Government Polytechnic, Sonepur

LECTURE NOTE

SUBJECT NAME- FERROUS METALLURGY II

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LECTURE-1

Introduction to Steel Making

1. What is Steel?

Steel is an alloy that consists mostly of iron and has carbon content up to 2.11% by weight for plain carbon grade. In the reduction process, the iron absorbs about 3–4% C and other elements (like Si, Mn, P, S etc.) to form impure iron (i.e. hot metal). By solidification of hot metal into small casting that is known as pig iron. Hot metal is directly used as raw material for steelmaking and pig iron is used as raw material for foundry. But most of the steels contain less than 1.0% C, hence the excess carbon and other impurities must be removed from the hot metal to convert into steel. The excess carbon and other impurities are removed by controlled oxidation of hot metal in steelmaking furnace by oxygen to produce carbon steel of the desired carbon content.

Types of steels

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 STEEL

(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

ALLOY STEELS

(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

1.1 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. **Conventional 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 molten condition.

Pig iron + O_2 = 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

HEARTH PROCESS	PNEUMATIC PROCESS
1. Hearth is swallow, where maximum area provided for slag-metal interaction. 2. It is a slower process. 3. Ex.- Open Hearth furnace	1. Hearth is deep, & also gas pressure is provided. 2. It is a faster process. 3. Ex.- L.D.Converter

HISTORICAL DEVELOPMENT OF MODERN STEEL MAKING	
1856	The father of steel making is, Sir Henry Bessemer, a British engineer developed a process for bulk steel production calledAcid Bessemer Process.
1878	S.G thomas and Gilchrist developed basic bessemer process
1868	Siemens and Martins developed Open hearth process.
1900	Paul heroult showed use of electricity for steel making.
1928	Bulk oxygen production technology was developed.
1950	Oxygen was used to produce steel at Linz and Donawitz and process was termed LD converter.
1960	Continuous casting was developed.
1960 and till dat	Major developments took place Multi hole lances for blowing oxygen. Hot metal pretreatment to control S &P Simultaneous blowing of oxygen from top and inert gas /oxygen through bottom.

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1.2 Blister steel making

Since wrought iron lack-of hardness required for making cutting tools. It was carburized in solid state by heatingit in contact with carbonaceous materials for suffificiently long time to allow carbon to diffuse into the surface of wrought iron. The iron-carbon alloy thus formed at the surface was hard enough for making cutting tools. This was known as cementation process.

The amount of carbon absorbed depends on the temperature and the length of time for contact of two materials.The product of the cementation process was known as blister steel. The blister, which appeared on the surface of the bar and were usually hollow, were formed by liberation of CO gas. Since the wrought iron bars contained acertain amount of slag; the iron oxide (FeO) of the slag reacted with the carbon present toform CO gas.

1.3 Shear steel

A further refined form of blister steel known as shear steel- so called because the inventor was in the habit of stamping his product of a pair of shears to indicate its suitable application. Was formed by breaking the thin bars of blister steel to lengths of about 2-4 ft long and then heating 6 or so strips held together in a bundle.

1.4 Crucible steel making

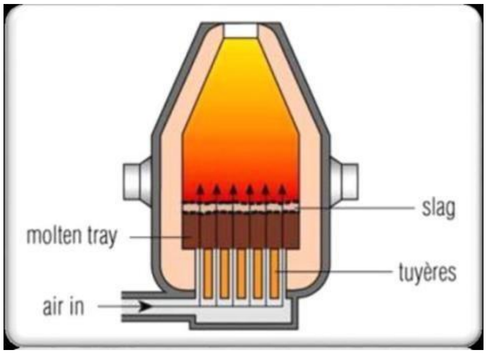
The crucible process is the first method of producing liquid steel and it was introduced by a clockmaker called Huntsman at Sheffield, UK in 1740.The crucible is made either of fireclay or graphite. Coke fired furnace (i.e. pitfurnace) is used for crucible process. When the crucible (which was placed on the furnace previously) and furnace was brought up gradually to a full red heat. Then the feed was charged into the crucible by means of a charging funnel. The lid was then placed on the crucible. Melting took 3–4 h. When melting was completed,thenthe killing fire was done. The killing process was done by addition of fresh coke and brings the metal up to a high temperature. During that period, carbon react with the fireclay resulting reduction of silica.

