^{5-} anions. Calculate the slag composition.

Solution: Take 1 gmol of slag. Therefore, the mole fraction X is same as the number of moles n . Hence,

$$\text{From oxygen balance,} \quad n_{CaO} + n_{SiO_2} + n_{Al_2O_3} = 1 \quad (\text{Ex. 4.6})$$

$$n_O = n_{CaO} + 2n_{SiO_2} + 3n_{Al_2O_3} \quad (\text{Ex. 4.7})$$

Again, since anions are $Si_2O_7^{6-}$, AlO_4^{5-} ,

$$n_O = \frac{7}{2} n_{SiO_2} + 8n_{Al_2O_3} \quad (\text{Ex. 4.8})$$

Noting that $n_{Al_2O_3} = 0.1$, and solving the above equations, the mole fractions of CaO , SiO_2 are 0.74 and 0.16 respectively.

LECTURE-7

Oxidation of Carbon

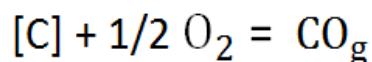
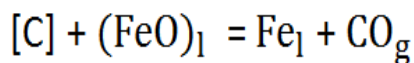
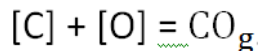
Pig iron/Hot Metal/ Molten Metal is the main component of the charge materials in Basic Oxygen Furnaces (BOF). The chief constituent of Pig Iron is Carbon (roughly 4wt.%) after Iron. But Steel contains much less C ,for which reason steelmaking process almost involve the C reaction as the ‘main’ reaction of these process.

It is important to note that amongst all steelmaking reactions, oxidation of carbon is the reaction whose product is gas i.e. CO. During oxidation of C,the metal is said to be ‘boil’,which is due to evolution of bubble of carbon Monoxide gas. This is called **“CARBON BOIL”**. Therefore this reaction is of very much significance during steelmaking.

Advantages of Carbon Boil

1. Carbon Boil can induce stirring in metal and slag phases during steelmaking leading to homogenization of bath temperature and composition and less sloping.
2. It is also responsible for increase in Metal-Slag, Metal-Gas and Slag-Gas interfacial area resulting in faster rate of reactions.
3. It also helps in removal of inclusions.
4. CO gas has a high calorific value and post combustion of CO in steelmaking can contribute to energy efficiency.

Chemical Reactions



Reaction with (FeO) is dominating, Because:

1. Solubility of Oxygen [O] in steel at 1600°C is only 0.23%

2. Pig Iron contains 90+% Fe. Chances of oxidizing Fe is more than C by $\{O_2\}$

Kinetics of the process

Step 1: Supply of reagents: C and O to the reaction site

Step 2: The reaction proper: $[C] + [O] = \{CO\}$

Step 3: Evolution of reaction products: CO bubbles into the gaseous phase

Step 2 is the chemical reaction which is instantaneous.

Step 1 and 3 are diffusion based (Rate Controlling Step)

The reaction goes in forward direction if the concentration of the reactants increases or the concentration of the products decreases.

Step 1

At higher conc level of carbon, the carbon oxidation is higher and at higher level of oxygen supply it is again higher.

It is to **EITHER** increase %C (which is not possible as the impurity level is fixed in the Pig Iron) **OR** increase the concentration/activity of oxygen. (activity of oxygen: air-0.21, pure oxygen-1).

On attaining a certain 'critical' level of conc of C (0.15-0.35%), the rate of carbon oxidation is observed to be dropped noticeably, and proportionate increase is not observed with Oxygen supply. This is called "**CRITICAL LEVEL OF CARBON**". In this case bath should be agitated forcibly (by argon stirring) in order to intensify the diffusion of C to the reaction site so as to increase the rate of C oxidation.

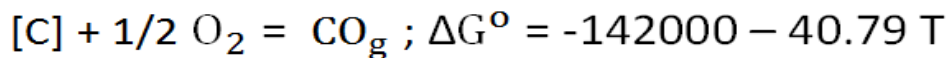
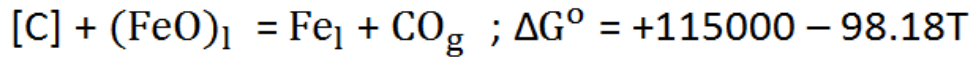
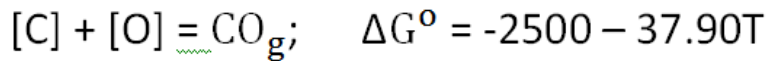
Step 3

Separation of product i.e. CO gas is enhanced by decreasing the concentration (partial pressure) of CO. This may be carried out in two ways

1. By introducing Argon gas
2. By introducing Vacuum

Therefore Effective Decarburization is possible in AOD and VOD Processes

Effect of Temperature



Thus, in all cases, the free energy change decreases with increasing temperature i.e., more favourable conditions are formed for the reaction of carbon oxidation. And it may be taken in to account that an increase in temp always promotes the reaction of carbon oxidation.

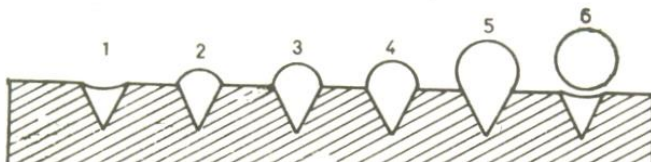
Effect of Lining

The conditions at the metals lining interface are favourable for the nucleation of CO bubbles. Any lining has large and fine pores. Due to surface tension liquid metal cannot fill these pores. As the evolution of CO is a heterogeneous nucleation it will nucleate at wall surface. For a bubble of CO to form in metal, it must overcome the pressure of the column of the metal, of the slag, and of the atmosphere above the bubble, and also the forces of cohesion with the liquid $2\sigma/r$ i.e.,

$$p_{CO}^{ev} \geq p_m + p_{sl} + p_{at} + 2\sigma/r$$

The of $2\sigma/r$ becomes practically sensible at low values of bubble radius $r > 1$ mm it can be neglected. Formation of bubbles in bulk in liquid metal interface is practically impossible.

Active site



The bubble attains hemispherical shapes before the partial pressure of CO attains its equilibrium value and hence the bubble are formed and being mechanically unstable are separated.

Inactive site



The CO partial pressure inside the bubble reaches its equilibrium value before the hemispherical shape is attained and hence no separation is possible.

Effect of Inert Gas Blowing

If inert gas is supplied along with oxygen then partial pressure of CO decreases and forward process continues. And the reaction shifts to right



Inert gas blowing of the metal can be done in simpler equipment than that need for vacuum treatment .This process is widely used for making steel of low carbon content

LECTURE-8, LECTURE-9

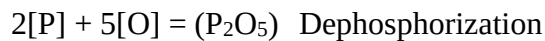
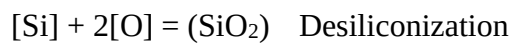
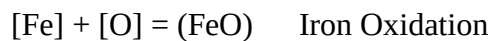
Oxidation of Iron, Silicon and Manganese

Introduction

As steelmaking is the oxidation process, impurities in molten pig iron like carbon, silicon, manganese and phosphorus are removed through respective oxidation reactions so as to produce steel of desired chemistry and cleanliness and the oxide by-products of these impurities form slag. When oxygen is supplied, oxidation of the impurities of hot metal including iron begins simultaneously.

Oxidation of an individual impurity is considered to figure out the favourable conditions for the removal of an impurity.

Important oxidation reactions of impurity elements by oxygen dissolved in hot metal or FeO content of slag taking place in steel making are:



Note:

- All reactions are exothermic in nature.
- C is removed as CO gas.
- Except C, all other impurities are removed as oxides and all these oxides float on the surface of the molten metal as slag phase during refining of hot metal to steel.

- Iron oxidation is unavoidable. Oxidation of Fe is loss in productivity; hence its oxidation must be controlled.
- Oxygen must be dissolved to remove an impurity from the hot metal.

Oxidation of Iron

Importance of iron Oxidation:

- ✓ It controls FeO content of slag and oxygen content of steel
- ✓ It is responsible for loss of iron in slag and hence affects productivity
- ✓ It alters the oxidation potential of slag
- ✓ Further FeO also helps in dissolution of lime in slag.

Consider the reaction $[\text{Fe}] + [\text{O}] = (\text{FeO})$

$$\text{Log } K_{Fe} = \frac{6150}{T} - 2.604$$

The equilibrium constant $K_{Fe} = \frac{a_{(\text{FeO})}}{a_{[\text{Fe}]} \cdot h_{[\text{O}]}} = \frac{a_{(\text{FeO})}}{a_{[\text{Fe}]} \cdot f_{\text{O}} \cdot \text{wt.\%}[\text{O}]}$

$a_{\text{Fe}}=1$, As it is pure

$\text{Log } f_{\text{O}} = -0.17[\text{wt\%O}]$

$$[\text{wt\%O}] \cdot 10^{-0.17[\text{wt\%O}]} = [a_{\text{FeO}} \{10^{\left(\frac{6150}{T} - 3.604\right)}\}^{-1}]$$

Consider a situation pure Fe in contact with pure FeO i.e. $a_{\text{FeO}}=1$

Solving the above equation for saturated amount of oxygen in melt

At **1873K [wt%O]= 0.233**

At 1923K [wt%O]= 0.285

➤ We note that increase in temperature increases oxygen dissolved in molten iron.

- The above values of dissolved oxygen correspond when pure FeO is in contact with Fe(pure). In steelmaking FeO is present along with other oxides like calcium oxide, magnesium oxide, silica, manganese oxide etc, hence activity of FeO is influenced by other solute oxides. Thus

$$a_{\text{FeO}} = \gamma_{\text{FeO}} N_{\text{FeO}}$$

Where γ_{FeO} is activity coefficient and N_{FeO} mole fraction of FeO in slag,. γ_{FeO} depends on slag composition.

In CaO- SiO₂-FeO system, as CaO/SiO₂ ratio (Basicity) increases a_{FeO} increases; physically it means that CaO replaces FeO from FeO. SiO₂ and more free FeO is available. The following expression is used to express a_{FeO} .

$$a_{\text{FeO}} = 0.514 (N_{\text{FeO}})^{0.2665}$$

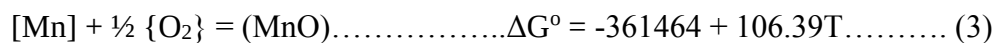
The amount of FeO in slag determines the oxidation and reduction potential of the slag. If FeO content in slag is low it behaves like reducing and if it is high then the atmosphere is oxidizing.

Oxidation and reduction of manganese

Behaviour of manganese in iron-carbon melt:

- Mn is soluble in iron in any proportion
- Mn forms ideal solutions with iron (They don't form any inter-metallic compound)
- Carbon lowers the activity of Mn in Fe-Mn-C system by forming Mn₃C.

Mn can be oxidized to form MnO, MnO₂, Mn₂O₃ etc. Under steel making conditions (high temperature) MnO is most stable, so, MnO is only considered.



The reaction 1 occurs with dissolved oxygen in metal, whereas reaction 2 is a slag/metal reaction. All the reactions are exothermic. Lower temperature favours oxidation of Mn from metal to slag; whereas higher temperature favours reduction of MnO of slag and there occurs reversal of Mn. Reduction of MnO can be carried out by C, Fe and Si;

Considering reaction 2:

$$K = \frac{a_{(MnO)} \cdot a_{[Fe]}}{h_{[Mn]} \cdot a_{(FeO)}}$$

Replacing activity by mole fraction and using $a_{[Fe]}=1$, we get,

γ = Raultian

f = Henerian (1wt% standard)

$$K = \frac{\gamma_{(MnO)} \cdot N_{(MnO)}}{f_{Mn} \cdot [wt\% Mn] \cdot \gamma_{(FeO)} \cdot N_{(FeO)}}$$

Grouping all activity coefficient terms and putting $N_{(MnO)} \approx (wt\% Mn)$ We get,

$$k^* = \frac{\gamma_{(FeO)} \cdot f_{Mn}}{\gamma_{(MnO)}}$$

$N_{(MnO)} \propto wt\% Mn$ in slag or (wt%Mn)

Where K^* is an equilibrium quotient and it depends on composition of slag. Distribution of Mn between slag and metal can be written as

$$\varphi = \frac{(wt. \% Mn)}{[wt. \% Mn]} = K^* N_{(FeO)}$$

Conditions for oxidation of Mn:

- High activity of FeO in slag which means an oxidizing slag
- High value of K^*

$$\text{Log } K^* = \frac{7940}{T} - 3.17$$

According to above equation K^* increases with decrease in temperature.

- Manganese oxide is a basic oxide, so that its activity in acid slags decreases due to the formation of manganese silicates. For this reason, manganese oxidation proceeds more deeply under an acidic slag.

Conditions for reduction of Mn:

- Low activity of FeO in slag
- High Temperature
- High basicity of slag

Consider a slag with V ratio 1.8 (CaO/SiO₂) Having FeO=0.25 mole fraction and N_{MnO} = 0.06, γ_{MnO} = 1.6. Determine the Mn and O content of steel at 1600°C. R= 1.987



$$\Delta G^{\circ} = -RT \ln \frac{a_{\text{Fe}} \cdot \gamma_{\text{MnO}} \cdot N_{\text{MnO}}}{[\text{wt. \%Mn}] \cdot a_{(\text{FeO})}}$$

$$\ln[\%Mn] = \frac{\Delta G^{\circ}}{RT} + \ln \frac{a_{\text{Fe}} \cdot \gamma_{\text{MnO}} \cdot N_{\text{MnO}}}{a_{(\text{FeO})}}$$

$$a_{\text{FeO}} = 0.514 (N_{\text{FeO}})^{0.2665} = 0.514(0.25)^{0.2665} = 0.36$$

T=1600°C+273=1873K.

$$\ln[\%Mn] = \frac{-5720}{1.987 \times 1873} + \ln \frac{1 \times 1.6 \times 0.06}{3.6}$$

[%Mn]=0.048

Saturated amount of oxygen in melt At 1873K [wt%O]= 0.233

[%O]=0.233 X 0.36= 0.8388

OXIDATION AND REDUCTION OF SILICON

- Silicon can be melted with iron in any proportions and when dissolved in iron, liberates enormous quantity of heat, so, it can be said that, reaction of silicon with iron oxide is an exothermic one.
- For a solution of silicon in iron, the deviation from Raoult's law is found to be negative. Hence, the bonding between them is stronger than the bonding between Fe-Fe or Si-Si atoms.

Oxidation of silicon dissolved in the metal can occur due to its interactions with

- (a) dissolved oxygen in metal :



- (b) oxygen in gaseous phase :



- (c) iron oxides in the slag :



Effect of temperature:-

All the reactions are exothermic.

- The values of free energy change indicate that, oxidation of silicon can occur intensively in the presence an oxidant in the whole range of steelmaking temperatures.

Consider Silicon oxidation reaction: $[\text{Si}] + 2[\text{O}] = (\text{SiO}_2)$

$$K_{\text{Si}} = a_{(\text{SiO}_2)} / [\text{wt}\% \text{ Si}][\text{wt}\% \text{ O}]^2$$

$$[\text{wt}\% \text{ Si}] \times [\text{wt}\% \text{ O}]^2 = a_{(\text{SiO}_2)} / K_{\text{Si}}$$

Different sources give the following expression for K_{Si}

$$\log K_{Si} = \frac{30110}{T} - 11.4$$

$$\log K_{Si} = \frac{29700}{T} - 11.25$$

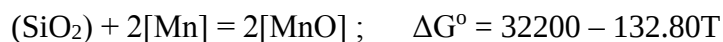
Both equations predict that decrease in temperature increases K_{Si} .

Favourable conditions for silicon oxidation are:

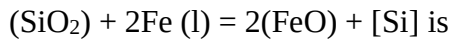
- Low temperature
- Oxidizing atmosphere
- Basic slag

Effect of slag composition:-

- In steelmaking plants with basic slags the silicon oxidation reaction occurs practically to the end, since the activity of SiO_2 in basic slags ($CaO-FeO-P_2O_5$) is negligible.
- Acid slags ($FeO-MnO-SiO_2$), on the other hand, are saturated with silica, at least at the end of heat. The activity of silica in acid slags is close to unity.
- If there is no intensive supply of oxidants to a melt under an acid slag, the slag will be saturated with silica and can enter the following reactions with melt components.



- The above reactions are endothermic
- The equilibrium constant of the reaction

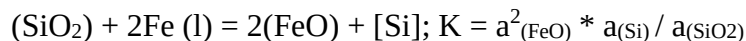


$$K = a_{(\text{FeO})}^2 * a_{[\text{Si}]} / a_{(\text{SiO}_2)}$$

For slags saturated with SiO_2 , $a_{(\text{SiO}_2)} = 1$ and

$$K = a_{(\text{FeO})}^2 * a_{[\text{Si}]}$$

- Silicon reduction proceeds more rapidly when iron oxide in slags have lower activity.
- Some component of the melt like carbon, manganese lowers the oxygen content in the metal and increase the degree of silicon reduction.
- FeO is a basic oxide; in acid slags, it is combined with silica into iron silicates and its activity is low.
- If a stronger basic oxide like CaO is introduced into the slag, it will destroy iron silicates and form calcium silicate, so that the activity of iron oxide will rise and the process of silicon reduction is impeded.
- It is generally, taken that the process of silicon reduction from acid slags follows :-



and the components of metal and slag have a certain effect on activity of FeO by shifting the equilibrium of the reaction towards either reduction or oxidation of silicon.

- If the bath is supplied intensively with oxidant, this will oxidise iron. As a result activity of FeO increases and only traces of silicon remain in the metal.

Another important feature of silicon reaction is very high affinity of silicon with oxygen, silicon can be used as a deoxidizing agent.

$$[wt\% O] = \sqrt{\frac{a_{(SiO_2)}}{K_{Si} \cdot [wt\% Si]}}$$

$$\log K_{Si} = \frac{29700}{T} - 11.25$$

At 1773K,

$K_{Si} = 3.24 \times 10^5$ and using $a_{SiO_2} = 1$, we get

$$[wt\% O] = \sqrt{\frac{0.308 \times 10^{-5}}{[wt\% Si]}}$$

The above equation shows drastic reduction in oxygen content of steel due to addition of silicon. This suggests that silicon is a very effective deoxidizer. Normally silicon is used as ferrosilicon in steelmaking

LECTURE-10

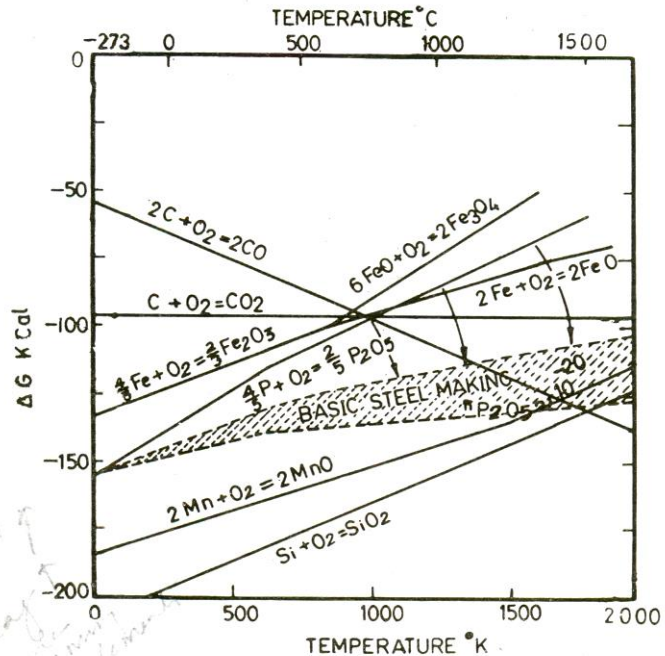
Dephosphorization & Desulphurization

Dephosphorization:

Phosphorus removal from hot metal is the most important refining reaction. Phosphorus has atomic number 15 and it can give up all 5 electrons from its outermost shell to become P^{5+} or accept 3 electrons to become P^{3-} to attain stable configuration. This means that phosphorus can be removed both under oxidizing as well as reducing conditions. But removal of phosphorus under reducing conditions is not practical since its removal is highly hazardous. Thus P removal is practised mostly under oxidizing conditions.

Effect of CaO

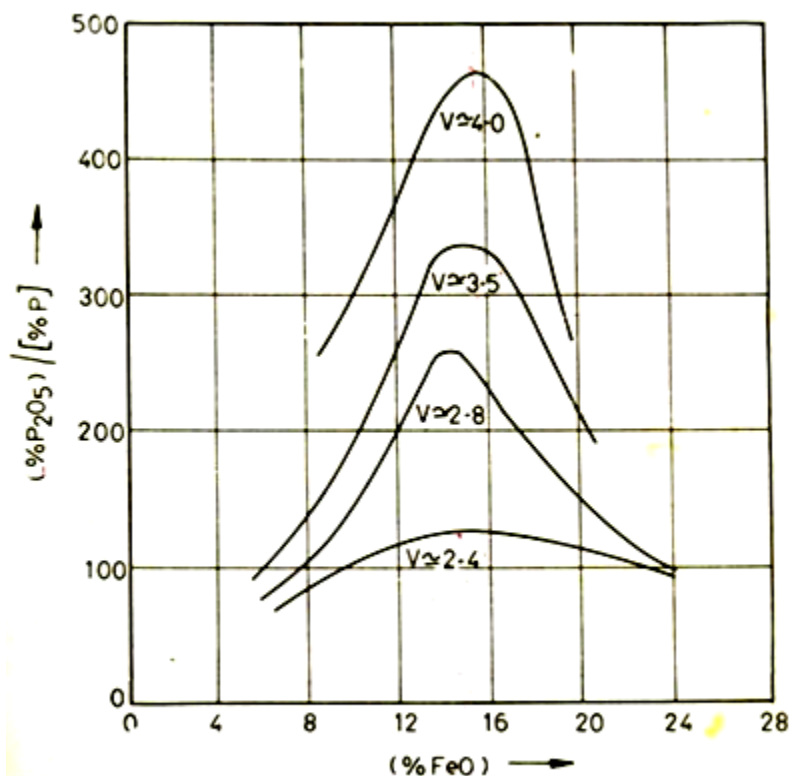
- The boiling point of phosphorus is very low but a considerable amount of it still remains dissolved in liquid iron because of its strong interaction with iron.
- The iron and phosphorus lines on the Ellingham diagram are so close to each other that the entire phosphorus in the burden gets reduced along with iron in the in an iron blast furnace.



- The two lines are separated by decreasing the activity of P_2O_5 using a strong and excess external basic flux like lime.
- $2[P] + 5 (FeO) + 3 (CaO) = (3 CaO.P_2O_5)$
- For a given basicity of slag, as FeO content of slag increases oxidizing power of slag and phosphorus oxidation will be favoured because CaO of slag decreases the activity of P_2O_5 by forming a stable compound.

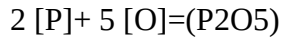
Effect of FeO

- Dephosphorization Index (D_p) = $\text{Wt\% P in slag} / \text{Wt\% P in metal} = (\% \text{P}_2\text{O}_5) / [\text{Wt\% P}]$
- The dephosphorization ratio increases with increase in FeO content of slag and becomes maximum in between 15-16% FeO at all basicity.
- Further increase in FeO beyond 15-16% dephosphorization decreases.
- The above behaviour is due to the dual role of FeO. FeO is the source of oxygen for oxidation of Phosphorous.
- Beyond the optimum value of FeO in slag FeO replaces. FeO is a weak base compared with CaO as a result of which basicity decreases and the dephosphorization ratio decreases with formation of FeO beyond optimum value.



The variation of D_p with FeO content of slag having various basicities (V ratios)

Effect of temperature



$$\Delta G^\circ = -740375 + 535.365T \text{ J/mol}$$

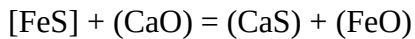
At $T > 1382K$, ΔG° becomes positive which results in decomposition of P_2O_5 to P and O.

Favourable Conditions for Phosphorous removal (Fluid, Ferruginous & Limy slag)

1. Thin slag for better reaction (High fluidity slag)
2. Oxidizing atmosphere i.e. High FeO:15-16% (Ferruginous slag)
3. High basicity (Limy slag)
4. Low temperature
5. High slag volume to decrease the activity of P_2O_5 in slag.

Desulphurization

- Although sulphur has a very low boiling point like phosphorus a considerable amount of it is found in liquid iron because of its strong interaction with iron.
- Sulphur can be assumed to exist as CaS in slag upto a few percent concentration. Partitioning of sulphur between slag and metal can be described as



$$\text{Desulphurization index} = (\%S)/[S]$$

For a fixed basicity the index is inversely proportional to the iron oxide content of the slag or the [O] content of the metal.

$$\text{i.e. } (\%S)/[S] \propto 1/(\%FeO)$$

Similarly for a fixed (FeO) content of slag

$$(\%S)/[S] \propto (\%CaO)$$

Favourable Conditions for Sulphur removal

1. High basicity
2. High temperature
3. Low oxidizing potential (reducing conditions i.e very low FeO content less than 1%)

Blast furnace is the best place for sulphur removal.

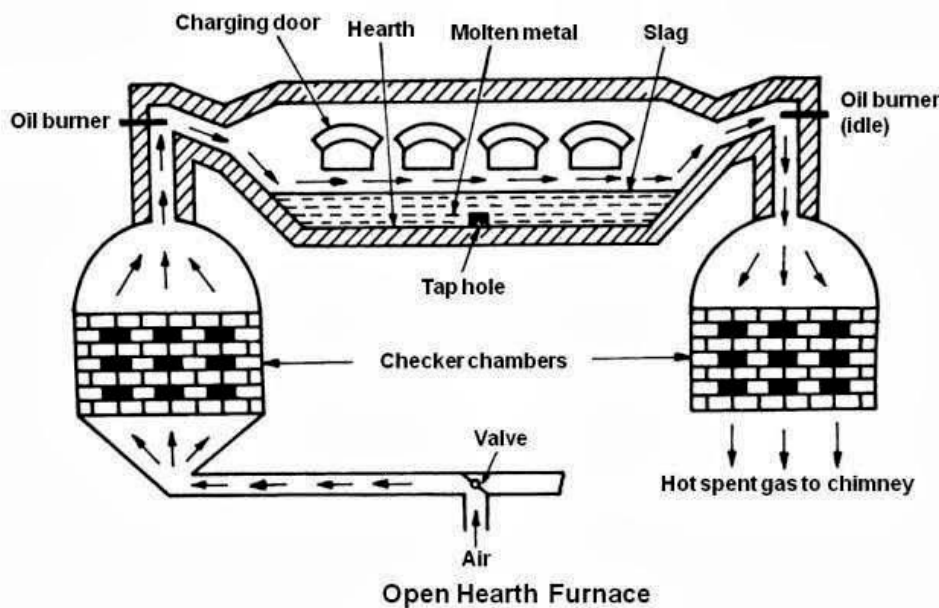
It is therefore desirable to remove sulphur in the blast furnace itself. But there is a limit to which it can be achieved in the blast furnace. It has been possible and economical to remove sulphur from pig iron outside the blast furnace before it enters the steel making furnace. This is known as '***External Desulphurization***'.

LECTURE 11, LECTURE-12

Open Hearth Steel Making Furnace and Practice

Introduction

The process was originally developed by Siemen in Germany and Martins in France in late nineteenth century. Open hearth process has been replaced by LD converter process all over the world. The ability of the open hearth process to melt both light and heavy scrap and to produce steel of any composition has saved the process till date. Open heart steel making process is a slow process. The thermal efficiency is usually low. Thermal requirements are met by combustion of gaseous or liquid fuel supplied from external source. This process is not autogenous.

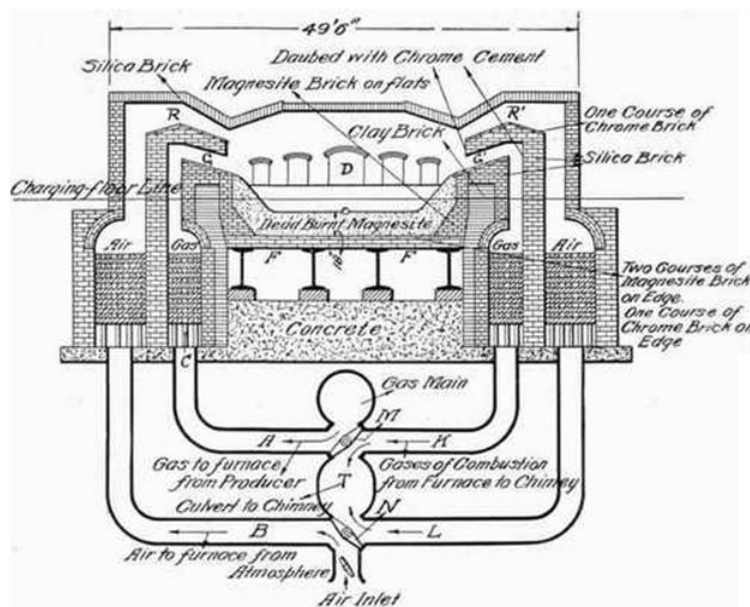


Construction:-

The capacity of an open hearth furnace may range upto 500 tons per heat. It is basically a reverberatory furnace in which hot metal and molten steel scrap are refined in a shallow basic lined hearth. Combustion air and gaseous fuel are admitted through ports on one side of the furnace. The fuel is burnt inside the furnace. Heat is transferred to the furnace through the intermediate slag layer. The exhaust gases are allowed to escape through located in the opposite end.

1. Hearth:-

The hearth is in the form of a pan fabricated from steel plates. The plates are covered with asbestos sheets, which are in turn covered with a layer of porous fireclay bricks. Thereafter a course of firebrick lining is provided. The working lining is usually made by ramming magnesia refractory. The lining usually slopes towards the taphole. The top layers of the back wall are made of chrome magnesite bricks to avoid acid base reaction with the silica roof. The roof is usually sprung arch type and is made of silica bricks. Silica bricks are lighter than basic bricks and hence used for roof construction.



Refractories used in OH furnace

2. Ports:-

Gas and air are admitted into the furnace through the ports. When the ports are used for admitting preheated air/gas, these are called uptakes. Downtakes carry away the products of combustion. Alternatively, the functions of uptakes and downtakes are reversed. The ports are usually lined with silica bricks.

3. Slag pocket:-

The exhaust gases escaping through the ports first enter slag pocket through a duct called fantail. The dust and slag particles carried with the gas drop off in the slag pocket. Slag pocket are lined with chrome magnesite bricks in basic furnaces.

4. Regenerators:-

The exhaust gas then passes through a regenerator. The facing lining of the chambers is made up of fireclay bricks. Checker works of refractory bricks are constructed inside the chambers. Usually, checkers are built of fireclay bricks to one half to two thirds of their height; silica or high alumina bricks are used for the upper courses. The cooled exhaust gas ultimately escapes through a *chimney*. The directions of flow of air and fuel gas, as well as that of exhaust gas are alternately reversed by means of a dampers. Slag pockets, regenerative chambers, flue systems and reversing valves constitute the lower part of an open hearth furnace

Operation:-

In Indian plants, usually steel scrap+ hot metal mix constitutes the basic charge materials. The silicon content in the hot metal is maintained around 1% or lower to ensure optimum slag basicity. The slag in an open hearth furnace has dual functions:-it is not only a receptacle of the impurities but it is also a refining medium. Steel making in a basic open hearth furnace consists of the following stages:-

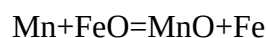
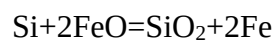
1. Charging
2. Melting down
3. Oxidation and refining
4. Finishing

1. Charging:-

Steel scrap , iron ore , lime/limestone are usually placed in charging buckets. The charging buckets are introduced into the furnace through the charging door by means of mechanical chargers. When buckets are tilted , the charge is dumped on the furnace floor. Hot metal is charged directly from ladle through spouts introduced through the charging door.

2. Melting down:-

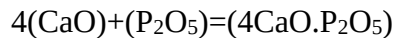
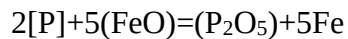
The burners are turned on in full. As the charge melts , Si and Mn are oxidised according to the following reactions:-



The carbon content is so adjusted that the opening C content in the bath is 0.2-0.3% higher than final C content. When the proportion of the steel scrap in the charge is very high, extra C in the form of coke/graphite is added, usually below the layer of steel scrap charge. Evolution of CO due to oxidation of C agitates the bath.

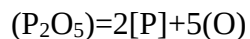
3. Oxidation and refining:-

Steel making is an oxidation process. In open hearth furnace steady supply of oxygen is ensured by the addition of Fe_2O_3 . Dissociation of Fe_2O_3 is an endothermic process. The dissociation of Fe_2O_3 is limited by heat supply to the slag metal interface. To accelerate the supply of oxygen, direct oxygen lancing into the bath is considered a better practice. As temp rises, more lime dissolves in the slag raising its basicity. CaF_2 (fluorspar) addition reduces the slag viscosity. Dephosphorization is favoured in open hearth furnace due to high FeO content of the slag and the oxidising nature of the slag.



4. Finishing:-

In this process, excess oxygen in the bath is removed by the addition of deoxidisers. However, the bath is only partially deoxidised by the addition of ferrosilicon and ferromanganese to avoid phosphorus reversion. Ability of the basic slag to hold (P_2O_5) in solution depends on its oxygen potential. Hence, too much reduction of (FeO) content of the slag leads to reversion reaction:



In order to avoid such possibilities, the final deoxidation is carried out in the ladle by the addition of Al.

Reasons for the decline of the open hearth process:-

1. Open hearth steel making is a very slow process. It cannot match the productivity of modern oxygen furnace.
2. The dependence on external fuel supply is a serious constraint of the open hearth process.
3. Construction and maintenance of the roof and substructure of the open hearth furnace is more difficult than the overall maintenance of a basic oxygen converter.

Modified open hearth practices

1. Consumable lance

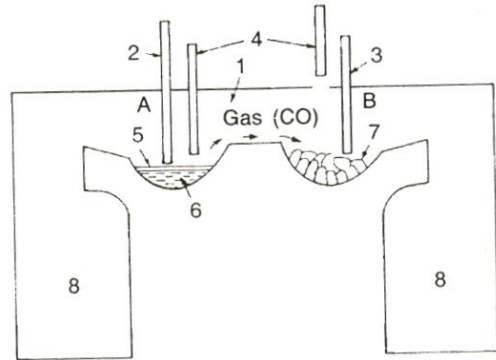
- In this process , a common steel pipe , 5-6m in length and 2-3m in diameter , is inserted in the furnace through the wicket hole.
- The other end is connected to the oxygen supply hose.
- The pipe is either held manually or in holding rack and is manoeuvred manually.
- An oxygen flow rate of 15-20m³/min cools the pipe and gives it a reasonable life.
- Consumable lance is used to blow oxygen after the addition of hot metal in the furnace to hasten the decarburization.
- However it interferes with the movement of charging machine and cranes on the shop floor.

2. Water cooled lance:-

- The disadvantages of a consumable lance can be eliminated by using a water cooled lance.
- The tip of the lance is made of copper and may have one or more nozzles.
- Multi-hole lances are preferred to single hole because of their ability to distribute oxygen over a much larger area.
- The lance is more commonly introduced through the roof.
- As the lance is progressively lowered the amount of splashing increases until a point and then decreases to a point of least splashing .
- It usually supplies oxygen at a rate of 12-15m³/min to keep fuming and splashing of slag to a minimum.
- Excessive fuming tends to clog the checkers and excessive oxidising slag causes the roofs and the walls to wear rapidly.

3. Twin-hearth process

- In this process, two basic lined are connected by an opening for the transfer of products of combustion from one hearth to the other.
- Regenerators are eliminated. Intensive oxygen lancing is carried out.
- The fundamental principle involves utilization of physical and chemical heat from the gases formed during blowing for directly heating the solid charge materials.
- Only a small quantity of external fuel is required for thinning the slag prior to tapping and maintaining the heat of the furnace during tapping and fettling.
- The heat time is reduced to half of that of the conventional open hearth furnace.



LECTURE-13

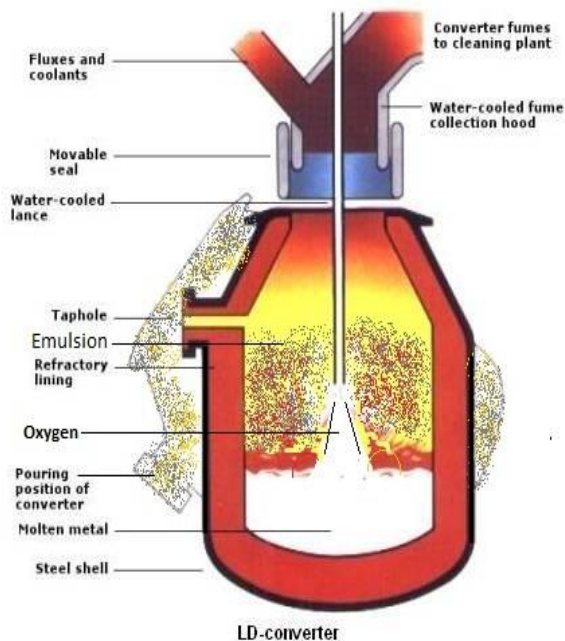
Steel Making in LD

Introduction:

Accounting for 60% of the world's total output of crude steel, the Basic Oxygen Steelmaking (BOS) process is the dominant steelmaking technology. There exist several variations on the BOS process: top blowing, bottom blowing, and a combination of the two, But LD is a top blowing (lancing) process.

- Refining of iron by oxygen lancing was first tried at Linz and Donawitz in Austria and hence the name LD. It's a very fast process :Heat 40-50min
- This Basic Oxygen Process (Pneumatic) is generally carried out in an LD shop which may consist of 2 or 3 number of LD vessels and 1 out of 2 or 2 out of 3 vessels operate at a time.
- Uses Oxygen Lance for Top Blowing
- It is autogenous, or self-sufficient in energy

Vessel Design

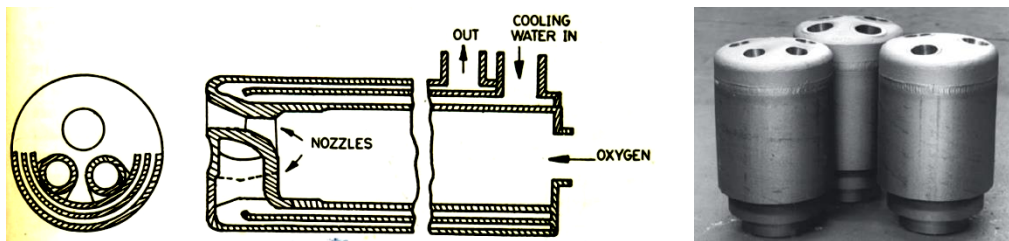


- The plant design mainly depends upon whether eccentric/concentric vessel is used.
- Universally eccentric vessel is used, the charging and tapping are carried out on the same side, hood is inclined but suffers from non-symmetrical lining unlike concentric vessel.
- 3 segments of vessel- the spherical bottom, the cylindrical body(or shell) and the conical top, each of which is a welded construction of non-ageing steel plates.
- It is Capable of rotating 360° but rarely exceeds 220

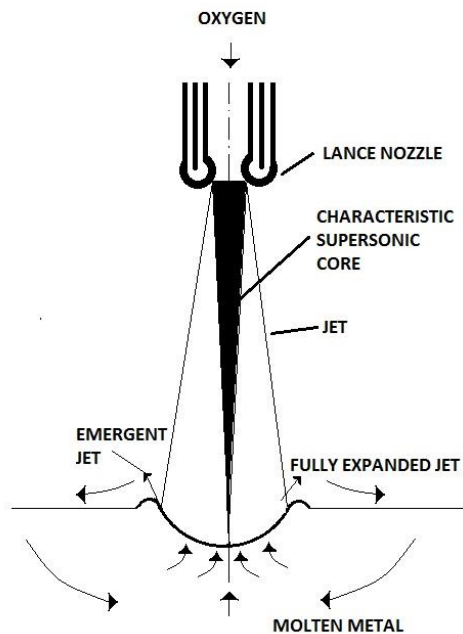
- The vessel top is a truncated frustum of a cone staggered by nearly $8-10^\circ$ to the main axis of the converter and is obliquely attached to the cylindrical body.
- A steel ring is welded from inside at the junction of the bottom and the body to support the permanent lining of the vessel.
- The vessel bath depth is in the range of 110-180 cm, depending on the vessel capacity. The depth should be maximum to prevent damage to the bottom during lancing.
- Generally the total lining thickness varies between 600-1000 mm and height between 7-10 m.
- The nose dia. and angle are chosen with reference to problems of heat loss, erosion, skulling, stability of nose lining etc. and are usually around $1/3$ rd the cell dia. And about 67° respectively.

Oxygen Lancing

Pure oxygen gas(refining agent) is fed to the LD f/c through a water cooled lance, which is made of 3 concentric steel tubes to circulate water around the central tube and pass oxygen through the most inner tube. A copper tip is welded to the steel tubes to withstand high temperature at the tip of the lance.



- The lance is nearly 8-10 m long and 20-25 cm dia.
- The lance is suspended by a wire rope and can be inserted in or withdrawn from the f/c by means of an electrically operated lance gear. Jigs are used to hold the lance in a fixed blowing position. A standby is always ready for replacement
- There are mainly 2 types of nozzle designs(cylindrical and laval shaped) for efficient refining i.e. for decarburization as well as dephosphorisation.



Effect of Supersonic Jet on Bath Circulation

➤ In laval shaped nozzle, the supersonic jet penetrates the bath more effectively than in cylindrical nozzle. Therefore the laval nozzle is universally adapted.

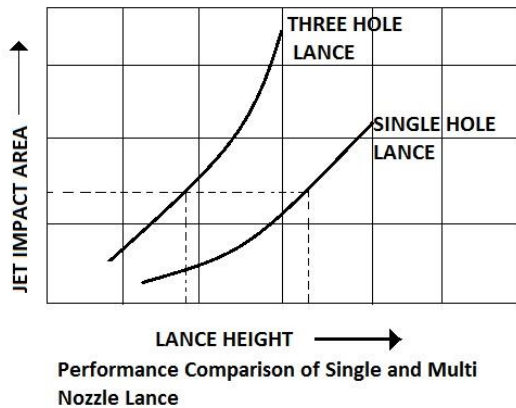
➤ Oxygen is generally blown at 8-10 atm.press. through a laval shaped nozzle, so that the jet at the nozzle exit is supersonic with a velocity between 1.5-2.5 times the velocity of sound.

➤ The jet consists of a potential core, a supersonic core and subsonic region.

➤ The depth of penetration of a jet can be expressed in terms of the Jet Force Number, as:

$$JFN = \frac{\text{Gas pressure} \times \text{Nozzle throat dia.}}{\text{Height of nozzle}}$$

- For a given nozzle size, the size of a supersonic core depends on the blowing pressure and the ratio of the densities of the jet-gas and the ambient temperature.
- Decarburization is faster for greater values of JFN, but dephosphorization is greater for reverse conditions.
- For small sized vessel, single nozzle lance is used but for large vessels, multi-nozzle lance is used to increase the impact area



Raw Materials

1. Iron Feed

A) Hot Metal (Temp: 1250-1300°C)

Impurity	Required%	Range used
C:	4.1-4.3	4.00-4.50
P:	0.1-0.25	0.05-0.45
Si:	0.50-0.85	0.65-1.40
Mn:	5.5-0.8	0.40-2.50
S:	0.02-0.03	0.02-0.06

S removal not recommended

- As LD is a Fast Process
- High Basicity ie. High Slag vol. required
- Always Oxidizing atmosphere

B) Scrap(<25%)

C) Cold Pig (coolant)

D) Iron Ore (coolant)

2. Flux

A) (Lime)

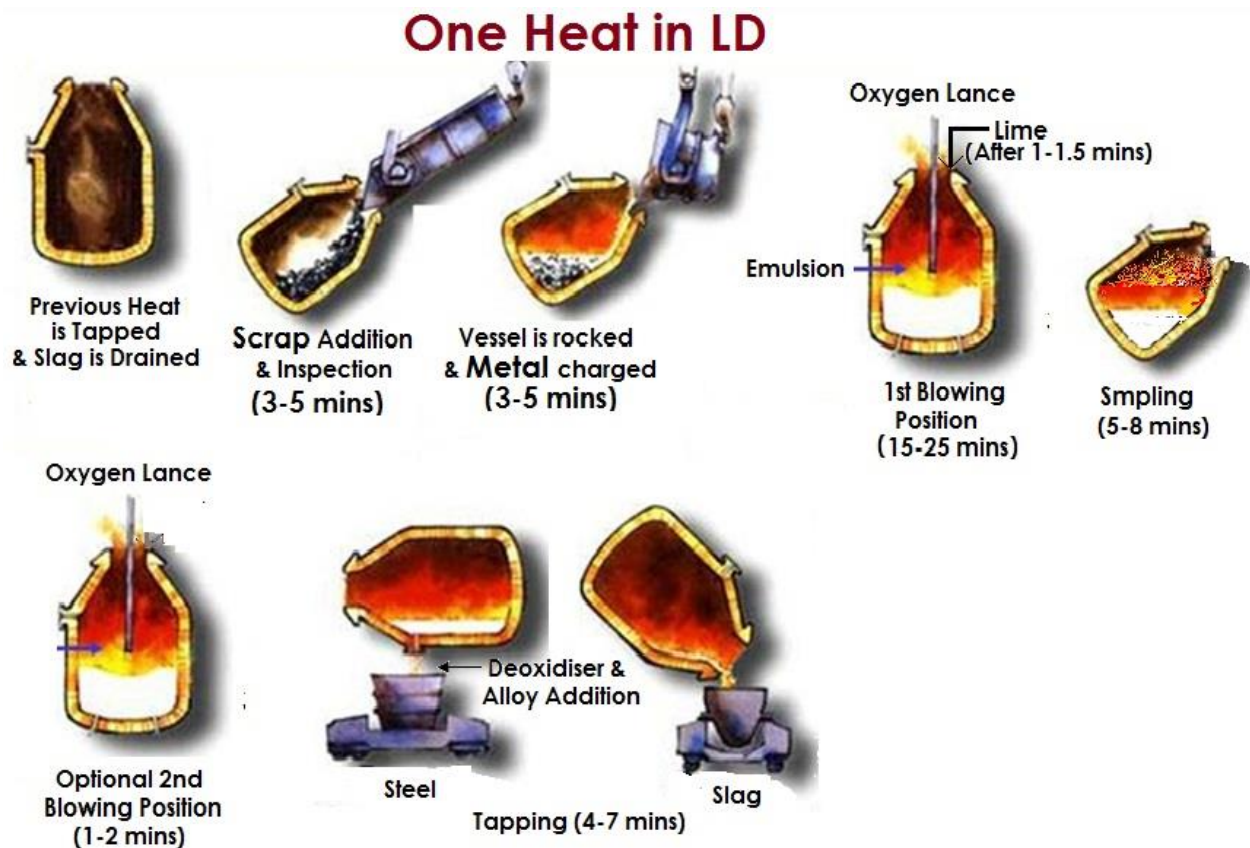
Limestone not recommended

- Endothermic decomposition Reaction
- Lime straightway available

B) Bauxite

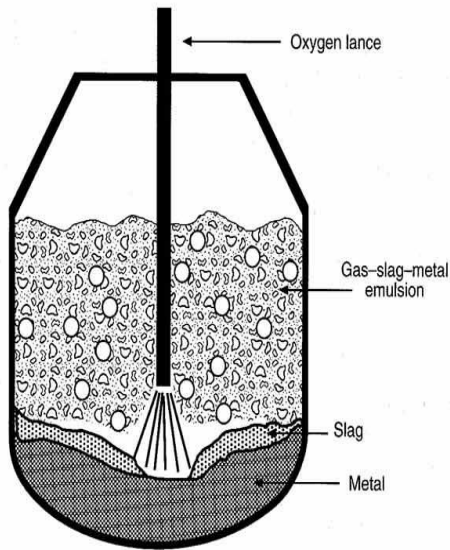
C) Silica-sand

D) Fluorspar



<http://www.bhpsteel.com.au/bhp/steel/steelenv/steelpath/steelbos.cfm>

Reactions:



The 3 stage reactions in LD:

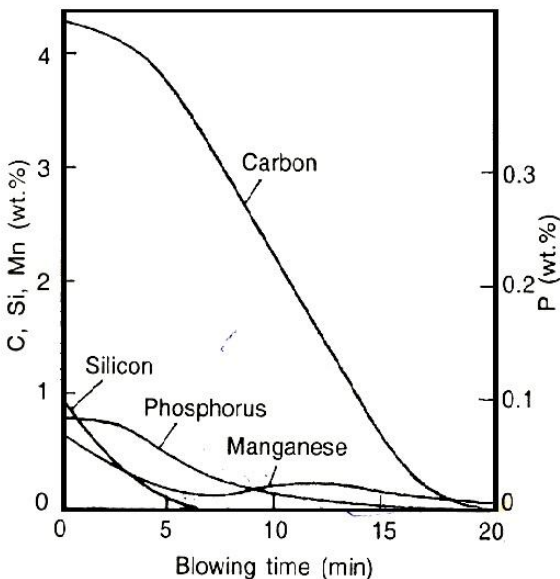
1. Bulk phase (Initially, emulsion yet to form)
2. Emulsion Phase
3. Bulk Phase (At the End, When emulsion collapses)

Emulsion:

The high velocity Jet tears off small droplets (14-100 mesh) of metal from the bath and throw them up in the vessel atmosphere. The presence of thin slag and slag-gas matrix inside the vessel leads to the formation of metal-slag-gas emulsion. The enormous refining rates as observed in LD

process are due to tremendous increase in interfacial areas of metal slag, metal-gas and slag-gas systems.

Sequence of Impurity Elimination



- Si oxidation is quite fast & almost complete in about 6 mins.
- There is a Mn hump
- After few minutes C & P oxidation starts together

Mn hump

- Initially Mn is oxidised to FeO-MnO-SiO_2 and the curve goes down with Silicon curve.
- Due to lime dissolution basicity increases CaO-SiO_2 formed & (FeO) , (MnO) rejected

- Mn reversion takes place: $(\text{MnO}) + [\text{C}] = \{\text{Mn}\} + \{\text{CO}\}$ & Curve goes up.
- At the end Carbon-Oxygen reaction decreases (FeO) increases ,oxidizes Mn again & the curve goes down again.

LECTURE-14

Process control in BOF

Introduction

Steelmaking in Basic Oxygen F/C (BOF) is very fast. It takes approximately 15 to 20 minutes for oxygen blowing and 50 to 60 minutes to tap molten steel. Liquid steel at turndown results from several non linear interconnected complex processes like gas/ liquid metal reaction as dependent on oxygen availability, slag/metal reaction as dependent on physico-chemical properties of slag and faster reaction rate induced by three phase dispersion (CO+ slag +metal droplets).

Control of the above processes is needed so that for a given input of hot metal, scrap, flux and oxygen flow rate, steel of the desired chemistry is produced with minimum loss of iron in slag.

Rates of gas/metal, slag/metal and gas/slag/metal droplet reaction are controlled by lance profile, oxygen flow rate and bottom stirring rate, it is required to raise or lower the lance distance for a given oxygen flow rate and bottom stirring rate so that steel of desired composition and tapping temperature can be obtained within the stipulated blowing time. For this purpose we need to develop process models which can describe the process quantitatively. These models must be supported by the data for accurate predictions for the future requirements.

Overall, First we have to understand the process with reference to quantification of the process; that is very important. Then, we should be able to identify the role of all the physical, chemical processes, which are responsible to convert reactant into product.

Secondly we have to identify the most contributory step. That means out of several physico-chemical processes, there are few, which are in fact very largely responsible for the conversion of reactant in to product. Once these are understood, then we can develop control strategy for that particular process and accordingly, the control models can be developed.

Process control:

Process control could be based on human expertise or so-called an operator. He will see the process and exercise control. Now, in order to exercise the control, He needs certain set of instructions, which he can execute in order to control the process. As this is purely based on human expertise and whatever instructions that are given to him, he will execute at a particular time that all has to be set in advance, so that he can do during the process. An operator having a long experience, can know what is happening at what time, He can exercise his experience and exercise the control accordingly; or, one has to develop models or for this, they are called the static models. In a static model, we have input, we have output; for a given output, we calculate the amount of input that is required; we pass on the instruction to the operator and tell him that these are the additions that have to be made at a time interval

Another type of process control that every technologist or engineer or a scientist dreams is computer control. That is a dream of every operator—he should sit in an air conditioned room and the output of a process is being controlled by a computer through set of instructions, which are given online and the information from the process is also received online. So, for computer control, some extra care has to be incorporated such as sophisticated sensors for analysis and data acquisition systems and programmable devices to carry out the instructions during the process.

Process Control Models

One of the objectives of the process control models is to predict turndown composition and temperature of steel so that unnecessary blowing of oxygen is not required. For a long time human expertise was the control tool. The operator used to deliver instructions to exercise the process control. These controls were human specific.

Developments in computer has resulted into development of sophisticated models, like

- a) Static model**
- b) Semi-dynamic model**
- c) Dynamic model**

Static Model

Static models are based on materials and heat balance by considering initial and final states of reactants. In the material balance, mass of all input and output elements is considered. Once mass balance is done then heat balance is carried out.

Sensible heat of all inputs+ Heat produced or absorbed by oxidation reaction= Heat taken out by steel, slag and exit gases and fumes+ heat losses from the converter mouth and through the lining of the converter+ any other heat losses

During materials and heat balance some assumptions may be required for example

- iron loss in slag,
- carbon removal in the form of CO,
- complete dissolution of CaO in slag
- basicity of slag
- thermo-physical and thermo-chemical properties of slag and metal

The above are some of the assumptions, further may be added.

By coupling of mass and balance one can predict

- i)** Quantity of hot metal and scrap
- ii)** Amount of flux
- iii)** Total quantity of oxygen required to be blown.
- iv)** Amount of slag produced
- v)** Volume of exit gases

It is very much important that the prediction based upon the model is verified by the actual plant data. Tuning of the model is necessary because the predictions are based on equilibrium considerations and uncertainties due to simplified assumptions.

Reliability of predictions increases when the predictions of the model are compared with the plant data for large number of heats. Statistical correlations can be developed and used to fine

tune the model. For this purpose it is of utmost necessary to collect the reliable data from the reliable instruments

BOF steelmaking is a stochastic process. Oxygen blowing produces lot of turbulent in the phases during hot metal refining. The amount of droplets emulsified in the slag, amount of lime dissolution, carbon removal rate, intensity of oxygen jet impinging the bath, lance distance, bottom stirring rate due to plugging of tuyeres etc. may vary from one heat to the other. The error in predictions may be due to

i) Error in weighing

ii) Differences in lime dissolution from one heat to the other

iii) Effect of size of scrap on its dissolution. Large size will take more time to dissolve as compared with smaller ones.

iv) State of foaming of slag and entrained metal droplets in slag. This may vary from one heat to other due to behavior of oxygen jet in a dynamic surrounding. As a result extent and magnitude of slag/metal reactions might change.

v) Converter lining profile due to wear.

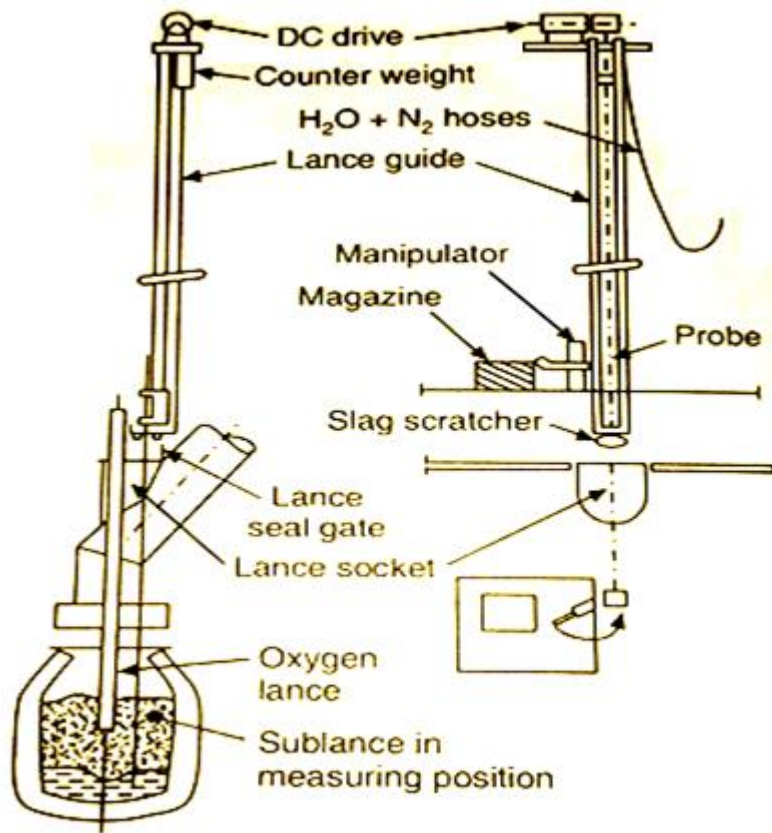
vi) Extent of mixing within the phases and between the phases.

Semi – dynamic model

The above features make static control models inadequate. Hence improvements are required. Static model predictions can be improved by measurements on temperature and composition of slag and metal by a sub lance during the blow.

Immersion type sensors can also be used to measure carbon and oxygen concentration during the blow. All these data are collected and fed into the computer which compares the model predictions to suggest the action to be taken by the operator. These are semi-dynamic model. It must be noted that error in carbon measurement may need to over blow the heat when end carbon measured is greater than specified carbon. Also if end point carbon measured is lower than the specified, carburization has to be done in the ladle for carbon adjustment.

Determination of carbon by a sub lance is indirectly done by measuring the temperature of steel through a sample collected by the sub lance during the flow.



Dynamic Models

Static models do not calculate the variation of blowing parameters as a function of time. For this purpose continuous measurement of some representative parameter is required during the blow. In a preprogrammed model, these values are fed continuously and corrections can be done during the blow. Dynamic models contain all features of static model; in addition it includes reaction kinetics and process dynamics. In steelmaking major reactions are oxidation of carbon and iron. In a dynamic model rate of decarburization and O₂ consumed are determined from exit analysis. Computation of Fe is then done.

Dynamic control requires measurements continuously. Exit gas temperature and its composition can be measured continuously and the data can be fed to computer. From the exit gas composition and temperature carbon, oxygen in bath can be determined as a function of time.

From carbon balance, decarburization rate can be determined. Oxygen balance provides the following information:

- Total rate of oxidation
- Relative fraction of oxygen reacting with carbon and iron and other elements

Enthalpy balance based on exit gas temperature and composition and amount gives information on energy leaving the system.