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

Demerits:-

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



Basic Bessemer

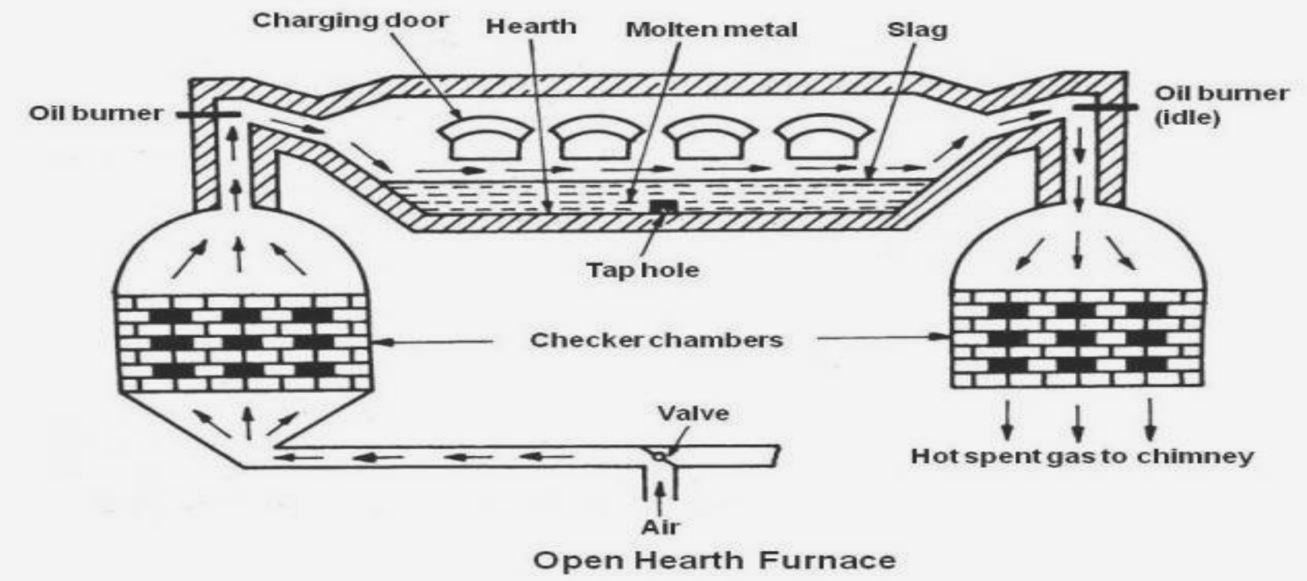
Basic Bessemer Process:-

- 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.

LECTURE-03

1.6 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 Furnace

Disadvantages

- The process is very slow.

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

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.

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.

2. 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 withchrome 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:-

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:-

Charge materials consist of (i) hot metal (50–75%), (ii) scrap (25–50%), (iii) limestone (5–7% of metallic charge) as flux, and (iv) iron ore (6% of metallic charge) as oxygen supplier (if 3rd charging option is adopted).Initially, solid scrap, limestone and iron ore can be charged by mechanically charging box to the furnacethrough the door. The materials should be charged in such a way that it is uniformly distributed over the entire hearth and that should not come in the way of free passage of the top hot flame from one end to the other end of the hearth.

2.Melting down:- The burners are turned on in full.As the charge melts , Si and Mn are oxidised according to the following reactions:-
$Si+2FeO=SiO_2+2Fe$
$Mn+FeO=MnO+Fe$

- The initial slag is formed as FeO–MnO–SiO2 type acidic slag, which react with basic lining (i.e. CaO and MgO) at the early stage.
- Carbon in metal reacts with oxygen to form CO gas evolution which create boiling action to the bath, that is known as **carbon boil**; since this boiling is due to oxygen supply from the iron ore, so this boiling action isknown as**ore boil.**Due to that, part of the slag comes out from the furnace through the middle doorautomatically and drops into a slag pocket.
- By the ore boil, the slag is flushing out from the furnace through the front doors, and this is known as**front flushing of slag.**

3. Oxidation and refining:-

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 (flouorspar) 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.

$2[P]+5(FeO)=(P_2O_5)+5Fe$

$4(CaO)+(P_2O_5)=(4CaO.P_2O_5)$

4. Finishing:-

In this process , excess oxygen in the bath is rmoved 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 (P2O5) in solution depends on its oxygen potential. Hence, too much reduction of (FeO) content of the slag leads to reversion reaction:
$(P_2O_5)=2[P]+5(O)$
In order to avoid such possibilities, the final deoxidation is carried out in the ladle by the addition of Al.