Slag height can also be determined by measuring the acoustic sound produced by the slag during the blow. Sonic meter measures the intensity of sound. Intensity of sound is fed to computer which in turn adjusts the lance height, oxygen flow rate and bottom stirring rate to control the slag/metal height.

Refractory lining loss is also to be taken into account for the effectiveness of the process control.

Questions for practice (Module-I)

What is carbon boil? What are its advantages?

What is critical level of carbon?

Which is the best site for CO nucleation?

What is the effect of inert gas blowing on carbon reaction?

Why there is a characteristic Mn hump?

15% FeO is best for maximum Dp-why?

What are the favourable conditions for S removal?

What is the effect of temperature on carbon oxidation?

Why effective decarburization occurs in AOD and VOD processes?

LECTURE-15

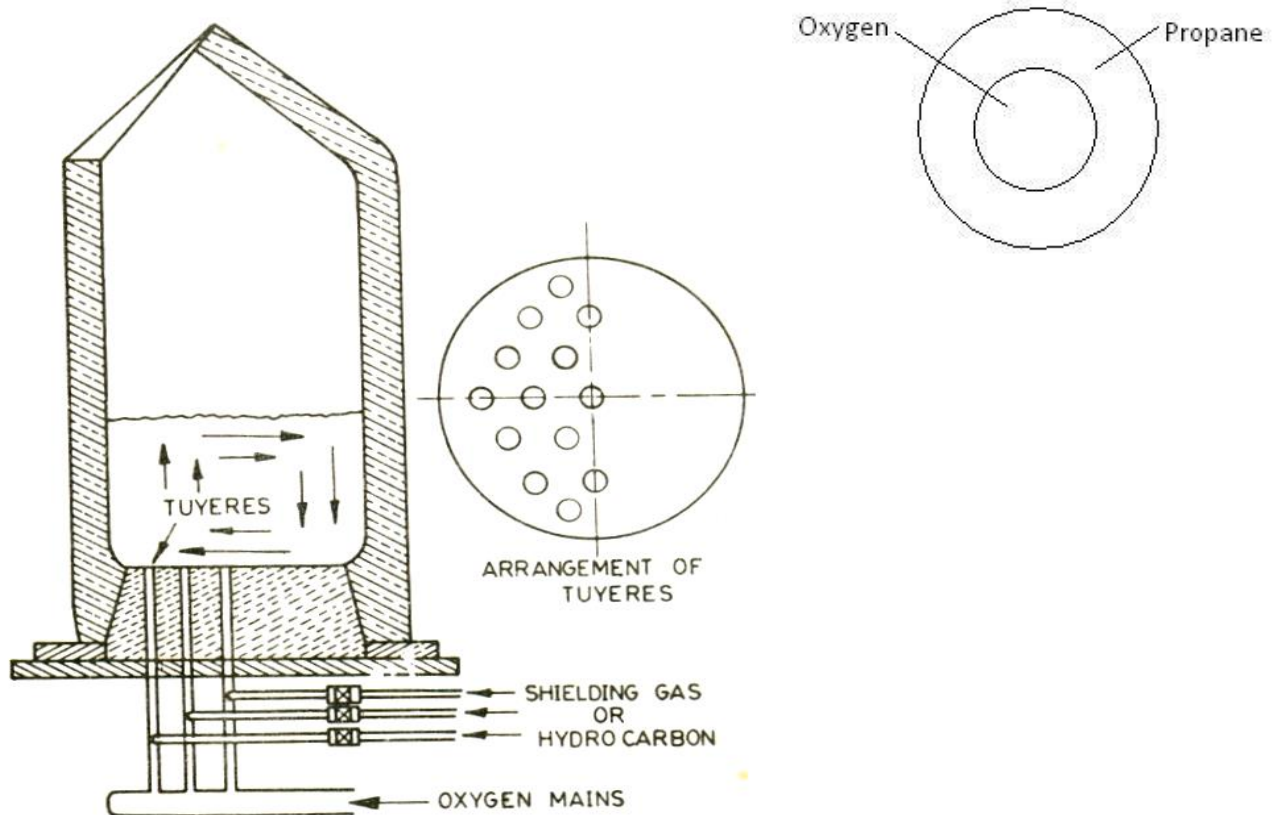
Bottom Blowing Process: OBM

Introduction

- To decrease the nitrogen content and its deleterious effect on steel produced by Bessemer process, oxygen enrichment of blast up to 40% was done with 20% scrap input, but pure oxygen could only be supplied in LD top blowing /Kaldo side blowing processes as it reduced the vessel bottom life drastically in bottom blowing process.
- The problem was solved by blowing oxygen along with protective fluid (Propane/gaseous Hydrocarbon) from bottom developed by the Maximilianshutte Iron & Steel Co., West Germany in 1967 named as OBM.
- In 1969 in France LWS process was developed using steam/fuel oil.
- US steel developed a similar process called Q-BOP (Quiet/Quick/Springing up oxygen bottom blowing process).
- Generally term OBM is used for such designs and processes.

Furnace Design

- In principle, oxygen is introduced from the bottom through tuyeres with peripheral shield of protective fluid. Therefore the tuyeres are made of two concentric tubes of stainless steel embedded in magnesite bottom.(oxygen from the inner tube, protective fluid through the annular space with a pressure 20-50% of oxygen)
- The vessel is like Bessemer fitted with a special bottom containing tuyeres.
- Tuyeres are arranged only half the vessel bottom to promote turbulence, damage during charging and higher working volume
- A few bigger tuyeres is better than large no of fine tuyeres w.r.t. maintenance



Why Protective fluid?

- **To protect tuyeres:**

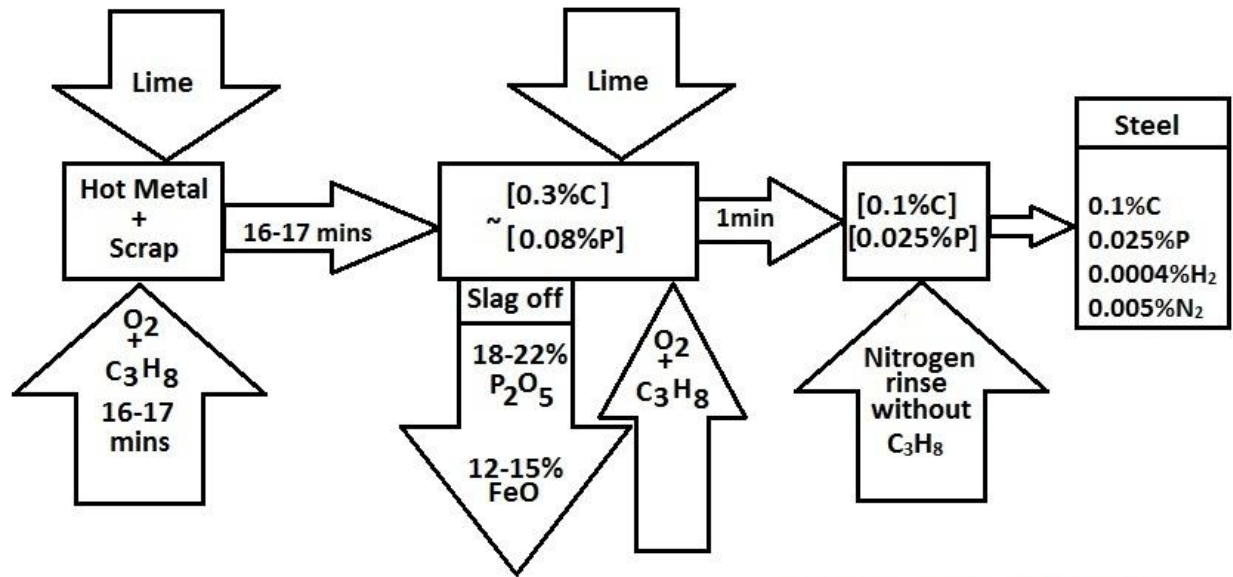
On entry Propane cracks down in an endothermic reaction & takes up some of the heat generated by the entry of oxygen at the tip. Further deposition of carbon (carbon mushroom) after cracking at the tuyere tip helps to protect it.

- **To provide heat:**

50% of the Hydrogen burns with dissolved oxygen and generates heat and rest makes its way to metal for which a nitrogen rinse is given at the end of refining to desorb dissolved hydrogen.

Operation (Sulzbach-Rosenberd Plant, Maximillianshutte)

Developed for Thomas Iron (1.8%P)



One Heat of OBM Process

Vessel Capacity	30tonne
Charge	20.5 ton Hot Metal + 12 ton scrap
O2 pressure	10atm
O2 consumption	60-65N-m3/ton
Propane pressure	6atm
Propane consumption	2N-m3/ton
Lime consumption	125kg/ton
Tap-Tap time	40mins
Yield	90-92%

Comparison with LD

LD		OBM
1	Top Blowing	Bottom Blowing
2	Oxygen supplied through slag layer to metal	Directly to metal
3	Over oxidising slag	Near Equilibrium
4	Even supersonic jet does not result in required stirring	Adequate stirring 10 times more than LD
5	Periodic slopping	No slopping
6	Post combustion of CO provides heat	98% oxygen reacted with metal
7	More scrap (3-6%)	Scrap rate is low
8	Iron loss is more(+5% than OBM)	It is less
9	High carbon steel readily obtained by Catch Carbon Technique with low P content	Such technique is not adoptable
10	Lower [H] content, Higher [N]	Lower [N], Higher [H] content due to hydro-carbon
11	Lower P,S partition coefficient	Higher P,S partition coefficient
12	Less Alloy recovery	Better Alloy recovery

Modern Developments

1. Use of Argon in place of Nitrogen for final rinse to decrease N_2 & H_2 content in steel.
2. Oxygen converter Gas (OG) recovery system introduced to enhance process economy
3. Lime stone as partial replacement of lime through the tuyeres to protect by endothermic decomposition
4. Automation and control by dynamic computer control

LECTURE-16

Hybrid Process of Steel Making

Introduction

Virtually every company has invented or modified a version of the oxygen steelmaking process to suit its own situation. Consequently, there are many designations for fairly similar processes.

The BOF is the overwhelmingly popular process selection for oxygen steelmaking. The usual reason to modify the BOF configuration is to lower the operating cost through better stirring action in the steel bath. It has been found by a number of companies and investigators that additional stirring of the bath from the furnace bottom reduces FeO in the slag. Lower FeO results in higher yield, and fewer oxidation losses of metallics. Bottom stirring increases slag forming, particularly if powdered limes are injected into the bath.

Bottom Stirring Practices

Inhomogenities in chemical composition and temperature are created in the melt during the oxygen blow in the top-blown BOF process due to lack of proper mixing. Bottom stirring practices using inert gases such as nitrogen and argon are being used extensively to improve the mixing conditions in the BOF. The inert gases are introduced at the bottom of the furnace by means of permeable elements (LBE process) or tuyeres. In a typical practice, nitrogen gas is introduced through tuyeres or permeable elements in the first 60 to 80% of the oxygen blow, and argon gas is switched on in the last 40 to 20% of the blow. The rapid evolution of CO in the first part of the oxygen blow prevents nitrogen pickup in the steel. Some of the effects of bottom stirring and the resulting improved mixing include:

(a) *Decreased FeO content in slag.* Better mixing conditions in the vessel causes the FeO in the slag to be closer to equilibrium conditions, which results in lower concentrations of FeO in the slag. Plant studies have shown that for low carbon heats, bottom stirring can cause a reduction in the FeO level in slag by approximately 5%. This results in better metallic yield, lower FeO level in the ladle slag and reduced slag attack on the refractories. Improvements in iron yield by as

much as 1.5% or more have been reported.²⁶ Lower levels of FeO in the steelmaking slag reduces the amount of heat generated during the oxygen blow, and hence reduces the maximum amount of scrap that can be charged in a heat.

(b) *Reduced dissolved oxygen in metal.* A study shows that bottom stirring can reduce the dissolved oxygen level in a low carbon heat by approximately 225 ppm. This lowering of dissolved oxygen leads to lower aluminum consumption in the ladle. Studies have shown aluminum savings of about 0.3 lb./ton due to bottom stirring.

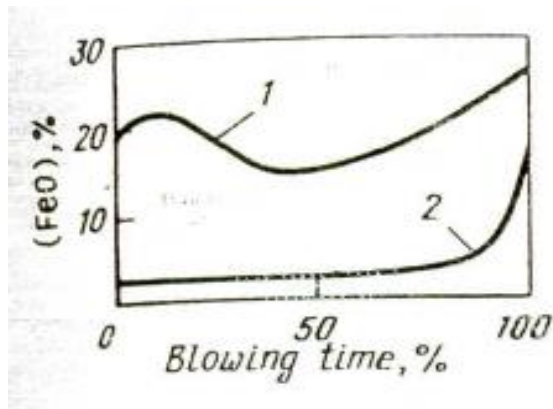
(c) *Higher manganese content in the metal at turndown.* An increase of approximately 0.03% in the turndown manganese content of the metal has been shown. This leads to a reduction in the consumption of ferro-manganese.

(d) *Sulfur and Phosphorus removal.* Bottom stirring has been found to enhance desulfurization due to improved stirring. However, phosphorus removal has not been found to improve substantially in some studies. Although bottom stirring drives the dephosphorization reaction towards equilibrium, the reduced levels of FeO in steelmaking slags tend to decrease the equilibrium phosphorus partition ratio ((%P in slag)/[%P in metal]).

Bottom blowing Vs Top blowing:

Oxidation of carbon : Bottom blowing increases sharply the intensity of bath stirring and increases the area of gas-metal boundaries (10-20 times the values typical of top blowing) .

- Since the hydrocarbons supplied into the bath together with oxygen dissociate into H₂, H₂O and CO₂ gas bubbles in the bath have a lower partial pressure of carbon monoxide (P_{CO})
- All these factors facilitate substantially the formation and evolution of carbon monoxide, which leads to a higher rate of decarburization in bottom blowing
- The degree of oxidation of metal and slag



- Removal of phosphorous: Since the slag of the bottom-blown converter process have a low degree of oxidation almost during the whole operation, the conditions existing during these periods are unfavorable for phosphorus removal

Hybrid blowing:

- A small amount of inert gas, about 3% of the volume of oxygen blown from top, introduced from bottom, agitates the bath so effectively that slopping is almost eliminated.
- However for obtaining near equilibrium state of the system inside the vessel a substantial amount of gas has to be introduced from the bottom.
- If 20-30% of the total oxygen, if blown from bottom, can cause adequate stirring for the system to achieve near equilibrium conditions. The increase beyond 30% therefore contributes negligible addition of benefits.
- The more the oxygen fraction blown from bottom the less is the post combustion of CO gas and consequently less is the scrap consumption in the charge under identical conditions of processing.
- Blowing of inert gas from bottom has a chilling effect on bath and hence should be minimum. On the contrary the more is the gas blown the more is the stirring effect and resultant better metallurgical results. A optimum choice therefore has to be made judiciously.

- As compared to top blowing, the hybrid blowing eliminates the temperature and concentration gradients and effects improved blowing control, less slopping and higher blowing rates. It also reduces over oxidation and improves the yield. It leads the process to near equilibrium with resultant effective dephosphorisation and desulphurisation and ability to make very low carbon steels.

The variety of hybrid processes along with amount of basal gas injected:

PROCESS	% Gas from the bottom					Type of gas from bottom
	1	5	10	20	100	
LD						No bottom gas
LD-KG						Inert gas
NK-CB						Inert gas
LD-OTB						Inert gas
LBE						Inert gas
STB						Inert gas + oxidising gas
BSC-BAP						Air + nitrogen
LD-OB						O ₂ + hydrocarbon
K-BOP						-----do-----
KMS						-----do-----
OBM						-----do-----
Stirring	weak		mode- rate		vigo- rous	

Metallurgical superiority of hybrid blowing:

- ▶ The processes have been developed to obtain the combined advantages of both **LD** and OBM to the extent possible. Therefore the metallurgical performance of a hybrid process has to be evaluated in relation to these two extremes, namely the **LD** and the OBM. The parameters on which this can be done are :
- ▶ Iron content of the slag as a function of carbon content of bath
- ▶ Oxidation levels in slag and metal
- ▶ Manganese content of the bath at the turndown
- ▶ Desulphurisation efficiency in terms of partition coefficient
- ▶ Dephosphorisation efficiency in terms of partition coefficient
- ▶ Hydrogen and nitrogen contents of the bath at turndown
- ▶ Yield of liquid steel

LECTURE-17

Electric Arc Furnace Steel Making

Introduction

Electric furnaces are of three types:

1. Resistance furnace
2. Induction furnace
3. Arc furnace

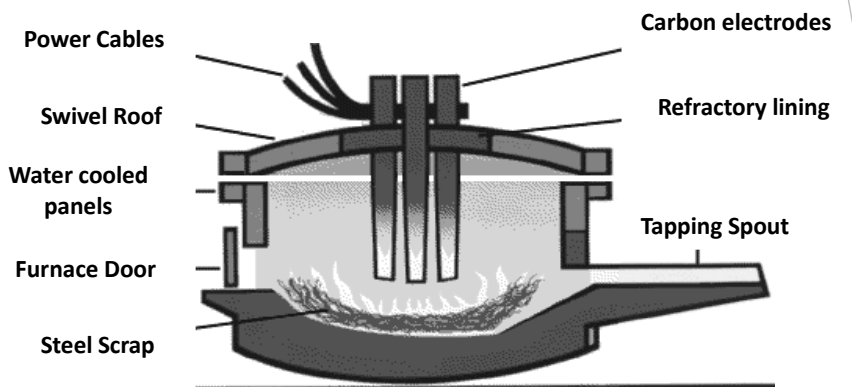
Arc furnaces are of two types:

1. Indirect and
2. Direct arc furnaces

In indirect arc f/c, arc is struck between two carbon electrodes & heat is transferred to the charge by radiations.

In direct arc f/c current flows from the electrode to the charge & heat is transferred from the arc to the charge primarily by radiation but a part of the heat is also generated in the charge itself. A three electrode EAF is used where one phase connected to each electrode and charge is the neutral point.

THE ELECTRIC ARC FURNACE



Construction of AC electric arc furnace

The furnace consists of a steel shell, lined with suitable refractory materials and is mounted on the tilting mechanism. The shell thickness is around 0.005 times the shell diameter. **Three electrodes** enter through the roof. The hood may be swung away for charging. Heat is generated by the hot area formed between the electrodes and the charge.

❑ Hearth

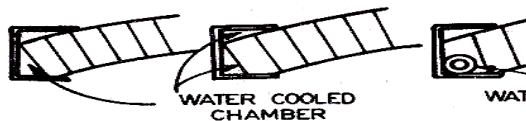
The hearth contains metal and slag. The hearth lining consists of backing lining and working lining. The backing lining is few layers of high fired magnesite bricks on which working lining is rammed with either dolomite or magnesite mass. Permeable blocks or porous refractory elements are introduced through the bottom to inject inert gas for stirring. The EAF steel bath is shallow so it called a **hearth process**

❖ Aspect ratio of the bath is around 0.2 to 0.22.

❑ Roof

The roof is exposed to more heat than other furnace elements. Its lining is also subjected to radiant heat reflected from the walls and slag. High alumina bricks and magnesite – chromite bricks are used for roof lining. The roof lining is water cooled which increases the life of refractory lining to at least 10-20 times more than without water cooling.

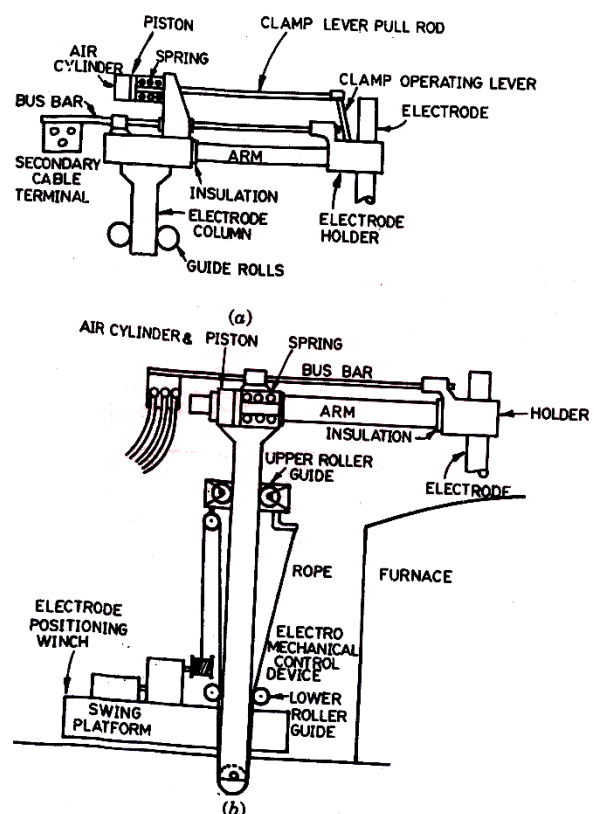
The roof has three holes to allow insertion of the electrodes.



❑ Electrode

A typical alternating current operated EAF has **three electrodes**.

Electrodes are round in section, and typically in segments with threaded coupling, so that as the electrodes wear,



new segments can be added. **Graphite electrodes** are preferred over carbon electrodes because of better electrical conductivity. The electrodes are automatically raised and lowered by a positioning system.

Electrode consumption depends on:

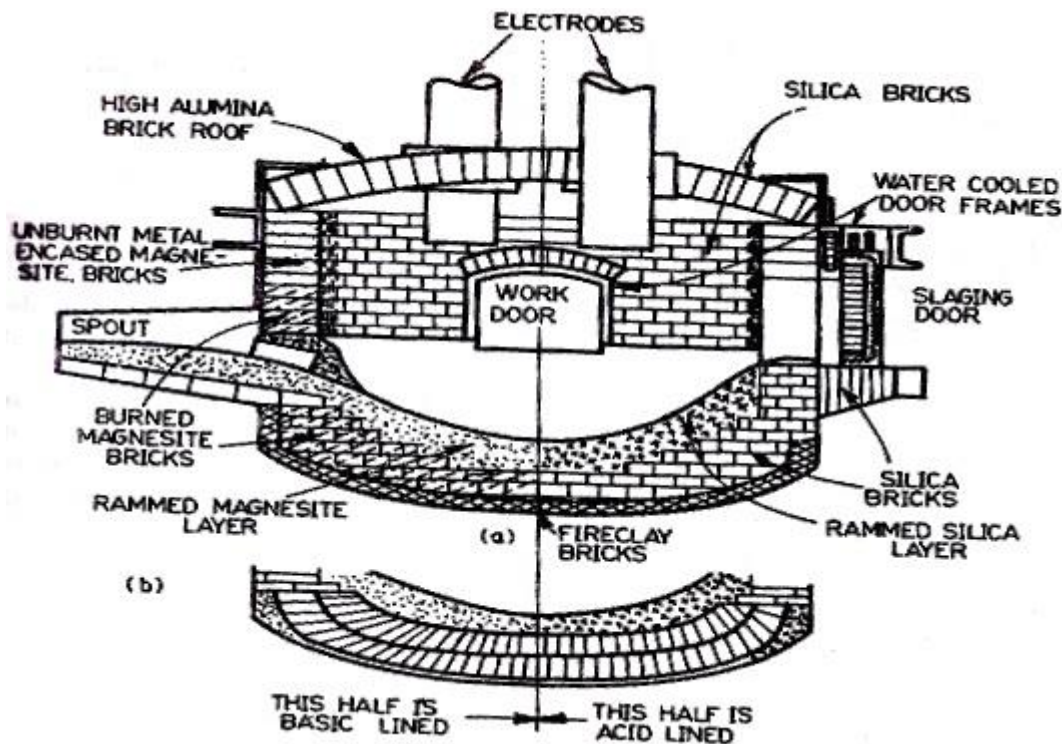
- Oxidation of the surface of the electrode
- Mechanical losses due to fracture
- Dissolution in slag during carbon boil

The electrode current could vary from 12 to 16A/cm² for 400 to 600 mm electrode diameter. Larger electrode diameter increases electric energy consumption.

The electrodes are positioned at apexes of an equilateral triangle. The diameter of the circle passing through the centres of electrodes is called the **diameter of the electrode spacing**.

❑ **Walls**

The side walls refractory materials should be able to withstand thermal shock and corrosive action of slag. Hot spot is formed on the side walls due to the radiation from arc flames, reflected from bath surface during power input. The side wall is lined with magnesite, dolomite or chrome magnesite bricks up to the slag line.



❑ Transformer power

Electric furnaces are powerful consumers of electric energy. The operating voltage of a furnace is 100-800V and the current may reach several thousand amperes. The furnace transformer transforms high voltage energy into low voltage. The melting process consists of two periods: melt-down and refining period.

In melt down period higher electric energy is required as compared to refining period.

❑ Charge materials

Steel scrap is the principal raw material. It may constitute 60 to 80% of the charge. In some practices **sponge iron** and or **pig iron** is also used for chemical balance. In basic furnaces slag formers like **limestone, fluorspar, sand, and quartzite** are used to form a slag to refine the metal. For decarburization oxygen lancing is used. Iron ore is also added. Ferro-manganese, ferrosilicon or aluminium are used for deoxidation. To produce alloy steels, alloying elements are added.

Process types known by their slags

1. **Acid process:** If the raw materials are very low in P & S acid lined f/c can be used for refining. It is generally restricted to foundries.
2. **Basic process:** It is capable of refining any type of charge by maintaining basic slag in a basic lined f/c. *EAF doesn't have any atmosphere of its own.* Oxidizing as well as reducing conditions for refining can be maintained by making slags of suitable compositions. Oxidizing refining is carried out under a slag containing a good amount of iron oxide. Reducing conditions can be maintained by having the slag highly basic but free of FeO.

The following describes the ways in which these slags are used for refining in an EAF:

- i. **Oxidizing single slag practice:** It is used for making carbon or low alloy steels. The charge is melted & refined under a basic oxidizing slag as in an open hearth.
- ii. **Oxidizing double slag practice:** It is a modification over the single slag practice. The early slag is removed and a similar new slag is made again as in case of LDAC to obtain effective dephosphorization during refining.
- iii. **Reducing single slag practice:** It is used for high alloy steelmaking to attend maximum recovery of alloying elements from the scrap. Hardly any refining take place. C & P contents in the scrap must be below the specification levels. S is easily removed in this process as the conditions are reducing.
- iv. **Oxidizing slag converted to reducing:** It is meant to remove C but recovers most of the alloying contents like Cr, Mn, etc. present in the scrap during high alloy steelmaking. As reversion of P takes place it should be within safe limit in the raw materials.
- v. **Double slag practice:** It means refining under oxidizing as well as reducing slags made separately. The first slag is oxidizing & it eliminates all impurities like P, Si, C, Mn, etc. This slag is removed & a reducing slag is made by fresh additions of lime, coke, and spar to desulphurize the metal and to carry out alloying very effectively

General outline of an arc furnace heat

1. Charging

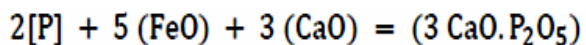
- The charge consists solely of steel scrap, lime/limestone and coke.
- Light scrap is charged first followed by heavy scrap.
- Ni or Cu may be charged with scrap. Refractory alloying elements are shovelled directly into the arc crater region.

2. Melting

- Melting starts below the electrode as the arc is struck. The electrode bore through the metallic charge and a pool of molten metal forms at the bottom. The arc stabilizes when the charge below the electrode melts completely.
- The melting may be hastened by forcing the unmelted stock from the banks into the molten pool either by mechanical rabbling or by rotating the hearth by few degrees.
- The power consumption is maximum during this period
- Slag formation takes place with the increase in basicity during this period.

3. Refining and finishing

- The slag formed during meltdown period contains various oxides like FeO, CaO, SiO₂, MnO, Al₂O₃, etc. Fluorspar, CaF₂ is added to maintain adequate fluidity in the slag.
- The refining process takes place under this **basic oxidising slag**. Carbon boil takes place forming CO resulting in the removal of dissolved gases and floatation of inclusions. For this the carbon content should be 0.25-0.3% higher than the desired carbon content.
- Dephosphorization is favoured:



- The flush slag practice is practised in EAF processes. The basicity of slag is maintained by periodic lime addition. Periodic addition of iron ore assists in continuing the oxidation reaction. After slag removal phosphorus level drops to 0.015-0.02%.
- At the end of oxidising period the slag is raked out manually. The bath is deoxidised by first addition of Ferro silicon and Ferro manganese and finally by addition of aluminium.

- Desulphurisation is favoured by the formation of **second reducing slag** after the first oxidising slag. This can be in two ways: Carbide slag and Lime slag
- The Carbide slag is formed by addition of flux materials consisting of burnt lime, sand and CaF_2 . Pulverized **coke is also added** to slag resulting in carbide formation.
- This carbide helps to maintain a low oxygen potential and helps in Desulphurization occurs according to the following reactions:
- $2(\text{FeO}) + (\text{CaC}_2) = (\text{CaO}) + \text{Fe} + 2[\text{CO}]$
- $(\text{CaO}) + [\text{FeS}] = (\text{CaS}) + (\text{FeO})$
- Carbide slag tends to recarburise the bath hence not suited for low carbon heats ($\text{C} < 0.15\%$). So **Lime slag** is made with lime, Fe-Si and Aluminium, **No coke added**.

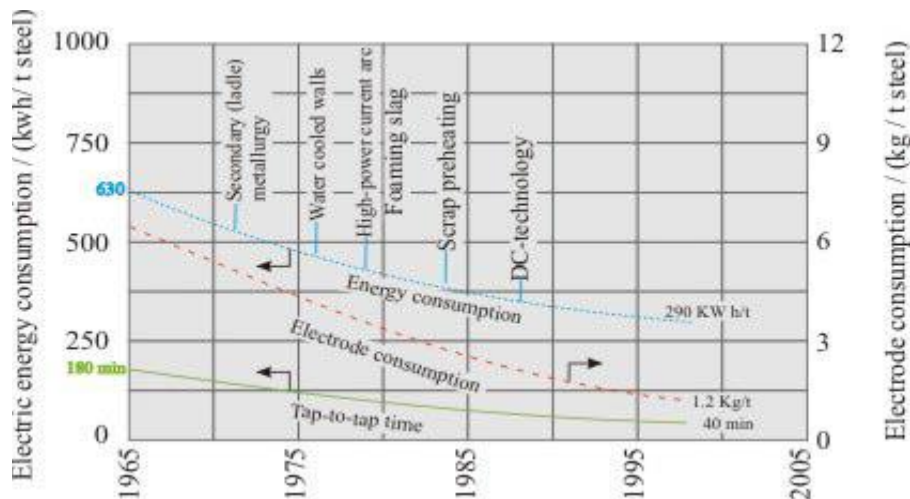
Constituents	% in Carbide slag	%in Lime slag
CaO	65-70	50-55
SiO_2	20-25	25-30
FeO	0.5max	1.0max
MgO	5-10	5-10

LECTURE 18

Developments in EAF steelmaking

Introduction

The growth of electric steel production around the world has been driven by lower investment, higher operational flexibility and easy adoptability to market demand on long or flat products of either plain carbon or alloy steels. Growth has been supported by updating installations and technologies to reduce the electric energy, electrode consumption and tap to tap time. Figure 22.1 shows the developments in



Trends in EAF steelmaking technologies developments in EAF steelmaking

Electric steelmaking technologies. Developments in EAF technologies are strongly supported by secondary steelmaking. One can note in the figure that the power consumption has decreased from 630

Kwh/ton of steel to 290kWh/ton. Similarly tap to tap time has decreased from 180 minutes to 40 minutes and electrode consumption has decreased from around 6.2 kg/ton to as low as 1.2 kg/ton within the periods of representation in the figure. This became possible with the several simultaneous developments in the secondary steel-making method. Table shows the various developments

Developments in EAF steelmaking

Furnace design:

- i) Construction of hearth and lower side section of the shell of larger diameter than the top opening. This leads to increase in shell volume which results in larger tonnage charge, lower heat losses and improved thermal efficiency.
- ii) In the split shell design, shell structure is constructed in two sections: lower section which contains hearth and free board allowance for slag, and upper section containing side wall and roof. The two sections are coupled such that the upper section can be repaired easily. This reduces the downtime and increases furnace availability.
- iii) High powered transformers are the current trends. Most modern furnaces operate at 500k VAton/ and the trend is towards ultra high power ranging in between 700k VAton/ to 1000k VAton/. Developments are in progress to install transformer with 1500k VAton/ capacity. It is claimed that a 120 tons operating at 180 MVA transformer capacity and by using refining combined burner technology through oxygen gas and carbon injection, it is possible to increase capacity by up to 50%. The largest transformer in AC EAF corresponds to a rated power of 240 MVA for 300 ton furnace.
- iv) Eccentric bottom tapping reduces tap times, temperature losses and slag carry over into ladle. The strip producing plants are equipped with eccentric bottom tapping in electric arc furnaces.
- v) DC (direct current) arc furnaces represent a different concept in arc furnace design. Most DC furnaces are with single electrode where current flows down from the carbon electrode to an anode mounted in the bottom of the furnace. Reduced electrode consumption of the order of 50

to 60 % is the major benefit of a dc furnace compared to a convectional three- phase arc furnace. Noise levels for the dc furnaces are lower. Lower maintenance costs are claimed and refractory costs are less for sidewall but more for the furnace bottom. A dc arc furnace requires an addition of the bottom electrode (anode), a dc reactor, and a thruster all of which add cost to a dc furnace. The electrode technology limits diameter to a maximum of 700 mm allowing a dc current of 100kA and 70 MVA power for single electrode furnace. Furnace size is limited to 200 tons. Further developments are in progress.

Process operating technologies

Most of the developments in process operating technologies are in AC- electric arc furnaces as these furnaces are popular.

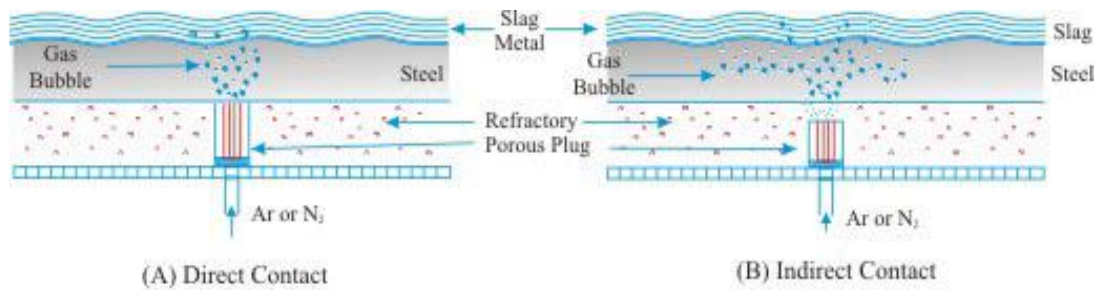
i) Bottom stirring

In convectional arc furnaces there is little natural electrical turbulence within the bath. Due to absence of stirring large piece of scrap can take a long time to melt and may require oxygen lancing. Argon or nitrogen stirring

- Eliminates temperature and concentration gradients
- Shortens tap-to-tap times
- Reduces refractory, electrode and power consumption and
- Improves yield of iron and alloys

Industrial systems for bottom stirring are either with direct contact plug or with indirect contact plug. In direct contact plug, the plug is in contact with molten metal, whereas in indirect one the plug is embedded in a porous bottom refractory. In the indirect contact, the plug is not directly in contact the molten metal. The gas enters the bath via the porous refractory hearth which results in stirring over a large area when compared with direct plug as shown in the figure. The figure

shows the direct contact and indirect contact plug for bottom stirring. Note that in indirect contact large area of the bath is stirred as compared with direct contact plug.



Industrial bottom stirring systems in electric arc furnace

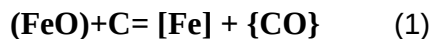
ii) Foamy slag practice

In EAF steelmaking, progressive melting of scrap increases the irradiative heat transfer from arc to the side walls of the furnace. By covering the arc in a layer of slag, the arc is shielded and more energy is transferred to the bath. The foaming slag during this period is beneficial.

The effectiveness of slag foaming depends on slag basicity, FeO content of slag, slag temperature and availability of carbon to react with either oxygen or FeO of slag.

Slag foams in steelmaking due to entrapment of gas bubbles. Gas producing reactions in steelmaking are:

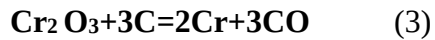
- a) Reaction between FeO of slag with carbon



- b) Between carbon and oxygen dissolved in metal



b) Between chromium oxide and carbon



Reactions 1 and 2 are important in carbon steelmaking whereas reaction 3 is important in stainless steel making. Slag foaming is discussed in lectures 4 and 5.

Injection of carbon and oxygen at several places in the bath assures slag foaming practice, when carbon content of the bath is insufficient. Typically carbon injection rates for slag foaming are 2.5 to 5 kg/ ton of steel. In high powered furnaces carbon injection is 5-10 kg/ton of steel.

In stainless steel making Cr_2O_3 forms in preference to FeO due to higher affinity of Cr to oxygen. The solubility of chromium oxide in the slag is considerably weaker in comparison to FeO for the same basicity and thermal conditions. The oxygen/carbon injection technique in the high chromium alloy steel production and to foam the slag is difficult. Moreover, additional chromium will also be lost due to oxygen injection.

The novel technology utilizes the reduction of iron and chromium oxide by carbon as well as thermal dissociation of limestone contained in small briquette. (See the reference given at the end of the lecture)

iii) Scrap preheating

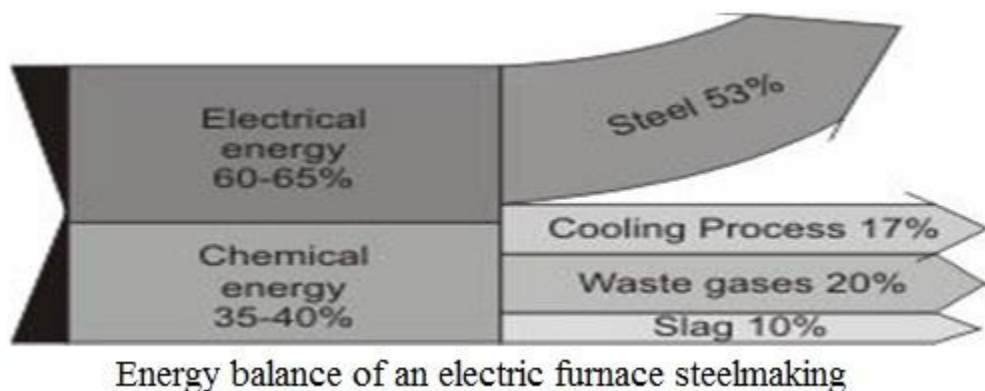
Preheating of scrap brings thermal energy into the furnace. Preheating of scrap to 540°C brings 81kwh/ton of additional energy.

Scrap preheating gives the following advantages:

- Reduction in energy consumption by 40-60 kwh/ton depending on the scrap preheat temperature

- Electrode consumption reduces by 0.3 to 0.36 kg/ton
- Refractory consumption decreases by 0.9 to 1.4 kg/ton
- Tap to tap time reduces by 5 to 8 minutes.

It is important to note that scrap preheating technology needs to be developed. Thermal energy is required to preheat the scrap and is economical only when the waste heat from the furnace is utilized. For this purpose it is important to know the energy balance of the electric furnace.



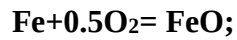
The energy balance of an EAF, as shown indicates that 20% of the total energy leaves the furnace in the waste gases and represents about 130 kWh/ton of steel produced. Efficient utilization of thermal energy of exit gas is the key to realize the advantages of preheating of scrap. Batch preheating and continuous preheating are the available technologies. In CONSTEEL, scrap and exit gases move counter current to each other. It is possible to preheat the scrap to ~320°C.

Usage of Chemical Energy

The high electrical energy costs pushed EAF steelmakers to look for alternative energy sources. One such source is the chemical energy derived from chemical reactions. In recent years the chemical energy supply amounts to 35% to 40% of the total energy in most of the modern EAFs. (See figure 16.3)

i) Oxidation reactions

The main oxidation reactions are oxidation of iron and carbon besides oxidation of silicon and manganese. The oxidation of iron though generates more energy than oxidation of carbon but iron oxidation results in loss in productivity.



Heat content 6kW/m³O₂



Heat content 3.5kW/m³O₂

Hence oxygen injection must be controlled such that iron oxidation is kept minimum. For bath carbon levels above 0.3%, all oxygen reacts with carbon to produce CO. Below 0.3% C, the efficiency of carbon oxidation to form CO drops and more and more FeO is generated in the slag.

For scrap carbon levels below 0.1%, FeO levels in the slag can be quite high and represents an unavoidable yield loss. Increased carbon injection is necessary to control slag FeO levels and to prevent excessive refractory wear. Efficiency of heat transfer from oxidation reactions is extremely high due to the fact that these reactions are occurring in the bath. Greater penetrability of oxygen jet ensures the occurrence of oxidation reactions in the bath.

ii) *Post combustion*

It is a practice of generating additional energy for melting steel by using the right amount of extra oxygen to combust CO and H₂ which evolve within the EAF. Carbon monoxide is generated in an EAF by

- Partially combusted hydrocarbons entering the furnace with the scrap
- Combustion of charged and injected carbon via $\text{C} + 0.5\text{O}_2 = \text{CO}$
- The reduction of FeO by carbon during slag foaming

Hydrogen is generated by:

- The cracking of hydrocarbons (oil in scrap, methane)
- The reduction of water: $\text{H}_2\text{O} + \text{CO} = \text{H}_2 + \text{CO}_2$ or $\text{H}_2\text{O} + \text{C} = \text{H}_2 + \text{CO}$

In EAF, carbon monoxide and hydrogen may be available at the freeboard, whereas the foaming slag contains carbon- monoxide. It must be noted that oxygen flow should have low velocity to promote mixing with the furnace gases and to avoid scrap oxidation and rebound of oxygen from the scrap to the water cooled panels. Post combustion in the slag typically aims at combustion of 20 to 30% of the CO generated in slag and 70 – 80% at the free board.

For post combustion speed of oxygen injection must be low and also uniform distribution of oxygen is required.

Iii) Oxy – fuel burner

Oxy-fuel burner uses natural gas or oil, together with pure oxygen to produce an extremely high flame temperature. Oxy- fuel burners are used to melt unmelted scrap between the electrodes and to provide

Heat to cold spot. On most modern UHP furnaces, the primary function of burners is to provide heat to cold spots to ensure even scrap melting and to decrease the melting time necessary to reach a flat bath. Typically industry practice indicates that 0.133 MW of burner rating should be supplied per ton of furnace capacity. Others recommend 32 k Wh/ ton of burner power to eliminate cold spots in a UHP furnace and 50 to 200 kWh/ ton of burner power for low powered furnaces.

iv) Carbon injection

Injection of carbon brings following benefits:

- i. For 100 percent scrap practice or when carbon content of the bath is insufficient to produce CO for slag foaming, carbon injection is beneficial.
- ii. Carbon oxidation produces CO which on post combustion generates thermal energy.

It is to be noted that carbon injection requires oxygen injection to onset carbon oxidation.

Requirements for chemical energy usage

The chemical energy usage requires developing a device to inject oxygen in different modes:

- ✓ Hold mode (to prevent plugging)
- ✓ Burner mode (to heat and melt scrap)
- ✓ Soft lancing mode (for post combustion)
- ✓ Supersonic lancing mode (for decarburization and slag foaming)
- ✓ Carbon injection mode (when slag foaming is required)

Injectors are either fixed type or moveable type. Submersible hand lances are used through the slag door. Large opening in EAF shell is required. Slag and metal splashing restricts the device movement. Excessive repairs and down-time are associated with this technology.

An innovative design is CO-jet injectors which are fixed type and can be mounted on the furnace shell. CO-jet injectors are highly flexible in usage. The reader may see the references given in this lecture.

The next lecture deals with charge mix in EAF steelmaking.

Future of EAF steelmaking

The EAF needs a metallurgical reactor that has the largest growth potential both in terms of production capacity and technology evolution. Future EAF will be equipped with all modern technologies- like Ultra high power input (up to 1500 kVA/t), latest oxygen and carbon injection technology and design features- like ultra high shell design, heavy mill type components.

This combination leads to an Electric Arc Furnace where the tap to tap times can be extremely short and the corresponding productivity reaches the level of larger furnace sizes or converter plants.

The two main reasons for this are:

- The possibility of a higher electrical power input and

- A far higher efficiency of chemical energy, decarburization and scrap preheating compared to the same size (tap weight) standard furnace.

It is interesting to compare a conventional 120ton EAF with the ultimate 120 ton EAF.

Conventional 120 ton EAF

Ultimate 120 ton EAF

2- bucket charge

1-bucket charge

Scrap bucket 130 m³

Scrap bucket 185 m³

Furnace volume 145 m³

Furnace volume 210 m³

Transformer design upto 1,000kVA/t,
120MVA for 120 ton tapping weight,

Transformer design upto 1,500kVA/t,
180MVA for 120 ton tapping weight,

Secondary voltage up to 1,200V

Secondary voltage up to 1,500V

Utilization of chemical energy

Utilization of chemical energy

3 oxygen gas burners

3 oxygen gas burners

3 refined combined burners (RCB)

5 refined combined burners (RCB)

2 carbon injectors

4 carbon injectors

4 post combustion injectors

Refined Combined Burner (RCB) technology combines a conventional oxy/gas burner with a supersonic oxygen injection lance and is designed to optimize the injection of carbon and oxygen into EAF. It supplies chemical energy through chemical reactions of fuel and gas, oxygen, and carbon injected into the furnace.

LECTURE-19

Alternative Charge Materials in EAF

Introduction

Raw materials and operating practices affect EAF efficiency and yield. The traditional EAF charge has been 100% cold scrap. The charge materials saturation is critical for several reasons:

- The product mix served by EAFs is moving more towards value-added steels, which are specified with low metallic residuals and low nitrogen levels (automotive flat rolled, cold heading- rolled and wire).
- The availability of scrap needed to meet the requirements of value added products is limited. The availability of scrap is decreasing as more and more near-net-shape metalworking operations appear.
- Yield and energy consumption are both strongly dependent on the quality and physical characteristics of the charge materials availability.

Type of metallic charge materials

- Pig iron/hot metal
- Directly reduce iron (DRI)
- Iron carbide (Fe_3C)

Pig iron

Pig iron is a good charge material because of its

- High density
- Low melting point
- Carbon contribution
- No tramp elements

It must be known that EAF is designed exclusively to use electrical energy. Pig iron contains 3–4 %C, 0.1–0.2% P, 0.6–0.8% Mn and 0.6–0.8% Si. Charging of pig iron means refining is to be

done in EAF. For example if we make a charge mix containing 20% hot metal with 3.5%C and 80% scrap with 0.1%C to produce 100 ton steel with 0.1% carbon. We need to remove around 640kg C. To remove this amount of carbon we would be needing $\approx 630 \text{ m}^3$ oxygen on the assumption that oxygen utilization is 100% and is used for removal of carbon only. Under actual conditions we would be needing more oxygen to remove carbon if we take into account oxidation of $\text{Fe} \rightarrow \text{FeO}$, $\text{Si} \rightarrow \text{SiO}_2$, $\text{Mn} \rightarrow \text{MnO}$ and $\text{P} \rightarrow \text{P}_2\text{O}_5$. More proportion of pig iron in charge mix will increase oxygen requirement. What we learn from this simple calculation is that one has to supply oxygen under EAF condition and has to handle large amount of CO as well. Extra decarburization will increase tap to tap time and may decrease productivity. Under practical condition 30% hot metal is suggested to give optimum results with regard to productivity, electric consumption etc. The source of hot metal is either blast furnace or smelting reduction process. Hot metal can only be used when EAF plant is in close proximity of the blast furnace or smelting reduction units, otherwise one has to use cold pig iron and extra energy would be required to melt the pig iron

Direct Reduced Iron

Direct reduced iron (DRI) or hot briquetted iron (HBI) has emerged as an important substitute of the scrap. DRI does not contain any tramp element; hence substituting DRI for scrap leads to dilution of tramp elements in steel. DRI is produced by reduction of iron ore with carbon or gaseous reducing agent. The product of gaseous reductant is HBI.

DRI contains: Free iron + oxygen combined with iron + free carbon + gangue minerals (SiO_2 , Al_2O_3 , P_2O_5 etc).

Quality of DRI is important. Quality of DRI can be judged in terms of metallization and oxygen remaining. Metallization (M) is defined as

$$M = \frac{\text{Free Iron} * 100}{\text{Total Iron}} \quad (1)$$

Higher is the metallization, less oxygen would be required to remove oxygen from iron oxide of DRI during steelmaking.

Consider 1000kg iron ore of composition 80% Fe_2O_3 and 20% gangue minerals. Reduction of iron ore produces DRI in which oxygen is present as FeO.

Metallization (%)	Free iron (kg)	Fe-FeO (kg)	Gangue (kg)	Oxygen with FeO(kg)	Total gangue (kg)
80	450	110	200	31.00	310
85	480	80	200	18.00	280
90	500	60	200	10.00	260
95	530	30	200	3.00	230

We note from the table the following:

- a) Increase in metallization increases free iron in DRI which is good.
- b) Increase in metallization decreases iron which is combined with FeO. Lower amount of heat and reductant would be required to recover iron of FeO from DRI. Reduction of FeO with C is endothermic. Energy is required to compensate for the endothermic reaction.
- c) Increase in metallization decreases the gangue minerals in DRI. Gangue minerals would be recovered as slag; decrease in gangue minerals will decrease slag volume during production of steel using high metalized DRI as a charge material.
- d) Because of b) and c), the overall effect would be decrease in electric consumption and reduced electrode wear.

The benefits arising due to the use of high metalized DRI in charge materials must be considered along with the production cost of metalized burden. Overall economics of metalized DRI in electric steelmaking is important while deciding % metallization in the feed.

Another important issue in case of DRI is the proportion of DRI in the charge. For this purpose 1000 kg sponge iron of 90% metallization is to be used in different proportions. We consider charge mix is scrap and DRI. Calculations show that 1300 kg iron ore would be needed to produce 1000 Kg DRI with 90% metallization. The following table illustrates the influence of proportion of DRI on the free iron and other variables of DRI:

DRI (%)	Free iron (kg)	Fe-FeO(kg)	Gangue (kg)	Total gangue (kg)
10	66	7	27	36
30	198	22.4	81	110
40	264	29.2	108	146
50	330	36.0	135	181

We note the following:

- i) Increase in proportion of DRI increases the free iron in the charge.
- ii) Fe which is combined with oxygen as FeO increases with increase in the proportion of DRI. This would require extra amount of heat energy both chemical and thermal to reduce FeO to Fe and to raise the temperature of reactants to 1500–1600°C.
- iii) Gangue content of the DRI increases with the increase in proportion of DRI. This would lead to increase in slag volume and heat load.

This results in following consequence:

- A) Tap to tap time may decrease with the increase in DRI but more proportion of DRI may increase tap to tap time for two reasons, namely more time is required to reduce $\text{FeO} \rightarrow \text{Fe}$ and, to handle increase volume of slag.
- B) Increased proportion of DRI beyond a limit may increase electrode consumption and refractory wear.

Carbon content in DRI

Carbon content in DRI helps reducing FeO to Fe. Excess carbon than required to reduce FeO would require oxygen injection. Oxygen in DRI is $0.286 \times \text{FeO}$. Reduction of FeO is



According to reaction 2 carbon requirement is 0.17 kg/kg FeO. Carbon content in excess of 0.17kg/kg FeO would require oxygen injection and CO will be generated. Excess carbon aids chemical energy which reduces electrical energy requirement. While producing DRI from carbonaceous reductant, excess carbon than reduction for FeO requirement is to be maintained. In DRI produced from gaseous reductant, extra carbon can be mixed with DRI or otherwise carbon injection is to be done.

Iron carbide

Other charging material is iron carbide which contains 6% carbon. It is prepared by heating iron oxide fines in a mixture of CO, CO₂, methane, H₂ and water vapour at temperatures between

550°C and 650°C and pressure 1.8 bar. Iron carbide is lighter than steel and is introduced pneumatically below the slag layer through a lance. Iron carbide has a melting point (2110 K) greater than molten steel and it dissolves in steel. On dissolution carbon of iron carbide is released, reacts with oxygen and releases heat which leads to saving in electric energy. Also CO produced foams the slag and brings advantages of slag foaming on the electric arc furnace operation. Iron carbide does not contain gangue and tramp elements. Use of iron carbide increases yield. However the benefits of iron carbide addition must be considered in relation to its cost of production and method of addition into electric arc furnace.

Charging methods for DRI

In small furnaces (lower than 5T) batch charging is preferred.

Continuous charging brings advantages like

- Less power off-time.
- Heat losses resulting from delays are eliminated.
- Lower electrical losses.
- Reaction between carbon and FeO of DRI produces strong carbon boil during charging which improves heat transfer and slag/metal mixing.
- Charging and refining take place simultaneously which reduces tap to tap time.

Continuous charging is preferred when the sponge iron or DRI is around 60%; the limitation is due to the small furnace capacity. However, ultra high powered furnaces can operate with 100% sponge iron.

LECTURE-20

Stainless Steel Making Technology

Introduction

Stainless steels contain typically 12-30 % chromium with/without other elements like C, Mn, Si, S etc. Chromium imparts corrosion resistance to steel. Varying amounts of other alloying elements like Ni, Mo, V, Ti, Ni, etc may be added to obtain certain specific property. A vast majority of these steels must contain carbon below 0.12wt%. A large proportion in fact contains 0.07-0.08%C and the Ni-Cr series is made with only 0.02% C.

There are different types of stainless steels like

Austenitic stainless steels: which contain 18% Cr, 8% Ni, and C is in between 0.03-0.15%

Ferritic stainless steels: which contain 12% to 30% Cr and 0.08% to 0.12%C.

Martensitic stainless steels: which contain around 13% Cr and C varying in between 0.15% to 0.25%. Certain grades contain C 0.6% to 0.95%.

It may be noted that all stainless steels contain chromium and carbon besides other elements. Production of stainless steels requires controlling chromium and carbon. That is to oxidize carbon without oxidizing the alloying element: Chromium. This is a big challenge in conventional steel making.

Stainless steel is generally manufactured with the use of Ferro chrome as a feed material for chromium.

Ferro-Chrome is an alloy of chromium and iron containing between 50% and 70% chromium. Ferro-Chrome with chrome content below 56% is known as 'charge chrome'. High Carbon Ferro-Chrome produced from higher grade ore is more commonly used in specialist applications such as engineering steels where a high Cr to Fe ratio and minimum levels of other elements such as sulfur, phosphorus and titanium are important. Low-carbon Ferro-Chrome is used during steel production to correct chrome percentages, without causing undesirable variations in the carbon or trace element percentages.

Charge Chrome:

Elements			% W / W
Chromium	Cr	49-55	% min
Carbon	C	9	% max
Silicon	Si	5	% max
Phosphorus	P	0.035	% max
Sulphur	S	0.05	% max

H-C Ferro Chrome:

Elements			% W / W
Chromium	Cr	60-65-68	% min
Carbon	C	9	% max
Silicon	Si	1-1.5-2-3	% max
Phosphorus	P	0.03	% max
Sulphur	S	0.05	% max

L-C Ferro Chrome:

Elements			% W / W
Chromium	Cr	58-60-65	% min
Carbon	C	0.05-0.06-0.10- 0.15-0.20-0.25	% max
Silicon	Si	1.5	% max
Phosphorus	P	0.03	% max
Sulphur	S	0.03	% max

From: www.fondel.com

Process Development

Prior to the late 1940s, stainless steel was made in the electric arc furnace by melting carbon steel scrap, iron ore and burnt lime; slagging off; adding burnt lime, ferrosilicon and fluorspar; increasing the temperature; and adding low carbon ferrochrome to attain the specified chromium. In this process (known as the "**Rustless Process**"), most stainless grades were made to an aim carbon specification of 0.08 percent. During this period, the only practical and economic way to use stainless scrap was to remelt it in induction furnaces. With the introduction of tonnage oxygen in the steel industry in the late 1940s, a new arc furnace practice evolved in which stainless scrap, high carbon ferrochrome, nickel, and lime were melted, the bath blown with oxygen to temperatures between 1850-1950°C, reduced with silicon and aluminum, and trimmed with low carbon ferrochrome. Relative to the "Rustless Process," this practice resulted in significant decreases in power consumption, process time, and the use of expensive low carbon ferrochrome as well as improved quality (decreased hydrogen contents) and increased chromium recoveries.

In 1954, W. Krivsky of Union Carbide was studying carbon-chrome-temperature relationships in ferrochromium melting in the laboratory. The experiments involved blowing oxygen onto the surface of molten chromium alloy baths under isothermal conditions. In order to control temperature, he added argon and found that he could decarburize the melt to low carbon levels without excessive chromium oxidation. Krivsky's observation led to plant-scale experiments injecting argon/oxygen mixtures by lance into the arc furnace between 1958 and 1962. Eventually, it was concluded that a separate refining vessel (**duplex process**) was necessary to develop a commercial process, and the first successful **AOD** (argon oxygen decarburization) heat was made in October 1967 in a modified 15-ton ladle. These trials resulted in the first commercial AOD installation at Joslyn (now Slater Steel) in July 1968.

During the late 1950s, vacuum degassing processes (DH, RH, ASEA-SKF, Finkl VAD, etc.) were developed for carbon steel production, and led to the development of vacuum decarburization processes for stainless steels in the mid-1960s. The **VOD** (vacuum oxygen decarburization) process was developed by Witten (now Thyssen) in Germany between 1962 and 1967. Between 1959 and 1962, Witten had produced stainless steels in their LD converter

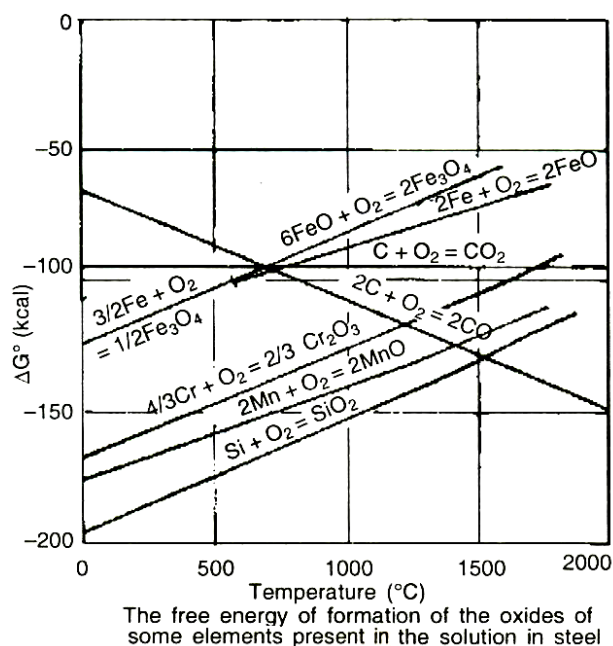
(decarburization of pig iron, addition of low carbon ferrochrome, and reduction with silicon and aluminum).