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2.1 PRINCIPLES OF STEEL MAKING

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

1. $[Fe] + [O] = (FeO)$
2. $[C] + [O] =\{CO\}$
3. $[Si] + 2[O] = (SiO_2)$
4. $[Mn] + [O] = (MnO)$
5. $2[P] + 5[O] = (P_2O_5)$
6. $[S] + (CaO) = (CaS) +[O]$

[ ] 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.

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).

Basic oxide: CaO, MgO, FeO, MnO

Acid Oxides: SiO_2, $P2O_5$.

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

Acid steel making process	**Basic steel making process**
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.

LECTURE-05

2.3.1 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-

$$[C] + 1/2\ O_2 = CO_g$$

$$[C] + [O] = CO_g$$

$$[C] + (FeO)_l = Fe_l + CO_g$$

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.

- 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 forcedly (by argon stirring) in order to intensify the diffusion of C to the reaction site so as to increase the rate of C oxidation.

- 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

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 2σ/r i.e.

, $p_{CO}^{ev} \geq p_m + p_{sl} + p_{at} + 2\sigma/r$ The of 2σ/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 possiblemonoxid

LECTURE-06

2.3 Oxidation of Iron, Silicon and Manganese

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.

$[Fe] + [O] = (FeO)$ Iron Oxidation
$[Mn] + [O] = (MnO)$
$[Si] + 2[O] = (SiO_2)$ Desiliconization
$[C] + [O] = \{CO\}$ Decarburization
$2[P] + 5[O] = (P_2O_5)$ Dephosphorization

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.

2.3.2 Oxidation and reduction of manganese

Behavoiur 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 Mn_3C.

Mn can be oxidized to form MnO, MnO_2, Mn_2O_3 etc. Under steel making conditions (high temperature) MnO is most stable, so, MnO is only considered.

[Mn] + [O] = (MnO) ………………$\Delta G° = -244521 + 108.78\ T_2$……………….(1)
[Mn] + (FeO) = (MnO) + [Fe] …… $\Delta G° = -123516 + 56.41\ T$ ....(2)
[Mn] + ½ {O_2} = (MnO)……………..$\Delta G_o = -361464 + 106.39T$ .... (3)

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;

Conditions for oxidation of Mn:
- High activity of FeO in slag which means an oxidizing slag
- High value of K*

$Log\ K_* = 7940T - 3.17$

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

2.3.3 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 exothermicone.

➢ 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 :
[Si] + 2 [O] = (SiO_2) $\Delta_o = -542165 + 202.83T$
➢ (b) oxygen in gaseous phase :

[Si] + O_2 = (SiO_2) $\Delta_o = -775851 + 198.04T$

➢ (c) iron oxides in the slag :

$[Si] + 2 [FeO] = (SiO_2) + 2[Fe]$ $\Delta_o = -29991 + 98.047T$

Favourable conditions for silicon oxidation are:
- Low temperature
- Oxidizing atmosphere
- Basic slag

LECTURE-07
2.3.4 Dephosphorization & Desulphurization

- 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.P2O5)

- 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.

- Dephosphorization Index (D_P)= Wt% P in slag/ Wt% P in metal= (% P_2O_5)/[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.

Favourable Conditions for Phosphorous removal
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 P2O5 in slag.

2.3.5 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

[FeS] + (CaO) = (CaS) + (FeO)

Desulphurization index= (%S)/[%S]For a fixed basicity the index is inversely proportional to the ironoxide content of the slag or the [O] content of the metal.
e (%S)/[S] α1/(%FeO)
Similarly for a fixed (FeO) content of slag
(%S)/[%S] α(%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-08

3.1 RAW MATERIALS FOR STEEL MAKING

The main raw materials for steelmaking are as follows:

- Sources of metallic iron,
- Oxidizing agents,
- Fluxes,coolant
- Deoxidizers and alloy additions,
- Furnace refractory and
- Sources of heat.

SOURCES OF METALLIC IRON

Primary source of metallic iron is hot metal from blast furnace. Hot metal, which is molten form of impure iron, is the product of blast furnace after the reduction of iron ore. Pig iron is a solid form of impure iron after cast in a small piece.
Secondary sources of metallic iron are (i) steel scrap, (ii) sponge iron/DRI/HBI and (iii) iron carbide.