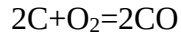
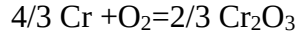
With the installation of their ladle vacuum degassing unit in 1962, they began trials duplexing premelt from the LD to the vacuum degasser. Initially, iron ore was used for decarburization. Later, premelting took place in the arc furnace, and oxygen was top blown onto the bath surface in the degassing ladle.

The AVR process, in which oxygen was injected below the surface by top lance in the degassing ladle, was developed by Allegheny Ludlum in the mid-1960s. In recent years, Allegheny has used their TMBI (top mixed bottom inert) process metal supplied from their induction furnaces when stainless demand exceeded AOD capacity. The development of the AOD and VOD processes between 1954 and 1968 revolutionized stainless steelmaking and was the primary impetus for the dramatic growth in production between 1970 and the present. The use of these or similar processes resulted in significant decreases in raw material costs, increases in productivity, and improved quality.

Thermodynamics of decarburization of chromium melt

In stainless steel making both chromium and carbon oxidizes when decarburization of melt is done.



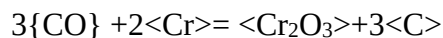


The above two reactions are in equilibrium at 1220°C which is evident from the Ellingham diagram for oxide formation and indicates that carbon oxidation in preference to chromium oxidation can only occur at temperatures greater than 1220°C, when both elements are in pure state. Under all practical conditions carbon oxidation can occur at temperatures above 1800°C in presence of chromium. When opening chromium content in the bath is higher carbon oxidation will predominate at still higher temperature. That's why the opening chromium and carbon content in the bath are restricted in stainless steel making and the required balance chromium is added in the form of low carbon Ferro-chrome.

The limitations of the classical process may be summarized as follows:

1. A higher percentage of stainless steel scrap cannot be used in the charge.
2. Only low carbon Ferro-chrome, which is quite costly, can be used for adjusting the finishing composition.
3. Severe refractory lining damage at 1800°C and above.
4. A complete heat of about 8hrs restricts productivity.

Combining the two reactions



The free energy change of the for the reaction at 1220°C is zero.

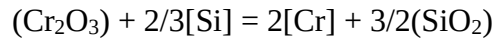
$$K = \frac{a_{\langle\text{Cr}_2\text{O}_3\rangle} a_{\langle\text{C}\rangle}^3}{a_{\langle\text{Cr}\rangle}^2 p_{\{\text{CO}\}}^3}$$

So, for low carbon stainless steel the K value has to be very much lower than unity. During refining in EAF the slag is almost saturated with Cr₂O₃ and the ambient atmosphere to be of CO at 1atm pressure. This condition can be summarized with the following figure (Tupkary-Pg-214 Cr Vs C at 1 atm pressure Plot)

It is evident that for 10% Cr in the bath 0.22%C is achieved at 1600°C which increases to 1800°C for achieving 0.05%C.

Higher temperature is required for stainless steel making

When carbon is down below the specification the atmosphere is reverted to reducing to get back the chromium from the slag. In basic steel making generally Fe-Si is added.



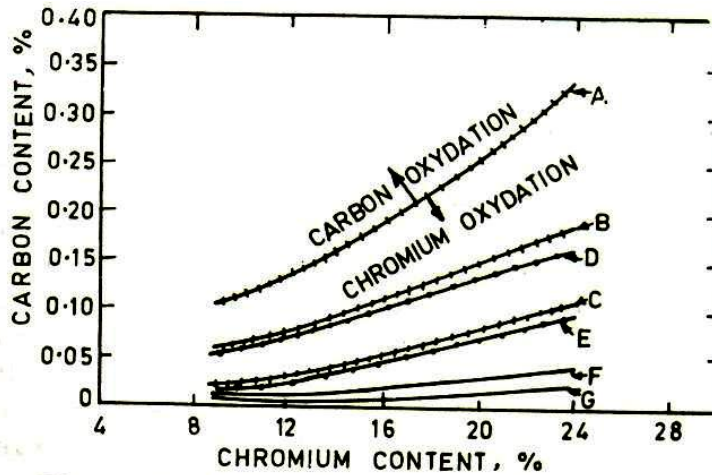
This may be approximately written as

$$\frac{(Cr)}{[Cr]} \propto \frac{h_{(SiO_2)}}{h_{[Si]}}$$

The activity of SiO_2 in basic slag is very low hence the chromium distribution is favoured in the direction of metal bath.

After preliminary analysis is known the final adjustment of the bath chemistry is done using low carbon Ferro-chrome.

As use of L-C Ferro-chrome is expensive and raising the temperature of the bath is limited by the economics of the lining life of the furnace the thermodynamic alternative is, therefore to reduce the equilibrium partial pressure of CO gas in the ambient atmosphere of the melt so that further decarburization shall take place in preference to chromium oxidation.



The inter-relationship of carbon and chromium dissolved in iron as a function of temperature and pressure

A-1700°C/1 atmos.,
 B-1800°C/1 atmos.
 C-1900°C/1 atmos.,
 D-1700°C/0.5 atmos.

E-1700°C/0.5 atmos.,
 F-1700°C/0.1 atmos.
 G-1800°C/0.6 atmos.

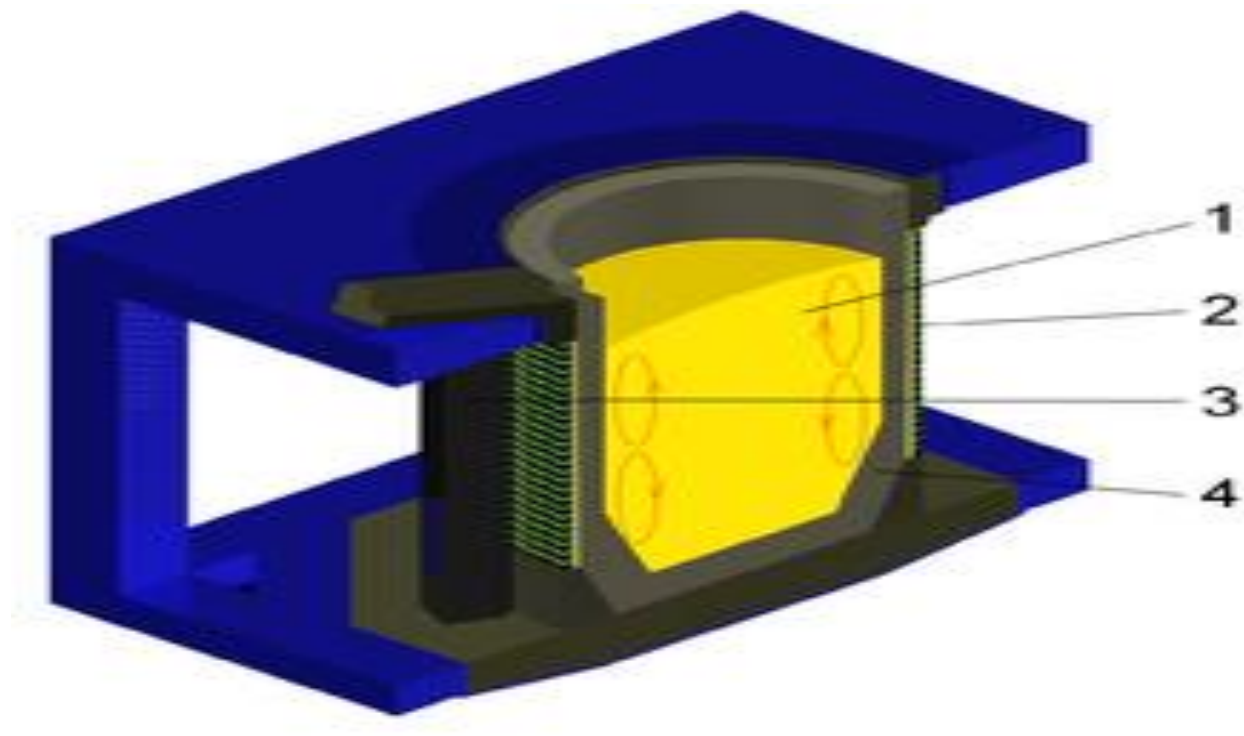
This leads to Argon Oxygen Decarburisation and latter Vacuum Oxygen Decarburisation techniques

LECTURE-21

Induction furnace

Introduction

The Induction furnace has several decades of history as a melting equipment in cast iron melting and duplex melting, our frequency furnace and intermediate frequency furnace has also been a wealth of experience in manufacturing applications work in the power structure, the inverter technology, integrated control circulating cooling technology have made remarkable progress. Induction melting furnace and insulation manufacturers are more and more. An induction furnace is an electrical furnace in which the heat is applied by induction heating of metal. The advantage of the induction furnace is a clean, energy-efficient and well-controllable melting process compared to most other means of metal melting. Most modern foundries use this type of furnace and now also more iron foundries are replacing cupolas with induction furnaces to melt cast iron, as the former emit lots of dust and other pollutants. Induction furnace capacities range from less than one kilogram to one hundred tones capacity and are used to melt iron and steel, copper, aluminum and precious metals. Since no arc or combustion is used, the temperature of the material is no higher than required to melt it. This can prevent loss of valuable alloying elements. The one major drawback to induction furnace usage in a foundry is the lack of refining capacity. Charge materials must be clean of oxidation products and of a known composition and some alloying elements may be lost due to oxidation and must be re-added to the melt. Operating frequencies range from utility frequency (50 or 60 Hz) to 400 kHz or higher, usually depending on the material being melted, the capacity (volume) of the furnace and the melting speed required. Generally the smaller is the volume of the melts, the higher is the frequency of the furnace used. This is due to the skin depth which is a measure of the distance an alternating current can penetrate beneath the surface of a conductor. For the same conductivity, the higher frequencies have a shallow skin depth—that is less penetration into the melt. Lower frequencies can generate stirring or turbulence in the metal.



1 – Melt

2 - water-cooled coil

3 – yokes

4 - crucible

A preheated, one-tone furnace melting iron can melt cold charge to tapping readiness within an hour. Power supplies range from 10 kW to 42 MW, with melt sizes of 20 kg to 65 tones of metal respectively.

An operating induction furnace usually emits a hum or whine (due to fluctuating magnetic forces and magnetostriction), the pitch of which can be used by operators to identify whether the furnace is operating correctly or at what power level.

Features:

1) For induction furnace melting, single manufacturing capacity of nearly one hundred tons, to meet the needs of large-scale production. However, the expansion of the power installed capacity is often many companies are difficult obstacle. Therefore, the induction furnace is more suitable for small and medium-sized production.

2) Induction furnace melting of various grades of steel and nonferrous metals. Only iron castings production, induction furnace is better than the product adaptability cupola, induction furnace melting a variety of high-alloy cast iron, such as high chromium cast iron.

3) Induction furnace is discontinuous melting interval equal to the stove capacity of liquid iron; **induction furnace** is more suitable for the production of the phase of the system.

4) impact on the environment: induction furnace soot oxide fine particles; strong electromagnetic pollution; the contamination whole in plant; **induction furnace** to electric energy per ton of molten iron consumption 2160MJ (600kWh) around.

Types

Coreless Induction Furnaces

According to Atlas Foundry Company, the coreless induction furnace melts all grades of steels and irons and many non-ferrous alloys. Coreless induction furnaces heat the metal using an external primary coil made of high-conductivity copper tubing. These water-cooled copper coils surround refractory-lined crucibles, which are containers lined with a metal that has a high melting point.

Induction melting uses frequencies that vary from 50 cycles per second to 10,000 cycles per second. Higher operating frequencies provide greater maximum power for a furnace of given capacity, which lowers the turbulence in the furnace.

According to the Illinois Sustainable Technology Center, smaller operations of five to ten tons typically use coreless induction furnaces, while channel induction furnaces are used for larger amounts of metal.

Channel Induction Furnaces

- In a channel induction furnace, a refractory-lined steel shell contains the molten metal. Attached to the steel shell is an induction unit that consists of an iron core in the form of a ring that has a primary induction coil wound around it.

According to Atlas Foundry Company, channel induction furnaces melt low-melting-point alloys or serve as a holding unit for high-melting-point alloys, such as cast iron.

Other Furnaces

In addition to induction furnaces, foundries commonly use four other types of furnaces to melt metal: cupola, electric arc, reverberatory and crucible.

Advantage:

1. Overall heating work piece deformation is small, small power consumption.
2. The pollution.
3. Heating speed, the work piece surface oxidation and decarburization lighter.
4. Surface hardened layer can be adjusted as needed, easy to control.
5. Heating equipment can be installed in the mechanical processing production line, easy to realize mechanization and automation, easy to manage, and can reduce the transportation, saving manpower, improve production efficiency.
6. Hardened layer marten site smaller, hardness, strength, toughness, are higher.
7. Surface hardening of the work piece surface greater compression internal stress, higher work piece anti-fatigue breaking ability.

Disadvantages:

Induction heating equipment is more complex and adaptability to poor, difficult to guarantee the quality of some of the complex shape of the work piece. The induction heater is more complex, once the cost of inputs is relatively high, interchangeability and adaptability of the induction coil (inductor) is poor, cannot be used for some complex shape of the work piece.

But obviously, the advantages outweighed the disadvantages. Therefore, the induction heating is a better choice of metalworking for replacing coal heating, oil heating, gas heating, electric cooker, electric oven heating and other heating methods.

Applications:

Induction heating is widely used for the surface hardening of the gears, shafts, crankshafts, cams, rollers, etc. of the work piece; the purpose is to improve the abrasion resistance and anti-fatigue breaking capability of these artifacts.

Automobile rear axle using induction heating surface hardening, fatigue design load cycles increases by about 10 times more than the quenched and tempered. Induction heating surface hardening of the work piece material is generally in the carbon steel. In order to meet the special needs of some of the work piece has been developed for induction heating surface hardening dedicated low harden ability steel. High-carbon steel and cast iron work piece can also be used induction heating surface hardening. The quenching medium commonly used is water or polymer solution.

LECTURE-22

Material Balance

Hot metal of composition 0.8% Si, 0.2% P, 0.25% Mn, 4% C and rest iron is refined in a converter to produce steel of composition 0.1% C and rest iron. Pure oxygen is blown. During refining scrap is charged whose amount is 15% of hot metal. The composition of slag is CaO 54%, FeO 18%, and MnO 2.5%, with $\text{CaO/SiO}_2=3.5$. Exit gases analyses 15% CO_2 and 85% CO . Calculate amount of steel, slag, oxygen and waste gases per ton hot metal.

Basis: 1000 kg hot metal.

Fe balance: Let X kg is mass of steel and Y kg mass of slag

$$\text{Fe in hot metal} + \text{Fe in scrap} = \text{Fe in steel} + \text{Fe in slag} \dots\dots\dots(3)$$

Mn balance:

$$\text{Mn in hot metal} = \text{Mn in slag} \dots\dots\dots(4)$$

Putting the values in 3 and 4 we get.

$$X = 1080.68 \text{ kg steel}$$

$$Y = 126.7 \text{ kg slag.}$$

Carbon balance:

$$\text{C in hot metal} + \text{C in scrap} = \text{C in steel} + \text{C in waste gases} \dots\dots\dots (5)$$

$$\text{C in waste gases} = 39.07 \text{ kg}$$

$$\text{C in CO}_2=5.86 \text{ kg}$$

$$\text{C in CO} =33.21 \text{ kg}$$

$$\text{Exit gas volume} =73.93 \text{ m}^3 \text{ (1 atmospheric pressure and 273K).}$$

O_2 required can be calculated from Si, C, Mn and Fe balance.

$$\text{Calculations give } \text{O}_2= 52.70 \text{ m}^3 \text{ (1atmospheric pressure and 273K)}$$

Material balance gives an idea of the charge materials required.

For example 100 ton capacity would require approximately 93 tons hot metal and 1 ton scrap. The amount of slag would be 12 tons and total oxygen required would be 1900m^3 . The volume of exit gas is 6800m^3 . These are the approximate values and are given to develop a feel of the converter design.

Questions for practice (Module-II)

What is foamy slag practice in EAF? How does it help?

What is the role of propane in OBM process?

Lime stone is more preferable than lime in OBM-why

Explain different slag types and their role in EAF.

What are the advantages of inert gas stirring?

Compare and contrast top and bottom blowing.

What is duplexing?

What are the advantages of DRI over scrap in EAF?

LECTURE-23

Deoxidation of Steel

Introduction

- ⦿ Refining of hot metal to steel is done under Oxidising atmosphere. During refining oxygen dissolves in steel solubility of oxygen in steel is negligible small.
- ⦿ During solidification of molten steel, excess oxygen is rejected by the solidifying steel.
- ⦿ The excess oxygen produces defects like blowholes and non metallic oxide inclusion in solidified casting.
- ⦿ The removal of residual oxygen content of refined steel is known as deoxidation or killing of steel.

Source of oxygen in steel

- ⦿ Rust on steel
- ⦿ Oxygen blowing
- ⦿ Steelmaking slag
- ⦿ Atmospheric oxygen dissolved in steel during teeming
- ⦿ Oxidising refractories

At 1600° c solubility of oxygen in liquid steel is 0.23% which decreases to 0.003% in solid steel during solidification.

According to degree of deoxidation, carbon steel may be subdivided into 3 groups:

1. Killed steel: oxygen is removed completely
2. Semi killed steel: Partially/incompletely deoxidised steel containing some amount of oxygen which forms CO during solidification.
3. Rimming steel: Steel not deoxidised evolving CO during solidification.

Rimming Steel	Semi-killed Steel	Killed Steel
• No deoxidation • It requires a lot of gas evolution • $C < 0.15\%$ • Primary & secondary blow holes formed • The zone between the primary and secondary blow holes is known as a rim, minimum of pipe formation • Cast in narrow end-up moulds • Good surface finish for rolling products	• Partially Deoxidised • Gas is evolved at the end of solidification • $C: 0.15-0.30\%$ • Blow holes at the middle part, little at the lower part • Pipe is compensated by gas evolution and entrapment • -- • Structural shapes, plates and merchant products	• Fully Deoxidised • No CO gas evolution • $C > 0.30\%$, alloy steels • V or A type segregation • Cast in wide end-up moulds with hot tops • Sound and dense castings for forging products

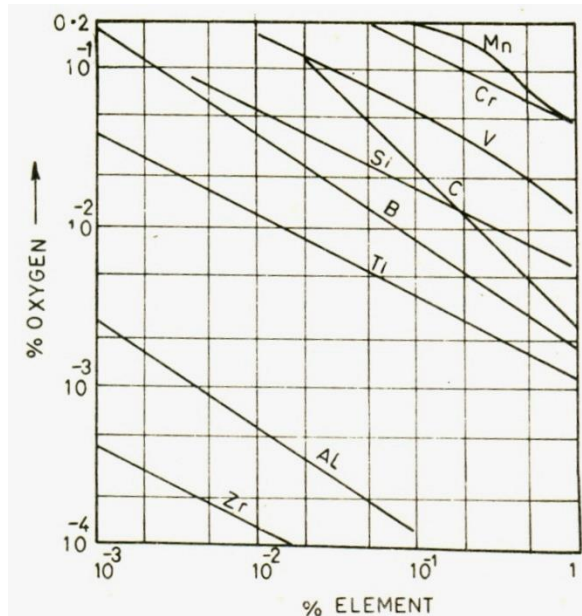
Types of deoxidation

- ☉ **Diffusion Deoxidation:** The dissolved oxygen content is lowered by inducing it to diffuse into the slag inside steelmaking furnace itself or under vacuum separately outside.
- ☉ **Precipitation Deoxidation:** Deoxidiser used to precipitate oxide.
- ☉ Deoxidation can be carried out either by single element such as Si, Al, Mn etc or by mixture of element such as Si+Mn, Ca-Si-Al etc. Deoxidation by single element is known as **simple deoxidation**, whereas deoxidation by a mixture of element is known as **complex deoxidation**.
- ☉ In complex deoxidation where a mixture of Si+Mn, Ca+Si, Ca+Si+Al is used the following advantages are reported with simple one..

1. The dissolved oxygen is minimum

2. Due to formation of liquid deoxidation product agglomeration of the product into large size and can be floated easily.

Choice of deoxidiser



- ☉ **Thermodynamically** the best deoxidiser should have the minimum %[O] in equilibrium with its own minimum content, Zr is costly
- ☉ **Chemically** the residual deoxidiser content in steel should be within the range of chemical specification at the end of deoxidation
- ☉ **Kinetically** the deoxidiser should be quick in action to obtain its high percentage utilization.
- ☉ The **physics** of the process should be such that the deoxidation product should not be mechanically entrapped as non-metallic inclusions to maintain the cleanliness of steel.

Mechanisms of deoxidation

Total oxygen in steel equals to dissolved oxygen + oxygen present in deoxidation products. The deoxidation process consists of the following steps:

1. Dissolution and homogenisation: **Deoxidisers are used in the form of Ferro-Alloys** where Fe acts as carrier dissolution and homogenisation is easier unlike virgin elements which form impervious adherent layer of oxide on their surface and may not dissolve readily.
2. Formation of Critical nuclei: Nucleation of deoxidation product become easier if interface is present. Pre-deoxidation by Al produces alumina-steel interface that is useful for nucleation.
3. Growth of deoxidation product: A liquid product can coalesce easily as compared with solid product. **Fe-Mn is added first then Fe-Si** in ratio 7:1 to 4:1 to produce FeO-MnO slag which is liquid at steel making temperatures and takes solid SiO₂ into solution readily.
4. Removal of oxidation product: Floatation of an oxide product depends among physical properties of steel, on the size of the product. The rate of rise of a spherical particle in a quiet fluid or in a fluid of laminar flow (i.e. at very low Reynold's number) can be described at steady state by Stoke's law:

$$V_t = \frac{gd^2\Delta\rho}{18\eta}$$

V_t = terminal velocity (m/s) of the inclusion

g = acceleration due to gravity (m/s²)

$\Delta\rho$ = difference in density of steel and deoxidation product and

η = viscosity of steel (kg/m.s).

Deoxidation practice

☉ Furnace Deoxidation

In acid steel making deoxidation of the bath can be fully carried out inside the furnace even if the refining slag is in contact with the bath. Though deoxidation decreases the oxidising potential of the bath SiO₂ and MnO are not prone to reversion being stable.

☉ Ladle Deoxidation

In basic process P₂O₅ from the slag is very readily reduced back to the metal if the oxidation potential drops. It can be alternatively carried out in the ladle.

☉ Mould 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 is not adequate

LECTURE-24

Clean Steel and Non-Metallic Inclusions

Introduction:

Clean steel refers to steel free from inclusions. Inclusions are non metallic particles embedded in the steel matrix. Practically it is not possible to produce steel with no inclusion. Therefore we can talk about cleanliness of steel. The amount, distribution, shape and size of inclusions affect mechanical properties of steel. These are not always detrimental.

Types of inclusions:

Inclusions are chemical compounds of metals like (Fe, Mn, Al, Si, Ca etc) with non metals (O, S, N, C, H). Different types are:

- **Oxides:** FeO , Al_2O_3 , SiO_2 , MnO , $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$, $\text{FeO} \cdot \text{Al}_2\text{O}_3$, $\text{MgO} \cdot \text{Al}_2\text{O}_3$, $\text{MnO} \cdot \text{SiO}_2$
- **Sulphides:** FeS , CaS , MnS , MgS , Ce_2S_3 , Nitrides: TiN , AlN , VN , BN etc.
- **Oxysulphides:** $\text{MnS} \cdot \text{MnO}$, $\text{Al}_2\text{O}_3 \cdot \text{CaS}$, etc
- **Carbonitrides:** Titanium/ vanadium/ Niobium carbonitrides, etc
- **Phosphides:** Fe_3P , Fe_2P , Mn_5P_2

Iron and manganese sulfides are unstable inclusions.

Shape	Effect	Examples
Globular shape	Desirable	MnS , oxy-sulphides, iron aluminates and silicates
Platelet shape	Undesirable	Al deoxidized steels contain MnS in the form of thin films located along the grain boundaries.
Polyhedral	Not very harmful	

Size

Macro-inclusions (size greater than $100\mu\text{m}$): Macro inclusions are harmful and must be removed

Micro inclusions (size $1-100\mu\text{m}$): Micro inclusions are beneficial as they restrict grain growth, increase yield strength and hardness. Micro- inclusions act as nuclei for precipitation of carbides and nitrides. Micro inclusions can be used to enhance strengthening by dispersing them uniformly in the matrix.

Thermal expansion

An inclusion is a mismatch with the steel matrix with respect to thermal expansion.

- ✓ MnS, Ca S, etc. have thermal expansion greater than steel matrix. On heating steel with these types of inclusions voids or parting of the matrix can occur. The void can act as cracks.
- ✓ On the other hand Al_2O_3 , SiO_2 and $\text{CaO}.\text{Al}_2\text{O}_3$, etc inclusions have thermal expansion smaller than steel matrix. On heating steels with these types of inclusions internal stresses can develop.

Density and melting point

Inclusions	Melting point($^{\circ}\text{C}$)	Density at $20^{\circ}\text{C}(\text{g}/\text{cm}^2)$
Ferrous oxides (FeO)	1369	5.8
Manganous oxides (MnO)	1785	5.5
Silica	1710	2.2-2.6
Alumina (Al_2O_3)	2050	4.0
Chrome oxide Cr_2O_3	2280	5.0
Titanium oxide, TiO_2	1825	4.2

Zirconium oxide, ZrO_2	2700	5.75
Iron silicate, $(\text{FeO})_2\text{SiO}_2$	1205	4.35
Iron sulphide, FeS	988	4.6
Manganese sulphide, MnS	1620	4.04
Magnesia, MgO	2800	3.58

Hot shortness in steel due to FeS (low melting point)

Inclusions like MgO , Al_2O_3 , TiO_2 are solid at steelmaking temperature.

Sources of inclusion formation:

Two types:

1. Endogenous Inclusion: Impurities in the steel itself.
2. Exogenous inclusions: Foreign impurities

Mechanisms:

- i. Reaction between rejected solute elements during solidification, for example, reaction between sulphur and manganese, and between oxygen and aluminium etc.
- ii. Mechanical and chemical erosion of refractory and other materials.
- iii. Gas pickup during teeming stream and consequent compound formation.

Inclusions produced by mechanism (i) are called endogenous, whereas mechanisms ii and iii produce exogenous inclusions. Inclusions can form during

- a) Tapping and Teeming of molten stream from furnace or ladle. Erosion of launder refractory is the possible source. Pick up of oxygen from atmosphere and formation of FeO .
- b) Treatment of steel in ladle in contact with synthetic slag

- c) Solidification in mould due to precipitation of excess solute elements.
- d) Heat treatment and deformation processing without inert atmosphere.
- e) Fusion welding. Oxidation of weld pool, electrode coatings are the possible source of inclusions in fusion welding processes.

Inclusion control:

Impact properties are adversely affected with an increase in volume fraction of inclusion as well as inclusion length; spherical inclusions are better. Brittle inclusions or inclusions that have low bond strength with the matrix break up during early straining and create voids at the inclusion/matrix interface. Hot fatigue strength of high strength steel is reduced by surface and subsurface inclusions those have lower expansion coefficient than steel. The hot workability of steel is affected by the low deformability of inclusions. Anisotropy of a property is caused by orientation of elongated inclusions along the direction of working. Macro inclusions of sulphides are desirable for better steel machining properties.

In view of the above, control of inclusion in steel is necessary and especially macro- inclusions must be controlled as they are harmful.

Inclusions can be controlled either at **(a)** during liquid steel processing stage or **(b)** during solid state processing.

I. Liquid state processing :

1. During tapping of molten stream from furnace carry- over of slag must be minimized.
2. Teeming of steel from ladle to tundish requires shrouding of molten steel stream in order to avoid reoxidation.
3. Use of tundish flux to avoid reoxidation.
4. Use of SEN (Submerged Entry Nozzle)
5. Use of refractory top to minimize vertex formation in tundish during change over.

II. Solid state processing:

In the solid state processing steel is heated to a temperature ranging in between 800–1200°C to perform heat treatment and hot working. Here steel must be heated under inert atmosphere to avoid oxidation. During fusion welding, liquid pool is in contact with air and steel is prone to oxidation. Inert shielding may avoid the inclusion formation.

Inclusion engineering:

Inclusions engineering technology is based on the design of inclusions so as to alleviate their harmful effects on the product properties. It does not refer to removal of inclusions but it refers to modify them either in terms of chemical composition or shape so that harmful effects of the inclusions can be converted to improve the steel properties. This also involves distribution of inclusion uniformly in the matrix. So that composite properties can be generated in the product. Calcium is used widely to modify inclusions in continuous casting of steel.

LECTURE-25

Secondary Steel Making-Ladle Metallurgy

Introduction

Primary steelmaking is aimed at fast melting and rapid refining. **It** is capable of refining at a macro level to arrive at broad steel specifications, but is not designed to meet the stringent demands on steel quality, and consistency of composition and temperature that is required for very sophisticated grades of steel. **In** order to achieve such requirements, liquid steel from primary steelmaking units has to be further refined in the ladle after tapping. This is known as *Secondary Steelmaking*.

Secondary steelmaking is resorted to achieve one or more of the following requirements :

- ❖ Improvement in quality
- ❖ Improvement in production rate
- ❖ Decrease in energy consumption
- ❖ Use of relatively cheaper grade or alternative raw materials
- ❖ Use of alternate sources of energy
- ❖ Higher recovery of alloying elements.

In steelmaking, ladles are employed to transfer molten steel from BOF/EAF to ingot casting or continuous casting. It has been realized that ladles can be used very effectively as a reactor which can perform any of the following functions:

- To desulphurize molten steel tapped from BOF/EAF
- To homogenize molten steel to minimize gradients in concentration and temperature and to attain desired teeming temperature.
- To deoxidize molten steel
- To improve cleanliness of steel by removing inclusions

- To engineer the inclusions so as to alleviate their harmful effects on mechanical properties of steel
- To add alloying elements
- To remove dissolved gases

Bath Stirring

Bath agitation would be required to carry-out the above functions effectively. At high temperature, bath can be agitated either by an inert gas or by induction. One has to determine the amount of stirring gas and location of the injection of gas in the ladle. The gas can either be injected through the nozzle or porous plugs. Location of the injection elements is an important issue. Injection elements could be located either axis-symmetric or asymmetric to the center of the ladle.

Enough free board height in the ladle must be available to accommodate the quantity of slag required for refining and to absorb inclusions. Additional heating may be required to keep the molten steel to the teeming temperature. This can be achieved either by tapping steel at slightly higher temperature or to provide addition heating arrangement in the ladle itself. In many situations it is required to inject the slag forming materials either for refining or for inclusion engineering. In this case suitable injection device must also be available. Above all, the most important would be the selection of refractory to meet the refining requirements. Refractory materials for injection elements and their fixing must also be considered.

Argon is usually bubbled into the molten steel covered with slag either through the top lance or through a porous plug fitted at the bottom. A plume of gas rises upwards when gas is injected through the bottom. The stirring homogenizes bath composition and temperature. With centrally placed nozzle at the bottom, stirring action is small near the bottom of the ladle. An asymmetrically placed bubble plume gives velocities near the bottom which are greater than for symmetrically placed nozzle.

The liquid flow in the ladle occurs via bulk motion of the metal. Very roughly, characteristic velocity V_c for gas bubbling is

$$V_c = \left(\frac{QgH^2}{v} \right)^{1/3}$$

Where Q = gas flow rate (m^3/s)

g is in m/s^2

H = bath height (m)

and V is bath volume (m^3).

Correct stirring is of utmost importance. It should be known when to stir what, and how vigorously. Stirring of the melt in the ladle by argon flowing through bottom tuyeres is a must for mixing and homogenisation, faster growth, and floatation of the deoxidation products. However, very high gas flow rates are not desirable from the cleanliness point of view, since it has the following adverse effects:

- Too vigorous stirring of the metal can cause disintegration of earlier formed inclusion conglomerates.
- Re-entrainment of slag particles into molten steel.
- Increased erosion of refractories and consequent generation of exogenous inclusions.
- More ejection of metal droplets into the atmosphere with consequent oxide formation

Process Varieties

The varieties of secondary steelmaking processes that have proved to be of commercial value can broadly be categorised as under:

- Stirring treatments
- Synthetic slag refining with stirring
- Vacuum treatments
- Decarburisation techniques
- Injection metallurgy

- Plunging techniques
- Post-solidification treatments.

Various secondary process and their capabilities

Item	Processes						
	VD	VOD	IGP	IM	VAD	LF	ASEA-SKF
Desulphurisation	minor	minor	minor	yes	yes	yes	yes
Deoxidation	yes	yes	yes	yes	yes	yes	yes
Decarburisation	minor	yes	no	no	no	no	yes
Heating	no/yes	yes*	no	no	yes	yes	yes
Alloying	minor	yes	minor	minor	yes	yes	yes
Degassing	yes	yes	no	no	yes	no	yes
Homogenisation	yes	yes	yes	yes	yes	yes	yes
Achieving more cleanliness (i.e. less inclusions)	yes	yes	yes	yes	yes	yes	yes
Inclusion modification	no	no	minor	yes	yes	yes	yes

* Chemical heating only

LECTURE-26

Secondary Steel Making-AOD, VOD, CLU, ESR & VAR

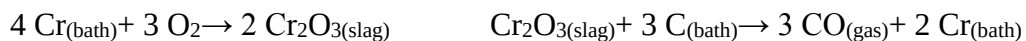
Introduction

- ▶ AOD is a process primarily used in sec. steel making and other high grade alloys with oxidizable elements (Cr and Al).
- ▶ Metal transferred to AOD is subjected to decarburization, reduction & desulphurization
- ▶ The VOD (Vacuum Oxygen Decarburisation) process is used for production of high chromium steels with lowest carbon contents
- ▶ It is a type of furnace in which the molten metal is placed under a vacuum chamber.
- ▶ ESR is a process of remelting and refining steel and other alloys for mission-critical applications in aircraft, thermal power stations, nuclear power plants, military technology
- ▶ VAR is a Secondary melting process for production of metal ingots with elevated chemical and mechanical homogeneity for highly demanding applications.

AOD Process

Decarburization

- ▶ Is controlled by ratios of oxygen to argon or nitrogen to remove the carbon from the metal bath.
- ▶ The gases are usually blown through a top lance (oxygen only) and tuyeres in the sides/bottom (oxygen with an inert gas shroud).
- ▶ The stages of blowing remove carbon by the combination of oxygen and carbon forming CO gas.



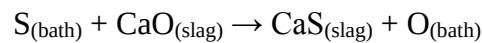
- ▶ To drive the reaction, the partial pressure of CO is lowered using argon or nitrogen.
- ▶ Since the AOD vessel isn't externally heated, the blowing stages are also used for temperature control.
- ▶ The burning of carbon increases the bath temperature.
- ▶ By the end of this process around 97% of Cr is retained in the steel.

Reduction

- ▶ Recovers the oxidized elements such as chromium from the slag by alloy additions are made with elements that have a higher affinity for oxygen than chromium, using either a silicon alloy or aluminum.
- ▶ The reduction mix also includes lime (CaO) and fluorspar (CaF₂).
- ▶ Addition of lime and fluorspar drive the reduction of Cr₂O₃ and manage the slag, keeping the slag fluid and volume small.

Desulphurization

- ▶ Achieved by having a high lime concentration in the slag and a low oxygen activity in the metal bath.



- ▶ Lime are added to dilute sulfur in the metal bath.
- ▶ Also, aluminum or silicon may be added to remove oxygen.
- ▶ Other trimming alloy additions might be added at the end of the step.
- ▶ After sulfur levels have been achieved the slag is removed from the AOD vessel and the metal bath is ready for tapping.
- ▶ The tapped bath is then either sent to a stir station for further chemistry trimming or to a caster for casting.

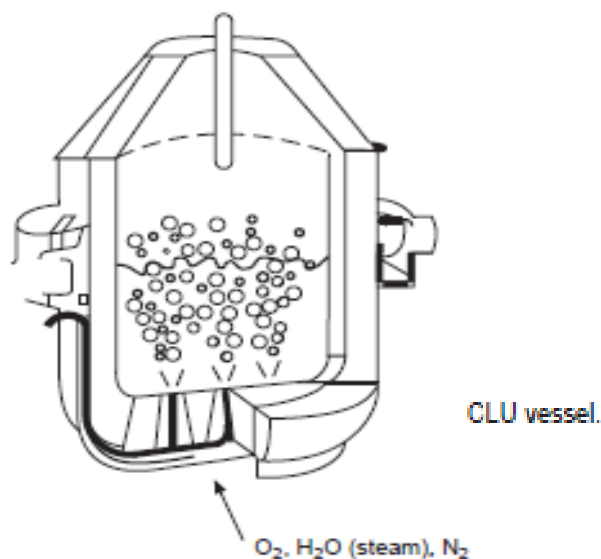
VOD Process

- ▶ An economical supplement, as operating time is reduced and temperatures are lower than in EAF steelmaking.
- ▶ Using VOD for refining stainless steel increases the availability of the EAF for melting purposes.
- ▶ Extensive decarburization is achievable with a Vacuum Oxygen.
- ▶ This unit is basically a tank degassing equipped with an oxygen blowing lance but specifically configured to withstand the heat load coming from an intense emission of CO.

- ▶ It is normally used for the deep decarburization of high-alloyed steel grades, usually to remove carbon without affecting the content of chromium in the production of stainless steel grades.
- ▶ It can be operated as the sole decarburization unit after the furnace (DUPLEX process) or as a refining stage after a rough decarburization by means of an AOD unit (the TRIPLEX process).
- ▶ oxygen lance in the centre of the tank lid to enhance carbon removal under vacuum. The VOD is often used to lower the carbon content of high-alloy steels without also overoxidizing such oxidizable alloying elements as chromium

Creusot-Loire-Uddeholm (CLU) Converter:

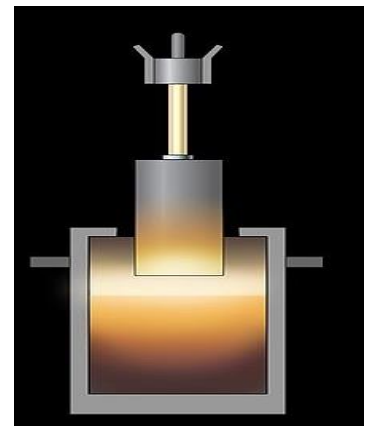
- ▶ The CLU Process is similar to the AOD process for making stainless steels. It also uses liquid steel from an electric arc furnace or similar melter. The major impetus for its development was the idea to substitute steam as the diluting gas rather than argon. The process was developed by Uddeholm of Belgium and Creusot-Loire of France. The converter is bottom-blown thus differentiating it from the side-blown AOD converter. The first commercial plant using the CLU process was built in 1973 by Uddeholm, now a part of Avesta-Sheffield Stainless Co. The process is also used by Samancor in South Africa for the production of medium carbon ferrochrome. Columbus Stainless in Middleburg, South Africa chose this process, supplied by VAI, for their newest stainless plant, which came on stream in 1996.



- ▶ The decarburization period consists of injecting an oxygen-steam mixture. The process is energy inefficient as the reaction of steam with the molten steel bath is endothermic. Chromium oxidation is higher than in the AOD process when decarburization is continued below about 0.18% carbon. Although the original goal of reducing argon consumption can be met, the increased silicon requirement for the reduction step does not necessarily lead to overall cost savings. Further, the use of steam throughout the entire period was found to lead to undesirable hydrogen contents in the refined steel. Therefore, practices have evolved which use various amounts of steam, argon, and nitrogen in the process.

Electro-Slag Remelting (ESR)

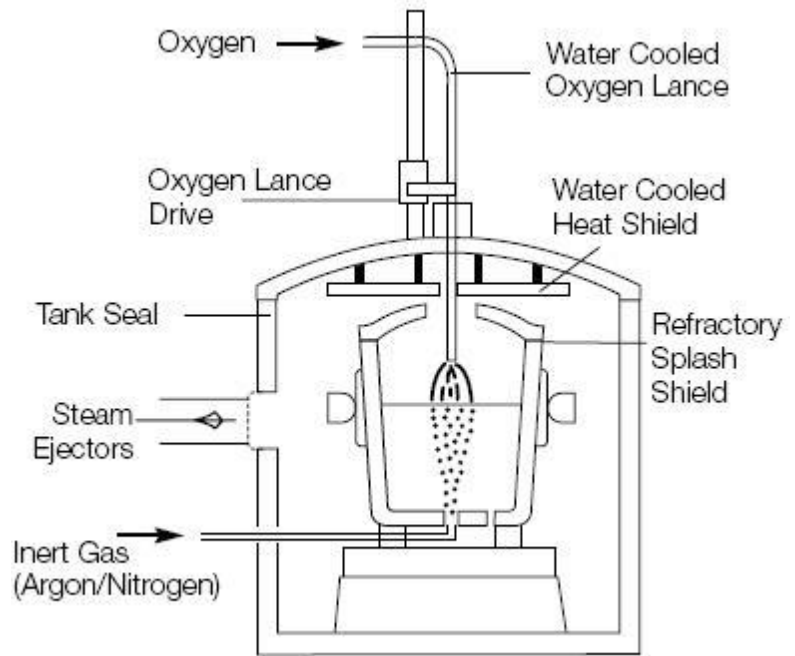
- ▶ Also known as electro-flux remelting.
- ▶ ESR process results in high-quality ingots. This process can be started up through vacuum induction melting.
- ▶ Uses the as-cast alloy as a consumable electrode.
- ▶ Electric current (generally AC) is passed between the electrode and the new ingot, which is formed in the bottom of a water-cooled copper mould.
- ▶ The new ingot is covered in an engineered slag that is superheated by the electric current.
- ▶ The electrode tip is slowly melted from contact with the slag.
- ▶ Metal droplets travel through the slag to the bottom of the water-cooled mould and slowly freeze as the ingot is directionally solidified upwards from the bottom of the mould.
- ▶ The slag pool floats above the refined alloy, continuously floating upwards as the alloy solidifies.
- ▶ The molten metal is cleaned of impurities that chemically react with the slag or otherwise float to the top of the molten pool as the molten droplets pass through the slag.
- ▶ Uses highly reactive slags (calcium fluoride, lime, alumina, or other oxides are usually the main components) to reduce the amount of type-A sulphide present in bio



metal alloys. It is a common practice in European industries. ESR reduces other types of inclusions as well, and is seen as an alternative to the vacuum arc remelting method that is prevalent in US industries.

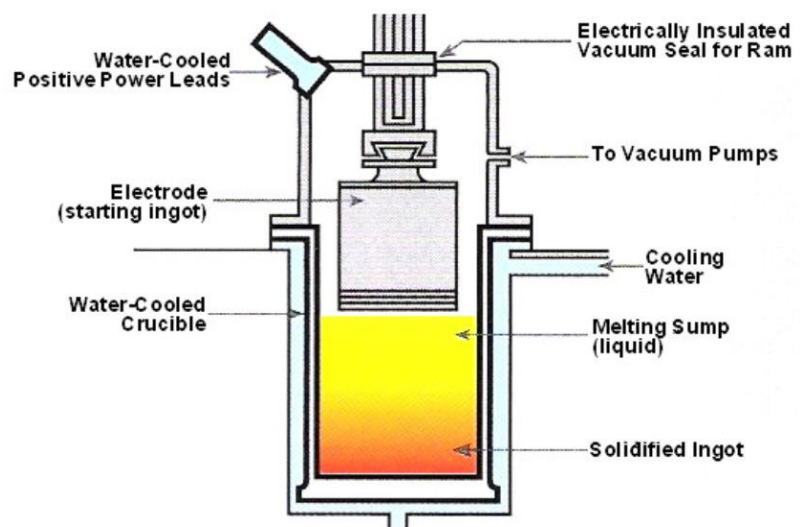
Metallurgical operations

- Extensive decarburization with low chromium losses
- Flexibility to use high carbon alloying materials of lower cost
- High rate of chromium recovery by proper additions
- Chemical heating of liquid steel
- Hydrogen and Nitrogen removal
- Improved conditions for desulfurization by proper additions
- Improved conditions for Inclusion flotation



Vacuum arc remelting (VAR)

- ▶ The VAR process has made possible incredibly controlled materials used in the biomedical, aviation, and aerospace fields.
- ▶ The solidification rate of molten material can be tightly controlled.
- ▶ This allows a high degree of control over the microstructure as well as the ability to minimize segregation



- ▶ The gases dissolved in liquid metal during melting metals in open furnaces, such as nitrogen, oxygen and hydrogen are considered to be detrimental to the majority of steels and alloys. Under vacuum conditions these gases escape from liquid metal to the vacuum chamber.
- ▶ Elements with high vapour pressure such as carbon, sulphur, and magnesium (frequently contaminants) are lowered in concentration.
- ▶ Centreline porosity and segregation are eliminated.
- ▶ Certain metals and alloys, such as Ti, cannot be melted in open air furnaces
- ▶ The alloy to undergo VAR is formed into a cylinder typically by vacuum induction melting (VIM) or ladle refining (air melt).
- ▶ This cylinder, referred to as an electrode is then put into a large cylindrical enclosed crucible and brought to a metallurgical vacuum (0.001–0.1 mmHg [0.13–13.33 Pa]).
- ▶ At the bottom of the crucible is a small amount of the alloy to be remelted, which the top electrode is brought close to prior to starting the melt.
- ▶ Several kilo amperes of DC current are used to start an arc between the two pieces, and from there, a continuous melt is derived.
- ▶ The crucible (typically made of copper) is surrounded by a water jacket used to cool the melt and control the solidification rate.
- ▶ To prevent arcing between the electrode and the crucible side walls, the diameter of the crucible is larger than that of the electrode. As a result, electrode must be lowered as the melt consumes it.
- ▶ Control of the current, cooling water, and electrode gap is essential to effective control of the process, and production of defect free material.

LECTURE-27

Gases in Steel and Degassing Technology

Introduction

During steelmaking gases like oxygen, hydrogen and nitrogen dissolve in steel from the ambient atmosphere or from the charge materials or due to the chemical reactions taking place. The term degassing is employed to remove nitrogen and hydrogen from steel. Dissolved oxygen from steel melt cannot be removed as molecular oxygen. Removal of oxygen is termed deoxidation and is discussed in other lecture. This lecture concerns with degassing.

Both nitrogen and hydrogen impair the mechanical properties of steel. The maximum solubility of nitrogen in liquid iron is 450ppm and less than 10ppm at room temperature. During solidification excess nitrogen is rejected which may form either blow holes or nitrides. Excess nitrogen causes embrittlement of heat affected zone of welded steels and impair cold formability. Hydrogen in steel impairs steel properties. Solubility of hydrogen in steel is low at ambient temperature. Excess hydrogen is rejected during solidification and results in pinhole formation and porosity in steel. Few ppm of hydrogen causes blistering and loss of tensile ductility. Thus removal of nitrogen and hydrogen from steel is necessary.

Principle

Sieverts' law, in metallurgy, is a rule to predict the solubility of gases in metals. It is named after German chemist Adolf Sieverts (1874–1947). The law states that the solubility of a diatomic gas in metal is proportional to the square root of the partial pressure of the gas in thermodynamic equilibrium. Hydrogen, oxygen and nitrogen are examples of dissolved diatomic gases of frequent interest in metallurgy.

Sieverts' law can be readily rationalized by considering the reaction of dissolution of the gas in the metal, which involves dissociation of the molecule of the gas. For example, for nitrogen:



For the above reaction, the equilibrium constant, K, is:

$$K^2 = \frac{C_N^2}{p_{N_2}}$$

Where:

- C is the concentration
- p is the equilibrium partial pressure

Therefore,

$$C_N = K \sqrt{p_{N_2}}$$

In steel making wt% may be taken as concentration

$$Wt\%N = K_N \cdot \sqrt{p_{N_2}}$$

General considerations

1. The desorption of gases is a gas/ metal interfacial reaction. The atomic nitrogen from the molten steel has to diffuse at the gas/metal interface, where it is converted to molecular nitrogen which can then be desorbed. The effectiveness of vacuum treatment increases with increase in surface area of liquid exposed to vacuum. The increased surface area of molten steel exposed to vacuum e.g. in the form of a thin stream or gas induced stirring will accelerate the degassing process.
2. Temperature of molten steel drops during vacuum treatment. More is the surface area of stream exposed to vacuum higher will be the temperature drop. To compensate for the loss of heat, the following alternative may be considered.
 - i. Tapping of steel at a higher temperature. This requires increased heat load in BOF/EAF
 - ii. Additional heating during vacuum treatment.
3. The degassing time must be kept to minimum
4. The degree of degassing increases with the degree of vacuum. Vacuum of the order of 1mm or even less than 1mm Hg (1mmHg=1torr) is employed in the practice. Vacuum pumping capacity should be adequate.

Side reactions

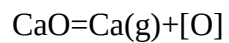
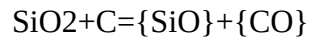
During vacuum degassing the following reaction may occur. Nitride and oxide inclusions can decompose according to



Application of vacuum decreases nitrogen which favors decomposition of Al N. Oxide inclusions can react with C



Lowering of CO pressure favours the forward reaction. Reaction between lining and carbon of liquid steel or decomposition of lining may occur:



Note that SiO is a highly reactive gas at the steelmaking temperature. All reactions generate one or more gaseous species, hence lowering of pressure promotes the occurrence of side reactions. Mg and Ca are stable gases at steelmaking temperatures.

Volatilization of elements of high vapor pressure may occur. Mn and Fe have high vapor pressures and their losses occur during vacuum treatment. Loss of Al and Si is negligible.

LECTURE-28

Degassing Practices

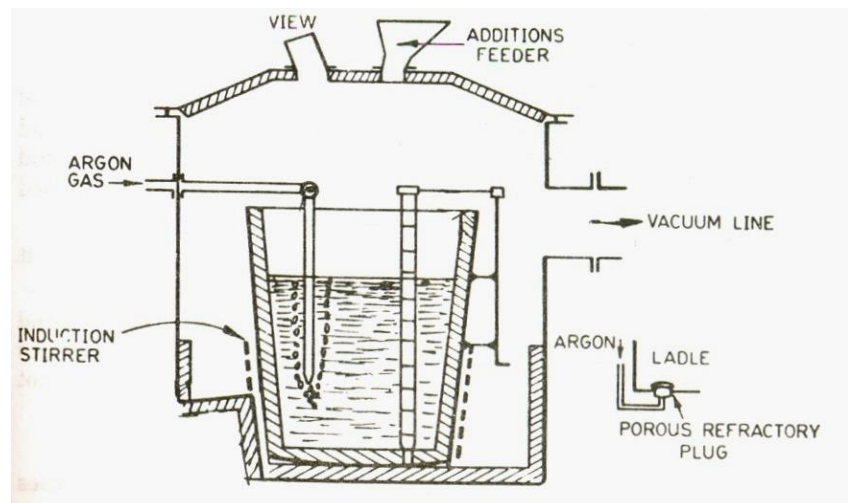
Degassing processes

There are 3 methods of degassing which are in practice

- i) Ladle degassing
- ii) Stream degassing
- iii) Circulation degassing

Ladle degassing

Ladle containing molten steel is placed in a chamber which is then evacuated. After a determined time ladle is removed from the chamber and is teemed for casting. Ladle is provided with a porous plug at its bottom to purge argon gas as shown in the figure. In a



vacuum chamber the ladle is placed. The vacuum chamber is equipped with a hopper so as to make additions of elements as and when it is needed. For effective degassing of fully killed steel, it is necessary to purge argon through the bottom of the ladle. Stirring the bath enhances rate of gas removal. Vigorous removal of gases causes metal splashing too. Therefore ladle is not filled completely and about 25% of its height is kept as freeboard to accommodate the splashed metal droplets. Pressure is maintained in between 1mmHg to 10mm Hg for effective degassing. During degassing additions are made for deoxidation and alloying. In certain cases ladle is heated to compensate for the loss of heat during degassing. For the effectiveness of degassing, it is necessary that carry-over slag either from BOF or EAF should be as low as possible. Carry-over

slag contains FeO and since oxygen content of steel is in equilibrium with FeO content of slag, oxygen content of steel increases.

Stirring gas is introduced either from top through the roof by a submerged refractory tube or through the porous plug fitted at the bottom of the ladle. Electromagnetic stirring is employed for degassing. For this purpose ladle has to be made of non magnetic austenitic stainless steel or stainless window could be provided. For certain grades of alloy steels, both induction stirring and arc heating are employed for degassing. The final content of gas in steel depends on degree of vacuum and time of treatment. Hydrogen is generally reduced to below 2ppm from 4 to 6ppm, nitrogen content of steel is also reduced. The pick-up of nitrogen from the atmospheric air may occur during open pouring of steel, which must be controlled. Ladles are generally lined with high alumina bricks at upper part of the ladle while the lower portion is lined with fireclay.

Stream degassing

In stream degassing technology, molten steel is teemed into another vessel which is under vacuum. Sudden exposure of molten stream in vacuum leads to very rapid degassing due to increased surface area created by breakup of stream into droplets. The major amount of degassing occurs during the fall of molten stream. Height of the pouring stream is an important design parameter.

Stream degassing technology has following variants in the practice

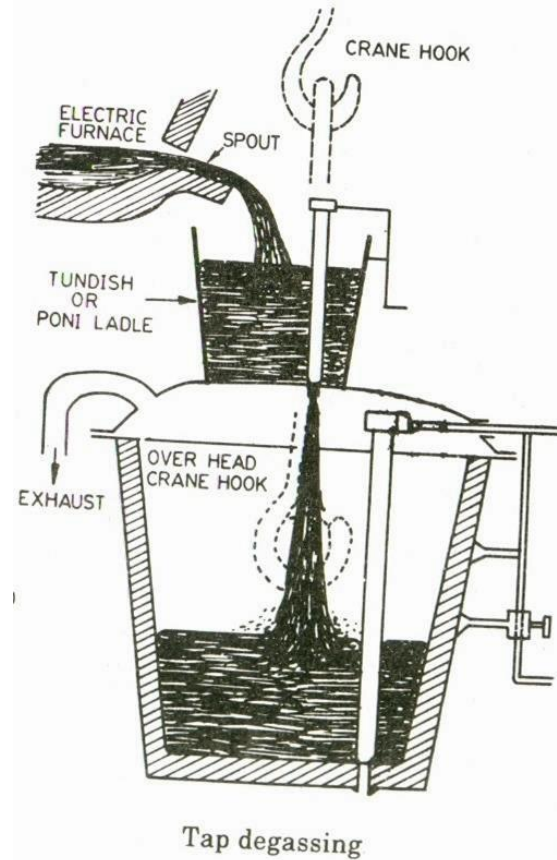
i. Ladle to mould degassing

Preheated mold with hot top is placed in vacuum chamber. Above the chamber a tundish is placed. Steel tapped in the ladle at superheat equivalent to 30°C is placed above the tundish. Steel is bottom poured in the tundish. One ingot could weigh around as high as 400tons and several heats from different furnaces are used for casting.

ii. Ladle to ladle degassing

In ladle to ladle degassing, a ladle with the stopper rod is placed in a vacuum chamber. Ladle containing molten steel from BOF or EAF is placed on top of the vacuum chamber and the gap is vacuum sealed. Alloy additions are made under vacuum. Stream is allowed to fall in the ladle where molten steel is degassed. Alloy additions are made under vacuum.

In some plants degassing is done during tapping. In this arrangement molten steel from EAF is tapped into tundish or pony ladle. From the pony ladle molten stream is allowed to fall into a ladle which is evacuated. Ladle is closed from top with a special cover which contains exhaust opening. Steel with 25°C to 30°C superheat is tapped into ladle.



Recirculation degassing

In the recirculation degassing technology, molten steel is allowed to circulate in the vacuum chamber continuously by special arrangement.

RH Degassing

In RH degassing technology (developed by Rheinstahl Heinrich – Shutte at Hattingen, Germany), a cylindrical refractory lined shell with two legs (also called snorkel) is designed such that steel is raised in one leg and falls back into the ladle after degassing through the second leg. Top side of the cylindrical shell is provided with exhaust, alloy additions, observation and control window. Cylindrical shell is lined with fire bricks in the upper portion and alumina bricks in the lower portion in order to sustain high temperature. The legs are lined with alumina

refractory. A lifter gas argon is injected at the inlet snorkel in order to increase the molten steel velocity entering into inlet snorkel.

The operation of RH degasser is as follows:

i) Cylindrical chamber is heated to the desired temperature (varies in between 900°C to 1500°C in different plants).

ii) The chamber is lowered into molten steel up to a desired level.

iii) The chamber is evacuated so that molten steel begins to rise in the chamber. Lifter gas is introduced. This gas expands and creates a buoyant force to increase the speed of molten steel rising into the inlet snorkel.

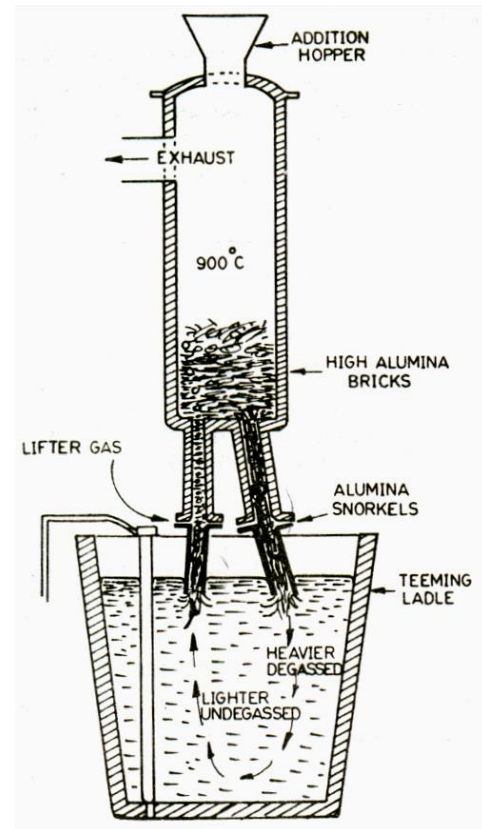
iv) Molten steel in the chamber is degassed and flows back through the other snorkel into the ladle. This degassed steel is slightly cooler than steel in the ladle. Buoyancy force created by density difference (density of cooler liquid steel is > hot steel) stirs the bath

v) Rate of circulation of molten steel in cylindrical chamber controls the degassing. Circulation rate depends upon amount of lifter gas and the degree of vacuum. A 110 T steel can be degassed in 20 minutes by circulating molten steel at 12 tons/min., amount of argon is around 0.075 m³/ton.

vi) Alloy additions can be made at the end of degassing depending on the superheat.

vii) Process has several advantages like

- Heat losses are relatively low.
- Alloy additions can be adjusted more closely
- Small vacuum pumping capacity is adequate since smaller volume is to be evacuated as compared with ladle to ladle or stream degassing.



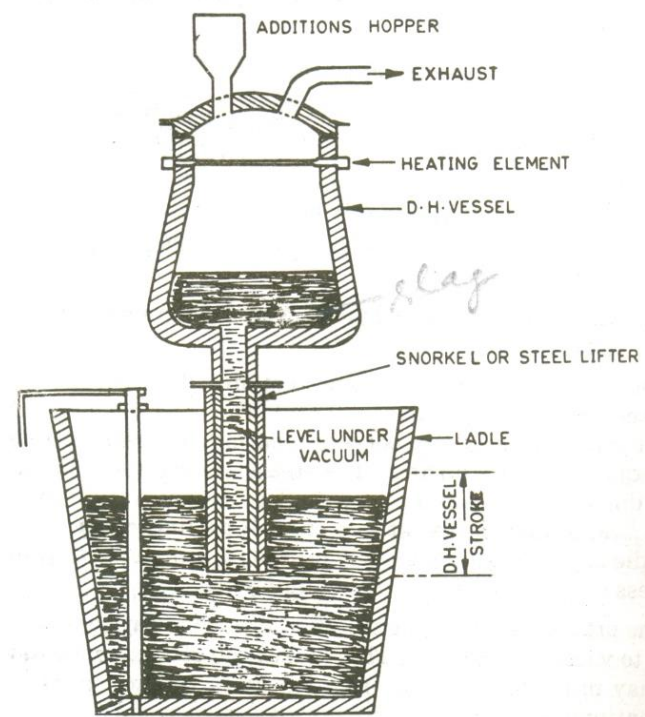
DH Degassing

In DH degassing, a small amount 10-15% of the total mass of steel is degassed at a time. The process is repeated until required level of degassing is achieved. The arrangement of a vessel and the ladle is somewhat similar to RH process except the following:

- In DH unit, the cylindrical vessel has one snorkel.
- Cylindrical vessel has heating facility.

The DH chamber is equipped with heating facility, alloying addition arrangement and exhaust systems. Bottom of the cylindrical vessel is provided with a snorkel which can be dipped into molten steel. The upper portion of the DH vessel is lined with the fireclay and the lower portion with the alumina bricks; snorkel is lined with high quality alumina brick. The length of the snorkel is sufficiently large to realize the effect of atmospheric pressure on rise of steel in the snorkel. The following steps may be noted for operation:

- DH vessel is preheated and lowered in the ladle so that snorkel tip dips below the molten steel surface
- The evacuated chamber is moved up and down so that steel enters the chamber
- The chamber is moved for 50-60 times with a cycle time of 20 seconds.
- Adequate degassing is possible in 20 -30 cycles.
- A layer of slag is kept in the ladle to minimize heat losses.
- The DH degassing unit can operate with lower superheats compared with RH since DH unit has heating facility



LECTURE-29

Degassing Calculations

According to Sieverts' law and from the previous lecture we know that

$$Wt\%N = K_N \cdot \sqrt{pN_2}$$

Further

$$Wt\%N = \frac{\sqrt{pN_2} \cdot K_N}{f_N}$$

Where f_N activity coefficient of nitrogen in steel

Again

$$\log f_N = e_N^i(\% i) + e_N^j(\% j) + \dots$$

Where e is the interaction parameter for the impurities $i, j, \dots$

$$\log K_N = -\frac{518}{T} + 2.937$$

$$\log K_H = -\frac{1905}{T} + 2.409$$

Some values of interaction parameters are given below:

Alloying elements (i)	C	Cr	Ti	P	Si
e_H^i	0.045	+0.005	-0.22	0.011	0.027
e_N^i	0.13	- 0.045	-	0.051	0.047

Let us calculate value of [Wt% H] when molten steel is degassed at 1850 K under vacuum. The pressure above the melt is reduced in one case to 1mm Hg and in other cases to 0.1 mm Hg and 10 mm Hg. Steel contains C=0.05%, Cr= 6% Ti= 0.6%, Ni =2% rest iron. Assume $e_H^{Ni}=0$.

$$\log f_H = 0.05 \times 0.045 + 0.005 \times 6 + 0.22 \times 0.6$$

$$f_H = 0.795$$

$$K_H = 23.94$$

Pressure (mmHg)	[ppm H]
0.1	0.218
1.0	1.092
10	3.450

We note that with the decreasing pressure above the melt dissolved hydrogen in steel decreases. At 10 mm Hg pressure above the melt, dissolved hydrogen is 3.450 ppm which decreases to 0.218 ppm at 0.1mm Hg pressure, which is 6% of hydrogen at 10mm Hg pressure. Higher degree of vacuum is beneficial with reference to degassing. But higher degree of vacuum requires proper selection of ladle refractory material to avoid decomposition of the refractory and vacuum equipment. Also side reactions may occur at higher degree of vacuum.

LECTURE- 30

Ingot Casting

Introduction

Molten steel from BOF/EAF is tapped into a teeming ladle. Deoxidizers, decarburizes and alloying elements if required, are added for the final finishing with respect to oxygen content and other elements in steel. The steel may be degassed either before or during casting. In the modern steel plants, steel is cast continuously. In several small scale plants, particularly those based on induction melting furnaces ingot casting is practiced.

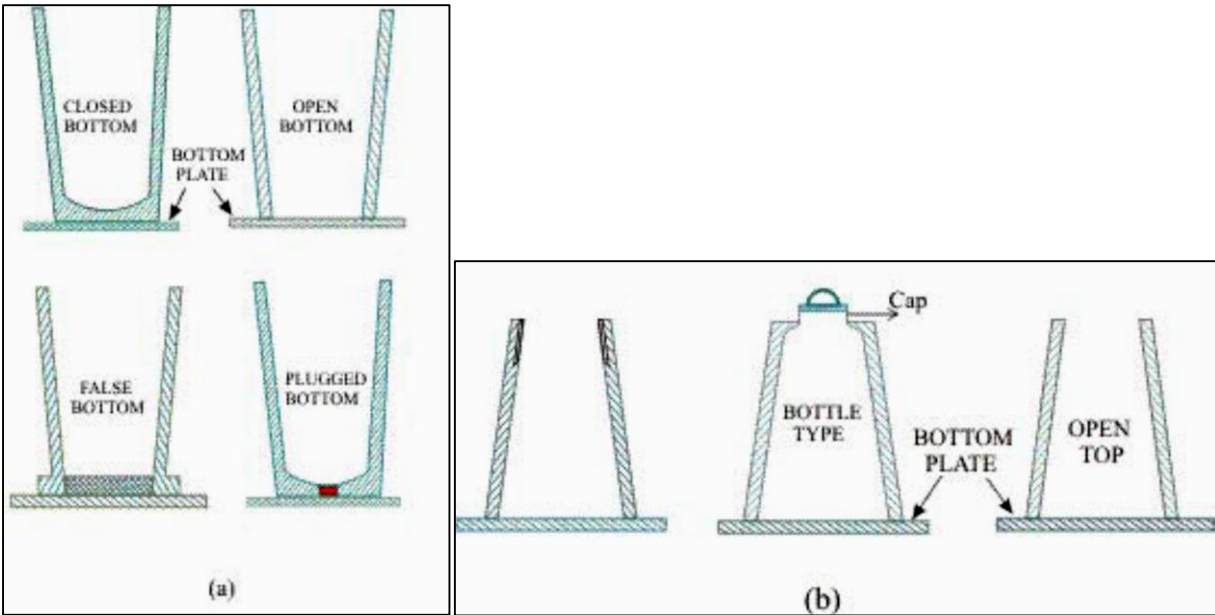
Ingot casting is done in cast iron moulds having square, round or polygon cross section. Ingots with square cross section are used for rolling into billets, rails and other structural sections. Whereas, ingots with rectangular cross section (also known as slab), are used for rolling into flat products. Round ingots are used for tube making. Polygon ingots are used to produce tyres, wheels, etc. Typically an ingot weighing 5-20 tons for rolling, whereas few hundred to 300 tons for forging.

Ingot mould types

Cast iron is used to fabricate the mould. Thermal coefficient of cast iron is lower than steel as a result, steel on solidification contracts more than cast iron which makes detachment of ingot easier from the mold. Inner walls of the mould are coated by tar or fine carbon. The coated material decomposes during solidification which prevents sticking of solidified ingots with the inner walls of the mold.

Molds are essentially of two types:

- a) Wide end up or narrow end down
- b) Narrow end up or big end down



(a) Wide end up moulds

(b) Narrow end up moulds

Wide end up moulds are used to produce forging ingots of killed plain carbon or alloy steels. Wide end up molds may have a solid bottom. Narrow end up molds are commonly used to produce rimming and semi-killed steel ingots. Narrow-end-up molds facilitate easy escape of rimming reaction product, CO.

Fully deoxidized or killed steel used for high quality forgings this shrinks on solidification and may lead to formation of pipe. Molds are generally provided with hot top which acts as reservoir to feed the metal and to avoid formation of pipe. Insulating and exothermic materials are put on the top ingot which ensures availability of hot metal towards the end of solidification. Both bottom pouring and top pouring of steel are used in ingot casting.

Mechanism of solidification

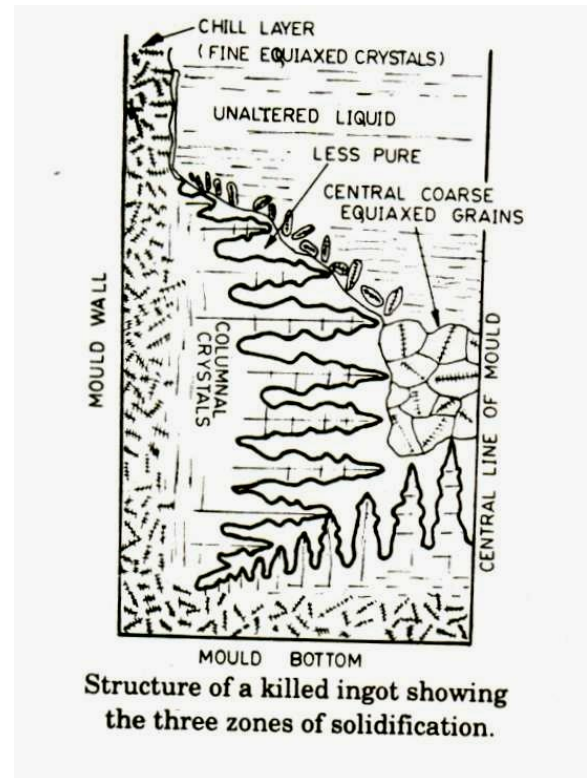
Molds are water cooled. Killed steel solidifies in the ingot form as follows:

- Metal near the mould walls and bottom is chilled by the cold surfaces and a thin shell or skin is formed on the ingot surface. This surface has a ***fine equiaxed*** grains at the skin. The formation of skin results in decrease in rate of solidification.

ii) Due to expansion of mould through the heat transferred from the solidifying steel and contraction of solidified skin an air gap forms between the mould and the skin. This results in decrease in the heat transfer rate, because air gap has a high thermal resistance to heat flow

iii) The solidification front perpendicular to the mold faces moves inwards and towards the centre as a result **columnar grains** form next to the chill surface. The columnar crystals rarely extend to the centre of the mould.

iv) The central portion of the ingot solidifies as **coarse equi-axed grains** of bigger size due to slow rate of solidification.



The above zones of solidification depend on the evolution of CO gas due to carbon and oxygen reaction. In semi killed steels, not all oxygen removed from steel. Oxygen content of steel is very low. The necessary super saturation level of carbon and oxygen reaches towards the end of solidification. As a result the central zone of the equi- axed crystal is disturbed by way of formation of blow holes in the top middle portion of the ingot.

Solidification of rimming steels is controlled by evolution of CO during solidification. Rimming steels are not killed. The gas is evolved at the solid/liquid interface which stirs the molten steel during solidification. Stirring circulates molten steel which brings hot metal to the surface and solidification of steel at top is delayed. Columnar grain formation is prevented due to a more uniform temperature at interior of an ingot. This gives rise to rimming ingots in which gas is entrapped mechanically as blow holes.

Ingot defects: Causes and remedies

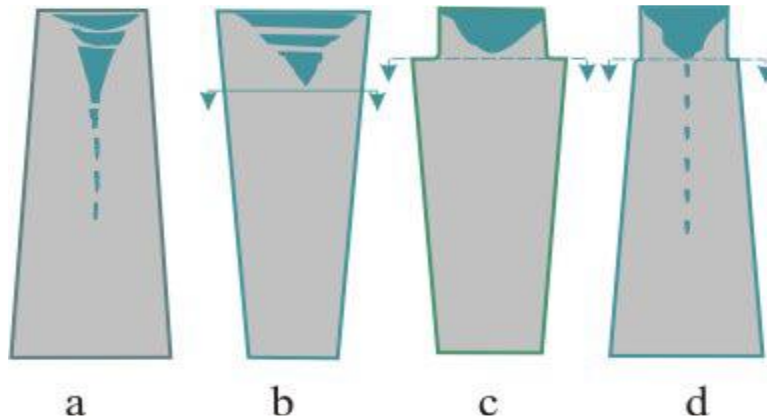
i) Pipe:

Cause: Steel contracts on solidification. The volumetric shrinkage leads to formation of pipe. In killed steels pipe formation occurs toward the end of solidification. Figure (a) shows primary and

secondary pipe in narrow end up mould and (b) in wide end up mould while casting killed steel. Only primary pipe can be seen in wide end up mould.

Figure (a) Narrow end up mould showing long pipe in killed steel

Figure (b) Wide end of mould showing pipe in killed steel



Rimming and semi-killed steels show very less tendency for pipe formation. Wide end up moulds show smaller pipe as compared with narrow end up mould (in figure (a) longer pipe can be seen). The portion of ingot containing pipe has to be discarded which affects yields.

Remedy: use of hot top on the mold. The volume of the hot top is 10-15% higher than ingot volume. Pipe formation is restricted in the hot top which can be discarded. Use of exothermic materials in the hot top keeps the metal hot in the top portion and pipe formation can be avoided. Another method is to pour extra mass of metal.

ii) Blow holes

Cause: Evolution of gas during solidification of steel. Entrapment of gas produces blow holes in the ingot. Blow holes located inside the ingot can be welded during rolling. Rimming steels show blow holes due to rimming reaction between carbon and oxygen. The rimming reaction produces CO, which when is unable to escape during solidification, produces blow holes. Semi-killed steels also show tendency to blow hole formation.

Remedy: Control of gas evolution during solidification so that blow hole forms only within the ingot skin of adequate thickness.

iii) Segregation: It is the difference in composition of steel within the ingot than some average composition. Segregation is due to

a) Difference in solubility of solute elements in liquid and solid steel i.e. partition coefficient of element in steel. Partition coefficient of solute (K) is defined as

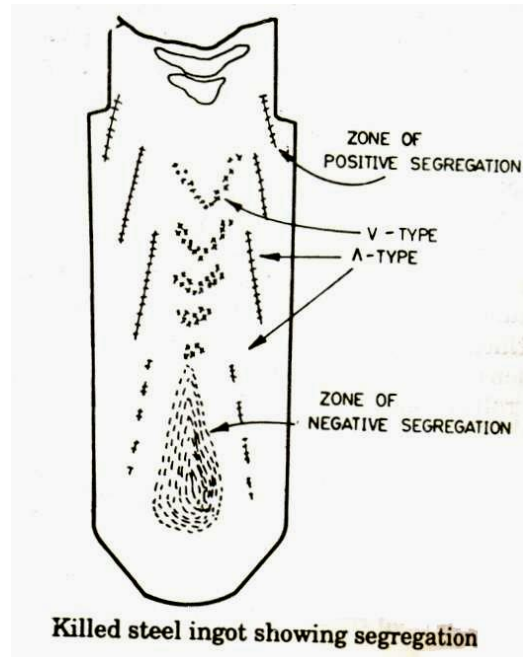
$$k = \left(\frac{\text{concentration of solute in solid}}{\text{concentration of solute in solid in liquid}} \right)$$

The value of $K \leq 1$. The solute elements whose $K = 1$ do not segregate. All elements whose $K < 1$ tend to segregate.

b) Rate of solidification: faster rate of solidification avoids the elements to segregate. The initial chill layer of ingot has practically the same composition as that of liquid steel. Decrease in rate of solidification causes elements to segregate.

c) Larger size ingots are prone to segregation than smaller size ones. Larger size ingots require more time for solidification.

Remedy: soaking of ingots at high temperature can minimize segregation.



iv) Non metallic inclusions:

Non metallic inclusions are inorganic oxides, sulphides and nitrides formed by reaction between metal like Fe, Ti, Zr, Mn, Si, Al with non metallic elements like oxygen, nitrogen, sulphur etc.. An inclusion is a mismatch with the steel matrix. Fine size inclusions when distributed uniformly are not harmful. Non deformable inclusions like Al_2O_3 are undesirable.

Remedy: Inclusion modification is the remedy to alleviate the harmful effect of inclusions on properties of steel.

v) *Ingot cracks*

Surface cracks are formed due to friction between mold and ingot surface. The improper design of mold taper and corner radius cause surface cracks. Different types of cracks are:

Transverse cracks: They are parallel to the base of ingot and are formed due to longitudinal tension in the ingot skin. As the aspect ratio of the ingot increases, tendency to transverse crack formation increases.

Longitudinal cracks are formed due to lateral tension in the skin. They are parallel to vertical axis of ingot. Alloy steels are more prone to longitudinal cracks than mild steels.

Sub- cutaneous cracks are internal fissures close to the surface. The cracks are formed due to thermal shocks. Restriction cracks can be near the corner radius of the ingot.

Remedy: Smooth corners of the mould and gradual curvature minimize restriction cracks.

LECTURE 31

Continuous Casting of Steel

Introduction

In the continuous casting, molten steel is poured from the tundish in the water cooled mold and partially solidified bloom/billet or slab (hereafter called strand) is withdrawn from the bottom of the mold into water spray so that solidified bloom/billet or slab is produced constantly and continuously. Continuous casting is widely adopted by steelmakers. The advantages of continuous casting over ingot casting are

- Quality of the cast product is better

- No need to have slabbing/blooming or billet mill as required when ingot casting is used.

- Higher extent of automation is possible

- Width of the slab can be adjusted with the downstream strip mill.

- Continuously cast products show less segregation.

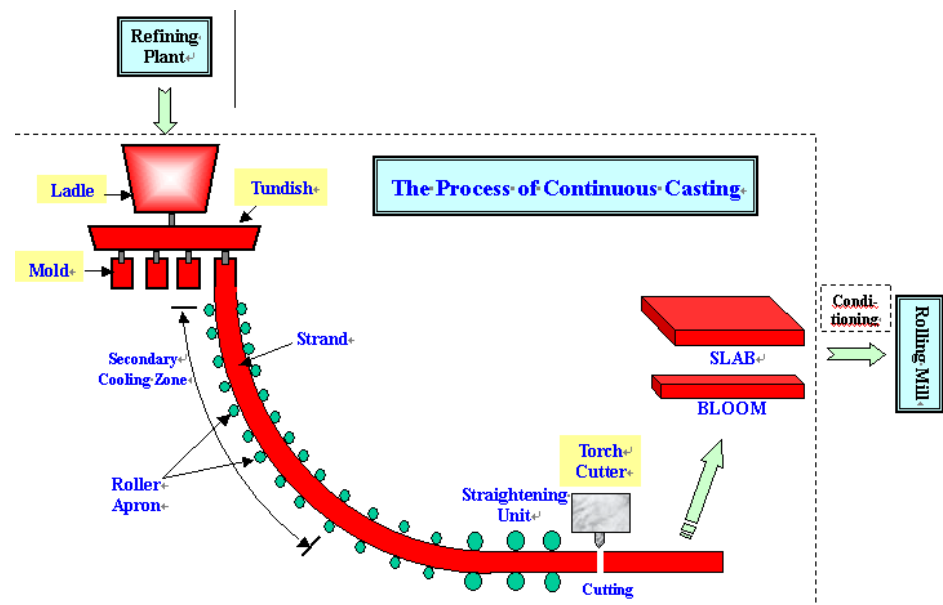
- Hot direct charging of the cast product for rolling is possible which leads to energy saving.

Principle: Continuous casting may be defined as teeming of liquid metal in a short mould with a false bottom through which partially solidified ingot is continuously withdrawn at the same rate at which metal is poured into the mould.



How casting is done continuously?

- The mould is open at both ends and is water cooled. The operation is started by fixing a dummy plug-bar to temporarily close the bottom of the mould. Steel is poured in the mould slowly via a tundish and as soon as the mould is full to a certain level withdrawal of the plug begins. The rate of withdrawal must exactly be equal to the rate of pouring for smooth operation of machine.
- Uninterrupted pouring and simultaneous withdrawal gives rise to the whole cast being poured in the form of one piece which may be cut into smaller pieces as per requirements.



The essential components of a continuous casting machine are tundish, water cooled mold, water spray and torch cutters. Tundish, mold and water spray are arranged such that molten stream is

poured from tundish to mold and solidified strand (billet/bloom/billet) is produced continuously. The required length of the strand is cut by torch cutter.

1. Tundish

Tundish is a refractory lined vessel. Liquid steel is usually tapped from ladle into tundish. The stream is shrouded as it enters from ladle to tundish. The functions of the tundish are:

a) Reservoir of molten steel

Tundish acts as a reservoir for molten steel. It supplies molten steel in presence of a slag cover to all continuous casting molds constantly and continuously at constant steel flow rate. The flow rate is maintained constant by maintaining a constant steel bath height in the tundish through teeming of molten steel from the ladle. The number of mold is either one or more than one. Normally bloom and billet casting machines are multi-strand i.e. number of molds are either 4 or 6 or 8. Slab casters usually have either single or two molds. During sequence casting and ladle change- over periods, tundish supplies molten steel to the molds.

b) Distributor

Tundish distributes molten steel to different molds of the continuous casting machine at constant flow rate and superheat which is required for strand similarly with reference to solidification microstructure. Control of superheat is required in all the moulds to reduce break-out. Location of ladles stream in the tundish is important. It may be located symmetric or asymmetric to the centre of the tundish depending on the number of mold. For single strand machines, molten stream enters from one side and exits the other side of the tundish. In multi-strand tundishes, ladle stream is either at the centre of the tundish or displaced to the width side of the tundish.

c) Inclusion removal

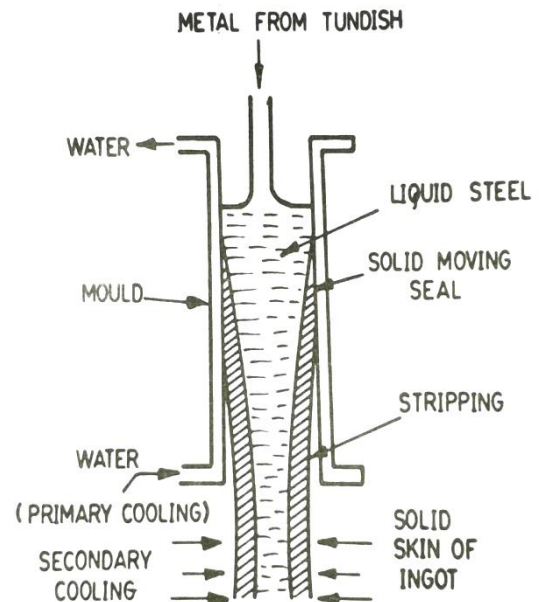
Tundish helps to remove inclusions during the process of continuous casting. For this purpose liquid steel flow in the tundish is modified by inserting dams, weirs, slotted dams etc. The whole idea is to utilize the residence time available before steel leaves the tundish. For example, if capacity of tundish is 40 tons and casting speed is 5 tons/min, then the average residence time of molten steel in the tundish is 8 minutes. During this average residence time, inclusion removal can be exercised. For this purpose flow of steel melt in the tundish has to be modified so as to accelerate the inclusion removal. The Inclusion removal is a two step unit operation, namely

floatation and absorption by a flux added on the surface of the tundish. Flux is usually rice husk, or fly ash or some synthetic powder.

2. Mold:

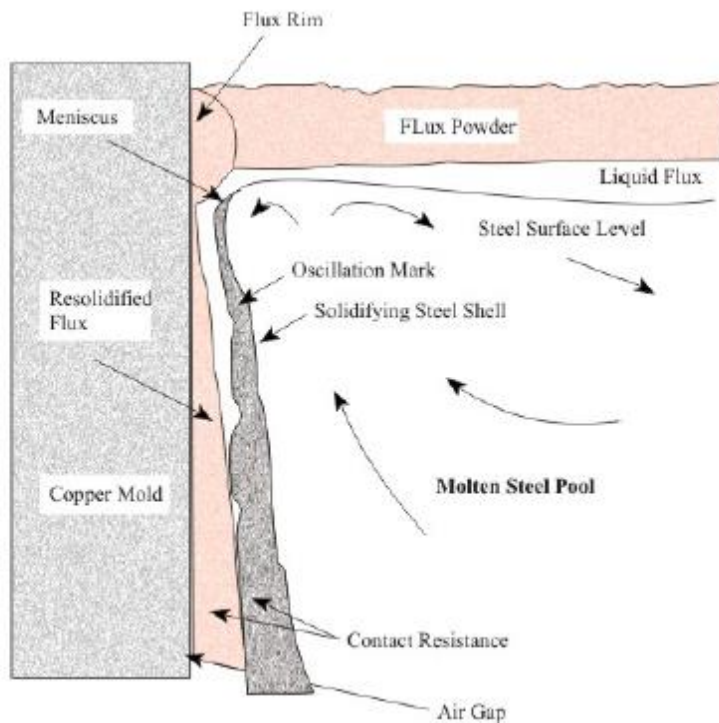
Mold is the heart of continuous casting. In the water cooled mold, molten stream enters from the tundish into mold in presence of flux through the submerged nozzle immersed in the liquid steel.

- Solidification of steel begins in the mold. Ingot does not completely solidify in the mould. As soon as a sufficiently thick skin which would be able to withstand the pressure of liquid core is formed, the withdrawing from mould commences. It is then cooled by secondary cooling.
- The mold is oscillated up and down to withdraw the partially solidified strand (strand is either billet or bloom or slab) which is called *mold stroke*. The oscillated frequency can be varied. At Tata steel slab caster frequency is varied in between 0 and 250cycles/min and the stroke length from 0 to 12mm.
- If the downward speed is more than the speed of withdrawal then it leads to negative stripping of ingot and in reverse major cracks are formed.
- The advantage of negative stripping are that transverse cracking is reduced, allows maximum rate of withdrawal, eliminates tensile forces and generates compressive stresses.



The casting powder is added onto the top of molten steel in the mold. It melts and penetrates between the surface of mold and the solidifying strand to minimize friction. Control of height of molten steel in the mould is crucial for the success of the continuous casting machine. The

solidification begins from the meniscus of steel level in the mould. Mold level sensors are used to control the meniscus level in the mould.



Role of flux in continuous casting mold

As seen in the figure, flux melts and enters into the gap between mold surface and solidified strand. Molds are made of copper alloys. Small amounts of alloying elements are added to increase the strength. Mold is tapered to reduce the air gap formation. Taper is typically 1% of the mold length. For cross section of mold the taper is about 1mm for 1m long mold. The cross section of the mold is the cross section of the slab/bloom/billet. Length of the mold is around 0.7 and is more for large cross sections. Mold cross section decreases gradually from top to bottom. Mould extracts around 10% of the total heat.

Steel level in mould is controlled, that is the meniscus for smooth caster operation. Sensors are used to control the meniscus level.

The functions of mold flux are:

- Inclusion absorption capability.
- Prevention of oxidation.

- Minimization of heat losses.
- Flux on melting enters into the air gap and provides lubrication.

For the above functions the flux should have the following properties.

Low viscosity

Low liquidus temperature

Melting rate of flux must match with the speed of the continuous casting.

Secondary Cooling - Having accomplished the initial cooling in the mould the solidification of remaining core and further cooling of solid product is accomplished by quenching using high pressure water sprays. The sprays are directed from all sides of the casting. As the ingot emerges from the mould it is positioned by the help of certain guide rolls held horizontally from all sides of the ingot. It is called roller apron. The roller apron supports the ingot and maintains its shape without causing cracking.

Withdrawal Rolls - These are one or two pair of rolls meant to finally grip the ingot and pull it out at a prefixed rate without deforming the product.

Dummy Bar – At the beginning the bottom of the mould is closed by what is called a dummy bar. It is meant to lead the product through the roller apron and the withdrawal rolls. The length of dummy bar in a vertical machine is equal to the vertical distance from the mould bottom to more than the cut-off point.

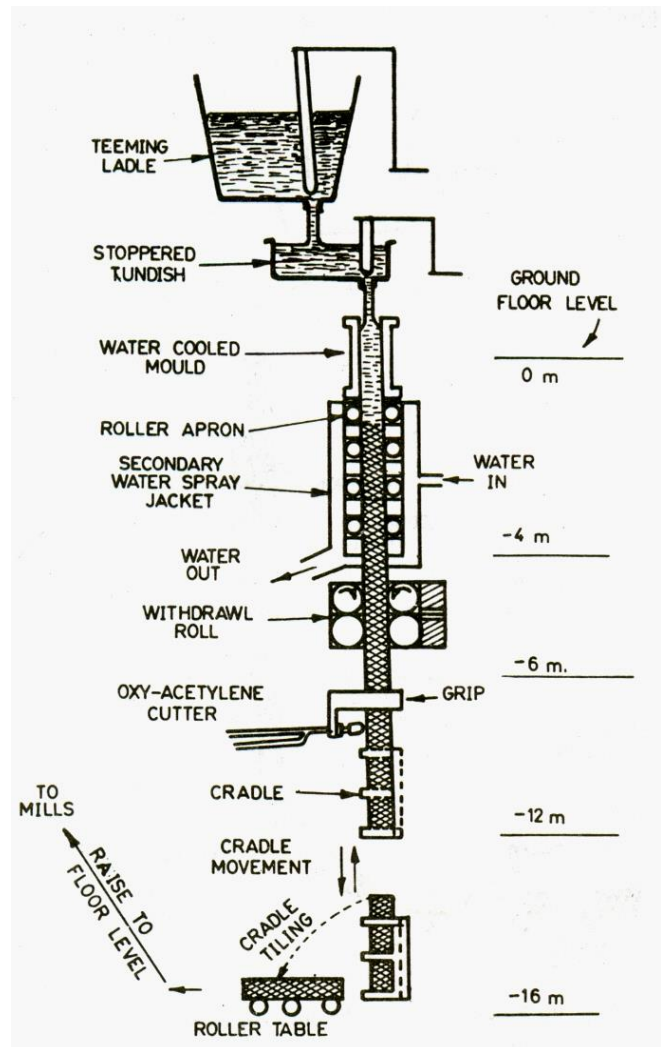
Types of Continuously Casting Machine

There are three types of continuous casting machine..

1. Vertical
2. Vertical mold horizontal Discharge
3. Curved mold (S type)

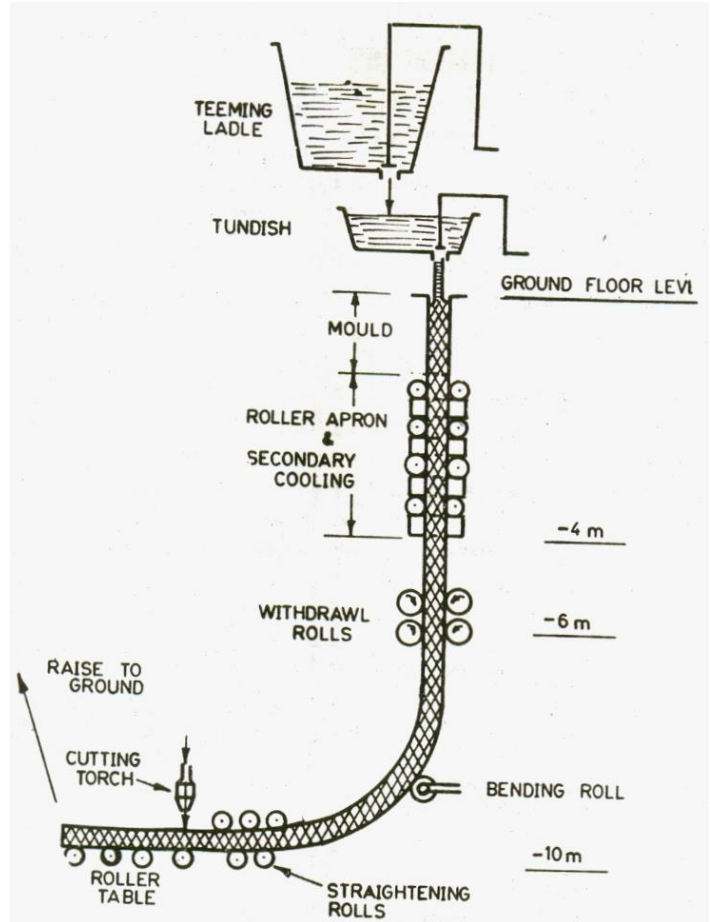
Vertical Type

- It is the first continuous casting system wherein the mould and the discharge are both vertical. Liquid steel is brought to the machine in a stopper controlled ladle and is teemed in a stopper controlled tundish which regulates the flow of steel into the mould.
- Below the mould is a secondary cooling zone with rollers and interspaced water sprayers called roller apron. The main withdrawal rolls are situated below the apron.
- This type of plant is very tall and high casting speeds cant be used here.
- It is good for slabs wherein bending is avoided for adverse effects.
- In the event of breakdown it is easy to repair and restart the machine.
- All steel qualities can be cast without fear of damage by bending and straightening.



The Vertical-Mould Horizontal Discharge Type

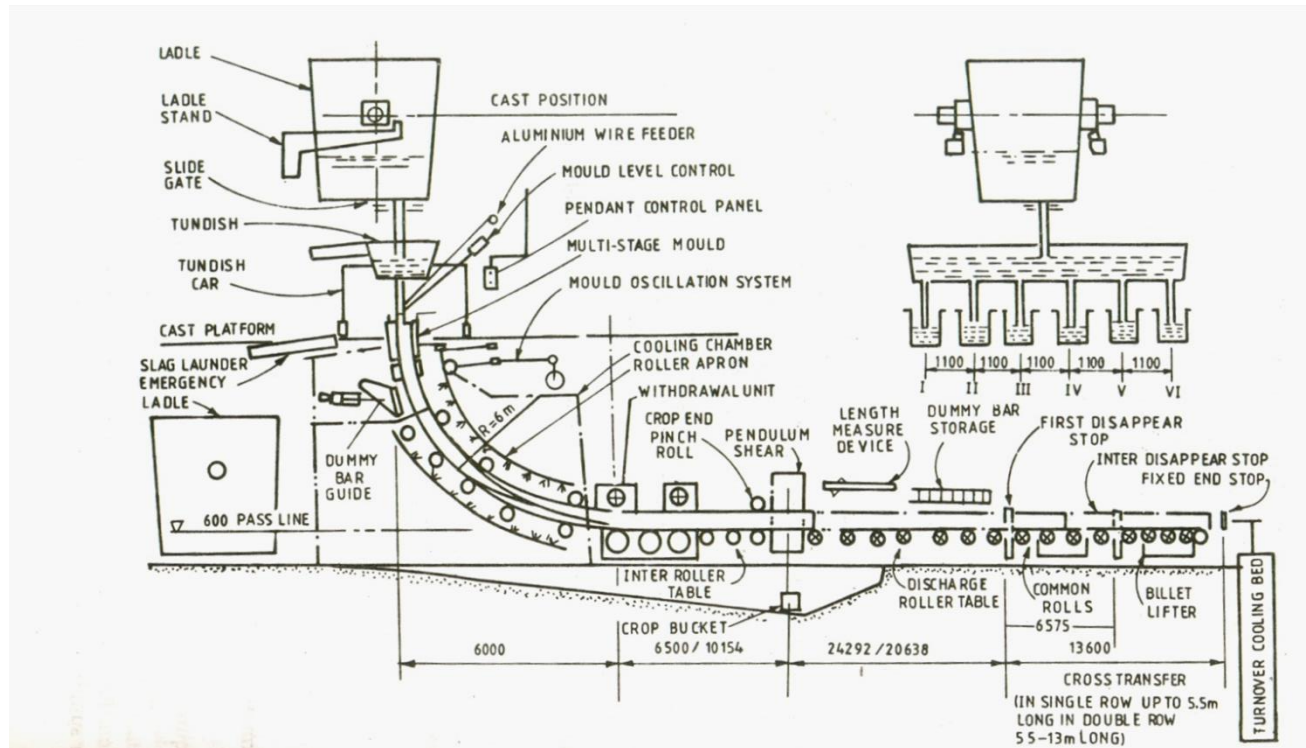
- This is a modification over the earlier vertical design to reduce the overall height of the machine. The mould, roller apron and the pinch rolls are similar in design to those of vertical machine.
- After the product emerges from the pinch rolls it is bent to obtain discharge horizontal. The cutting torch moves horizontally. Here the horizontal set of straightening rolls becomes necessary.
- Heavy sections difficult to bend cant be cast by this machine. In the event of breakdown it is more difficult to repair and restart. It is popular for small and medium sized cross-sections.



Curved Mould Type (S-Type)

- It is the universally adopted continuous casting of almost any sections like billets blooms and slabs.
- The mould is itself curved mould and rather than straight one employed in the earlier two designs.
- The strands come out of the mould in a curvilinear fashion with a fixed radius.
- It is bent before the entire cross-section is solidified.

- The curved strand is in fact straightened after it is fully solidified and cooled to the designed extent.
- The S-Type machine is a more popular name for it.
- The radius of curvature of the strand should be as high as possible to obtain smooth operation



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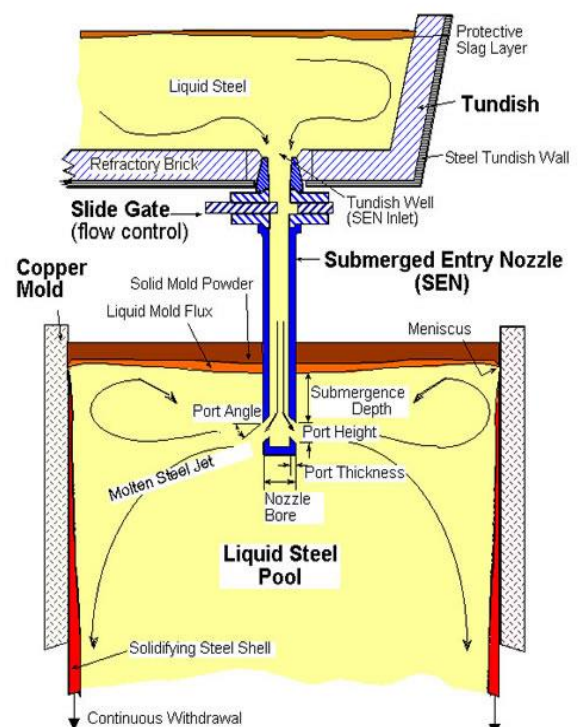
Developments in Continuous Casting of Steel

Introduction

Continuous casting is one of the most significant developments in the technology of steelmaking. A ladle containing 300 tons of molten steel at 1600°C can be cast into approximately 60 minutes in a semi-finished product like bloom, billet and slab. It reduces energy consumption, material handling and as a result lead to increase in plant productivity. In addition, continuous casting offers the possibility to integrate the hot strip or blooming mill by direct hot charging. In recent years considerable developments have taken place both in conventional continuous casting to improve the product quality and to develop new technology to produce nearly finished products. Some of the developments are briefly described.

- Use of submerged entry nozzle (SEN)
- Use of electro-magnetic stirring (EMS)
- Near net shape casting/Compact strip production(CSP)

Submerged Entry Nozzle – In early machines liquid steel was teemed into the con-cast mould in open air, which gave rise to various defects arising out of oxidation of metal stream in open atmosphere. This was avoided by enclosing the teeming area and introducing neutral gas to shroud the stream to avoid contact with atmosphere. SEN is a ceramic tube which has a closed bottom and is connected at one end to the tundish while the other end is dipped in molten pool. It has openings at the bottom to let



liquid flow. Argon gas may be introduced inside the SEN to prevent sticking of steel to the SEN surface.

Electromagnetic Stirring (EMS)

EMS is an electric method of inducing motion in liquid steel without using any mechanical device. In continuous casting EMS can be applied in mold and secondary cooling zone to

- Decrease segregation and porosity
- Improve steel cleanliness by forcing inclusions to float on the surface where they can be absorbed by a slag
- Improve the steel quality in terms of reducing defects

Stirring induced by EMS modifies the flow pattern of molten steel of the solidifying strand. Improved stirring reduces segregation. Because of the imposed stirring, the superheat of the melt can be quickly dissipated which results in modification of structure of the solidifying strand from columnar to equiaxed and then to globular structure.

EMS allows to increase the casting speed which increases productivity of the caster.

An inductive electromagnetic stirrer is the stator of an asynchronous motor, the rotor of which is the liquid core of the solidifying strand. This stator produces either a rotating or travelling magnetic field, which induces eddy current, perpendicular to the magnetic field and its velocity vector. Due to this, an electromagnetic force is created which causes stirring in the bath. The mains frequency is usually used for stirring billets or small blooms beneath the mold.

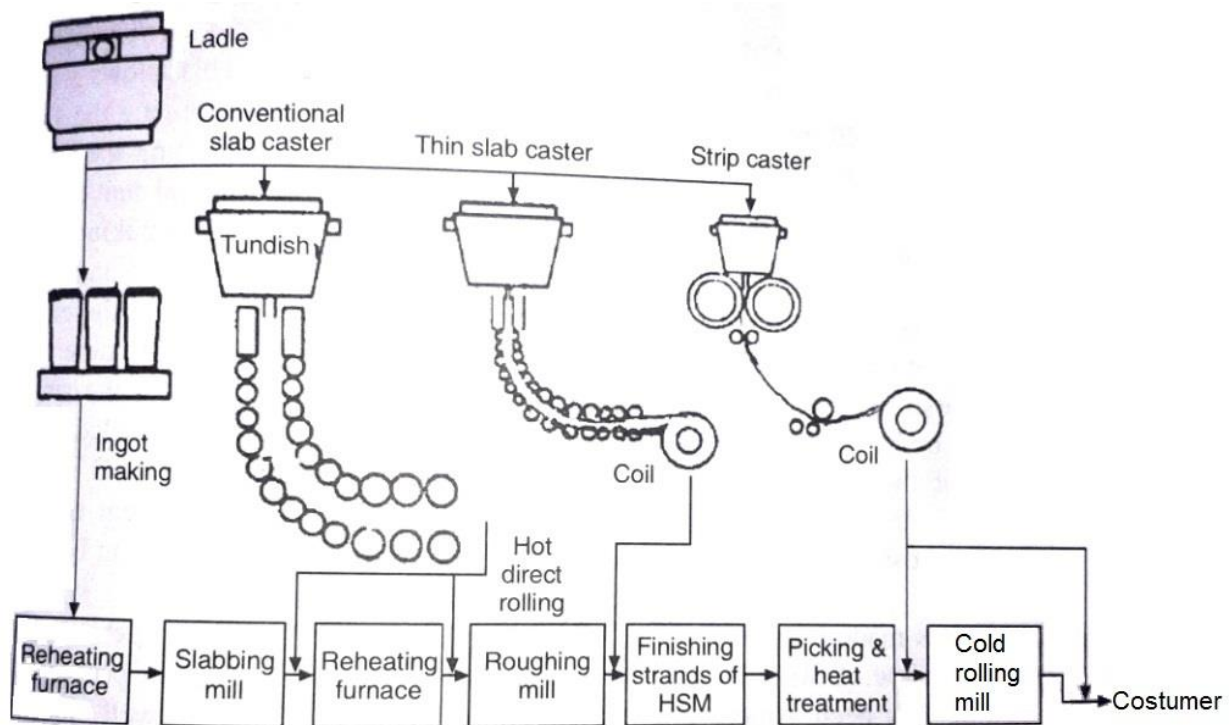
Near Net shape casting

The conventional methods of producing metallic strips and sheets require the casting of large ingots which are subsequently hot rolled and cold rolled to final thickness. Several unit operations like ingot soaking, slabbing mill, intermediate annealing, pickling are required to produce the strips. An alternate to this route is the near net shape casting or direct strip casting.

In this technology strips are cast close to the final desired thickness and thus many of the unit operations in the conventional technology can be eliminated.

The near net shape casting units can be classified into following two categories:

- i) Thin slab caster producing 20mm to 70mm thick slabs of cross section 20mm to 70mm X 1000mm to 2000mm which could be fed directly into the finishing stands of the hot strip mill without any conditioning
- ii) Strip casters producing strips less than 10mm thickness which is sent directly to the cold strip mill



Different types of steel casting processes (schematic)

Thin Slab Casting

Thin slab casting aims at to cast slabs of thicknesses less than 100 mm, say around 60 to 80 mm. The objective is to integrate caster, reheating furnace and hot strip mill to increase the productivity. A slab of cross section 1500mm x 80mm would require melt flow rate 3.78

tons/min at 4.5 m/min casting speed. Since the mould size is smaller turbulence in the mould increases which results in entrapment of mould flux on surface causing surface defects.

Use of funnel shaped mould with enlarged cross section at the meniscus is one remedy. Electromagnetic brakes are very effective in parallel moulds.

Development of liquid core reduction is one such technology that has helped thin slab casting development. Solid ingot with liquid core is subjected to on-line rolling. This brings the following advantages:

- Rolling can be eliminated
- Improved internal quality in term of segregation

Thin slab caster can be integrated with EAF units and hence mini steel plants are using thin slab casting to produce hot strips with lower segregation, finer grain size and higher strength

Strip Casting

The set up for strip casting is totally different from that used in thin slab casting as there is no mold at all. The most popular method is to use a twin roll caster, which employs two water cooled rotating rolls. The liquid metal is directly fed into the gap and the solidified rolled strip emerges from the caster, which can be directly marketed or cold rolled into the final shapes.

As cast thin strips have many unique features such as very fine equiaxed grains, much less segregation and distinctly finer inclusions. These characteristics result in superior mechanical properties and higher corrosion resistance. The total issue of economics of thin strip casting has not yet been finally resolved, particularly for relatively less expensive grades like carbon steels.

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Pollution Control & Waste Management

Steel industry is both capital and energy intensive and its production volumes are very high. Process chains within the industry are long. Many different technologies are applied and the industry has a significant impact on the environment. One of the major concerns of world steel industry is the disposal of wastes generated at various stages of processing. Because of natural drive to be cost-effective, there is a growing trend of adopting such waste recovery technologies which convert wastes into wealth, thereby treating wastes as by-products. This has led to aiming at development of zero-waste technologies. The technologies developed to economically convert wastes of steel plants into wealth also provide new business opportunities for prospective entrepreneurs. As per World Steel Association (WSA), the world steel industry applies the principles of reduction, reuse and recycling (3 'R's) in many ways, in order to improve the sustainability of the industry. Due to this the industry has dramatically reduced need for raw materials.

The ultimate goal of the management must be the zero solid waste from the plant. For this follow-up and continuous improvements are crucial. Measurement and reporting of waste reduction and achievement of cost saving goals also helpful in improving the working results and the sustained development of the steel plant.

3 'R's of solid waste management is shown in figure



The process of industrialization and continuous exploitation of earth resources for sustainable growth of civilization has depleted the non-renewable resources of the earth thereby adversely affecting the environment.

An integrated steel plant unit exhausts several harmful dusts, fumes and substances that are quite injurious to human health, vegetation, crops, landscape, animals, machine life etc. Such discharges contaminate and damage inland waters, environment, soil, food, human settlement and even flora and fauna. Therefore, these wastes could not be left uncared for and that is why threshold limits for such harmful substances have been fixed and industries are required to adhere to these norms.

The Steel industry is considered as resource intensive and pollution prone. Production of steel involves several operations. It starts from naturally occurring raw materials like coal, iron ores

& fluxes to produce hot metal in blast furnace, convert hot metal into steel and subsequently to go for rolling of steel into finished product. Several other activities including production of refractory are also performed in varying magnitude inside the steel works. A large quantity of waste is generated as a sequel to such Activities. To make one-tonne of crude steel even with good raw materials and efficient operation, 5 tonnes of air, 2.8 tonnes of raw materials and 2.5 tonnes of water are required.

These will produce in addition to 1 tonne of crude steel, 8 tonnes of moist laden gases and 0.5 tonne of solid wastes. However, in SAIL plants, this figure varies from 820-1,200Kg/tonne of crude steel—which is very high. In a steel industry, all the three types of waste materials (gaseous, liquid and solid) are generated. The generation of gaseous waste material is the highest but the management of solid waste material is the most intricate. The steel plants of the seventies were characterized by higher waste generation rates associated with massive dumps around the steel works resulting in serious land, water and air pollution.

Over the years, due to technological changes in steel making and strict environmental regulations and legislation, emphasis on raw material quality and emergence of new markets coupled with innovative ideas of waste reduction and rescue have resulted in drastic reduction in the quantity of waste generated in steel works from 1,200 Kg to less than 200 Kg per tonne of crude steel and

recycling rates have reached 95-97% in some parts of the world. However, the solid waste generation presently in Indian steel industry is in range of 600-1,200 Kg/tonne of crude steel and recycling rate varies between 40- 70% which lead to higher production costs, lower productivity and further environmental degradation.

The following are the major solid wastes/co products/byproducts in various production processes of steel industry.

Coke making

The main solid wastes generated in the production of metallurgical coke are coal dust, coke dust, tar sludge and acid sludge. Coal dust is recycled back through the coal blend. Coal dust can also be recycled along with coke dust by adding them in the sinter charge mix. Tar sludge is added to the coal blend to improve its density. Acid sludge need to be neutralized before its disposal.

Sinter making

Solid wastes generated in the sinter making are dusts and sludges. Dusts are generated at sinter machine building floors, cyclones and ESP (Electrostatic precipitator). Sludge is generated at the clarifier of the water treatment plant. These dusts and sludges are rich in iron (Fe) and contain good amount of lime (CaO), magnesia (MgO) and carbon (C). These materials are very good materials for recycling back in sinter making. These materials are either blended with iron ore fines or briquetted for recycling.

Pellet plant

The major solid wastes generated in pellet plant are dusts and undersized green pellets. Both of these are recycled back in the pellet feed material.

Blast furnace iron making

Solid wastes generated during the blast furnace (BF) iron making process are dusts, burden screenings at the stock house, cast house runner jam, cast house muck, blast furnace slag, flue dust, GCP dust or sludge, refractory waste, and hot metal (HM) ladle skull.

Dusts and burden screenings are recycled back in sinter making. Cast house runner jams are either sold as iron scrap for re-melting or recycled in the steel melting shop. Cast house muck is dumped as land fill material.

Most of the BF liquid slag gets granulated and is sold to cement manufacturers for the manufacture of BF slag cement. A small amount of BF slag gets air cooled. The air cooled BF slag is either dumped as landfills or used in road repairs within the steel plant. In either case the iron contamination of the slag is separated and sold for re-melting.

Flue dust and GCP dry dust (in case of dry gas cleaning) are recycled in sinter making. GCP wet sludge (in case of wet gas cleaning) from the clarifier is dried and is either blended with the iron ore fines in the raw material yard or briquetted and recycled in sinter making.

Refractory waste from the ladle repair shop is sold and the same is used by the refractory manufacturer in the manufacture of mortars. HM ladle skull is broken either by dropping weight or by lancing and the broken skull is sold as iron scrap or used in steel melting shop.

Iron making by direct reduction

During the ironmaking process by direct reduction the main solid wastes are char (in case of plants using coal based technology), dusts (both coal and iron), under sized DRI (direct reduced iron) and DRI rejects. Char is used in captive power plant as fuel for the boiler. Coal and iron dusts are used in the sinter plants. Coal dust can also be used in the boiler. Iron dust can also be sold to the cement manufacturers. Under sized DRI is briquetted and used along with DRI in steel melting shop. DRI rejects are recycled back in the process.

Pig casting

During pig casting of hot metal, waste materials like plate jam, runner jam and lime sludge get generated. Plate jam and runner jams are sold as iron scrap after processing. Lime sludge is used for neutralizing purpose.

Basic oxygen steel making

The main waste materials in the BOF steel making are converter slag, scrap, waste refractories, converter muck, and gas cleaning plant (GCP) sludge. Except GCP sludge all other waste materials are usually generated in mixed condition which means that during generation one waste material gets contaminated with other waste material. Hence sorting is a very important step for recycling of the waste materials in steel making.

GCP wet sludge from the clarifier is dried and is either blended with the iron ore fines in the raw material yard or briquetted and recycled in sinter making.

Converter slag after removal of scrap is recycled in the sinter mix as a replacement for limestone. Converter slag is also used in road repairs, for railway track ballast, and as soil conditioner.

Scrap removed from converter slag as well as from the muck is recycled back in the converter for cooling purpose. Steel scrap also gets generated when there is ladle through or converter through though this phenomenon is very rare.

From converter muck scrap and refractory wastes are removed and balance is used for land fill.

Refractory wastes are usually of two types. First type is which comes out from used converter lining and mainly consists of magnesium carbon refractories. Most of these refractories which are not contaminated are used in the converter for the bottom patching. Second type is ladle refractory wastes. If these wastes are basic then they are treated similarly to converter refractory wastes. In case they are of alumina then the refractory waste is used for mortar manufacture.

Electric steel making

Main waste material in the electric steel making is EAF (electric arc furnace) GCP dust, slag, scrap and waste refractories. Magnesia carbon waste refractories are used as slag conditioner in the EAF.

Electric Arc Furnace (EAF) slag owing to its high crystallinity and high iron content has presently no well established method for potential recycling. The basicity index (BI) of the slag is generally between 1.2-1.8 which comes under the low hydraulic Merwinite group. Also the Grindability Index, which is a measure for the energy required for grinding a particular material to a given size, is high due to high Iron oxide content. This makes the further grinding and processing of EAF slag energy intensive. The slag has been used as an effective aggregate for road making. Vitrified ceramic tiles have also been developed from the EAF slag.

Continuous casting

Major waste materials generated in the continuous casting process is continuous casting scale, refractory waste, scrap, slag and muck. Here also waste materials are generated in the mixed condition and sorting is needed as the first step for separating different types of wastes.

Continuous casting scale is recycled in sinter plant. Scrap is recycled in the steel making. Other waste materials are used as land fill.

Rolling mills

Major solid waste materials generated in rolling mills are mill scale, refractory waste from reheating furnace, and scrap.

Mill scale is recycled in sinter plant. Scrap is recycled in steel melting shop. Refractory waste depending on the condition either goes for mortar manufacture or is dumped.

Lime calcining

Solid wastes generated at the calcining plant are limestone and dolomite screenings, lime dust and lime fines. Lime dust and lime fines are briquetted and recycled either in sinter plant or steel melting shop. Limestone and dolomite screenings are recycled in the sinter plant.

Conclusion

The detailed mineralogical and geochemical studies carried out on solid waste of steel plants has opened up a new vista for their utilization potential. This investigation has contributed in a big way towards enhancing the economy of steels plant through waste utilization in eco-friendly manner. The detailed characterization of the waste samples leads to the following conclusions.

- After treatment, LD slag is suitable for cement manufacture and Iron can be recovered from it.
- If carbon recovery from fly ash is possible then it will not only reduce the fuel consumption in power plant but also useful in cement manufacturing and setting up an ancillary industry.
- These are not only low cost methods but wastes can also be utilized and the most vital factor is that these are eco-saving measures.

Books for reference:

1. Ironmaking and Steelmaking Theory and Practice by A. Ghosh and A. Chatterjee, PHI.
 2. Steel Making by A.K.Chakravorty, PHI
 3. Electrometallurgy of Steel and Ferro-Alloys , Vol I, by F.P.Edneral, Mir Publishers
 4. Introduction to Modern Steel Making by R.H.Tupkary, Khanna Publishers, New Delhi1977
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Questions for practice

Q1 **State TRUE/FALSE and justify your answer:**

- a) Dephosphorisation is not achieved in the BF.
- b) Sub-lance is the substitute of lance in LD.
- c) Sulphur causes hot shortness in steel.
- d) Catch carbon technique is used to produce high carbon steel.
- e) Basic flux (CaO) is required for effective removal of Si and Mn.
- f) In electric arc f/c foaming of slag is desirable.
- g) Steel making in LD is autogeneous.
- h) Non-metallic inclusions always deteriorate the quality of steel.
- i) There is no hesitation to adopt continuous casting for killed steel.
- j) A typical Indian pig iron contains about 4wt% C.

Q2

- a) In terms of ionic Theory of slag explain desulphurization of molten iron phase.
- b) Explain how the distribution of elements such as Si, S and P in the production and refining of iron and steel depends upon the temperature and the respective activities in the metal and the slag phase.

Q3

- a) Draw and describe the sequence of impurity elimination curve in LD process with special reference to Mn.

- b) Given: In Hot Metal: Si=1%, P=0.15%, Mn=0.25%, C=3.5%,
Scrap=10% of Hot Metal.
In Steel at Tap: C=0.2%C.
In Slag: CaO=54%, FeO=18%, MgO=MnO=2.5% and
CaO/SiO₂ ratio=3.2.

Calculate the following per tonne of steel.

- i- Weight of Hot Metal Charge
- ii- Weight of slag produced
- ii- Quantity of lime required.

Q4 Explain the constructional, operational details and modern developments of OBM process. Compare with LD process.

Q5

- a) Describe the principle of vacuum degassing. Explain R-H process with suitable sketches.

- b) Consider removal of Hydrogen from liquid steel of composition C = 0.05%, Cr = 6%, Ti = 0.6%, Ni = 2%, rest Fe at 1850K under vacuum. Interaction parameters are:

Alloying elements, i	C	Cr	Ti	Ni
e_H^i	0.045	0.005	-0.22	0

$$\text{Log } K_H = -\frac{1905}{T} + 2.409$$

Calculate and compare the [wt. % H] in the steel at 10 mmHg and 0.1 mmHg pressure.

- Q6 a) Molten metal containing 5.25% impurity including 0.25% Mn refined to produce 0.1% C plain carbon steel. 15% (of hot metal) low carbon (0.2%) steel scrap is charged as raw material. Composition of slag is 54% CaO, 18% FeO and 2.5% MnO, with $\text{CaO/SiO}_2 = 3.5$. Calculate amount of steel and slag per tonne of hot metal produced. Also find out amount of Iron loss.
- b) What are the objectives of oxidizing and reducing periods in electric arc furnace steelmaking?
- Q7 a) What do you understand by complex deoxidation of steel melt? What are the advantages of complex deoxidation over simple deoxidation.
- b) Describe the carbon reaction in detail and its importance in steel making.
- Q8 Write short notes on (any two)
- Twin hearth process
 - VOD process
 - S-type continuous casting machine
 - Non-metallic inclusions