OXIDIZING AGENT

The oxidizing agents used for steelmaking are air, oxygen and iron oxide.

- ➢ Air was used for the Bessemer processes; nitrogen present in air was dissolved in liquid steel and that made steel brittle.
- ➢ Iron oxide is used in the form of (a) lump iron ore (Fe_2O_3) and (b) mill scale (Fe_3O_4, Fe_2O_3).
  (a) Iron ore contains 60–67% iron and 25–29% oxygen.
  (b) Mill scale is nearly pure form of oxides (93–95% Fe_3O_4), produced during hot deforming (i.e. rolling, forging, etc.) of steel.
- ➢ The use of iron oxide as an oxidizing agent results in improving the iron yield of the process, but it needs thermal energy to dissociate itself and make oxygen available for refining reactions.

FLUXES

A flux is a substance which is added during smelting and refining to bring down the softening point of the gangue materials, to lower down the viscosity of slag and to decrease the activity of some component to make it stable in the slag phase. Lime (CaO) is generally added during steelmaking to make the slag basic enough to retain phosphorus and sulphur in the slag phase. Fluorspar (CaF_2) and bauxite (Al_2O_3) are also added to decrease the viscosity of slags. Limestone is not used at all, except for open-hearth furnace, due to a lot of heatabsorbed during calcination of limestone as well as that takes time to dissociate; hence, the availability of CaO become late for slag formation.

Typical analyses of flfluxes are as follows:
(i) Lime: 90–95% CaO, 2–3% MgO, 1.5% SiO_2, 0.1–0.2% S.
(ii) Calcined dolomite: 55% CaO, 34–38% MgO, 3–4% SiO_2, 0.01% S.
(iii) Bauxite: 54–56% Al_2O_3, 11–14% Fe_2O_3, 1–2% SiO_2, 1–2% TiO_2.
(iv) Fluorspar (spar): 75–85% CaF_2, 10% max. SiO_2, 0.8% max. S.

Steel scrap acts as cooling material in steelmaking. Iron ore also acts as cooling material in Steelmaking.

Deoxidizers and Alloy Additions

Since steelmaking is an oxidizing process, some oxygen must be dissolved in liquid steel. To remove the excess oxygen in liquid steel, deoxidizers are used. Various deoxidizers are used in steelmaking as follows:
(i) Elements like Si (as Fe–Si), Mn (as Fe–Mn), Al, etc., are added primarily as common deoxidizers.
(ii) Elements like Zr, B, Ti, etc., are added for deoxidation in special cases.

Furnace Refractory

Steelmaking furnace is lined by suitable refractory materials. The lining is eroded during steelmaking due to chemical attract by the slag; hence, the material of lining is also required as a recurring consumable raw material.
(a) Acid furnace: fireclay, silica sand.
(b) Basic furnace: dolomite, dolomite enriched with magnesite, chrome-magnesite, etc. Typical composition of stabilized dolomite brick is 40.0% CaO, 40.3% MgO, 14.4% SiO_2, 3.5% Fe_2O_3 and 1.5% Al_2O_3.

Sources of Heat

In autogenous or pneumatic processes, heat of oxidations due to the refifining of impurities is enough to meet the heat requirement of steelmaking; that is, no extra heats are required from outside. The amount of heat generated is always more than necessary so that scrap and/or iron ore is charged to keep the bath temperature within required limits. External heats are required for non-autogenous processes. The sources of heats are as follows:
(a) **Chemical**: (i) liquid: oils, tar, etc., (ii) gas: producer gas, water gas, coke oven gas, natural gas and blast furnace gas. Chemical fuels should be burnt with excess air.
(b) **Electrical**: (i) induction heating, (ii) arc heating: AC and DC.

3.2 Important raw materials available in india

Magnetite The most important and best type of iron ore is magnetite.It has a metallic iron content of 72 percent. Karnataka, Andhra Pradesh, Rajasthan, Tamil Nadu, Goa, and Kerala are among the states where it can be found.

Hematite -80 per cent of haematite reserves are in Odisha, Jharkhand, Chhattisgarh and Andhra Pradesh.In the western section, Karnataka, Maharashtra and Goa has this kind of ore.

Limestone -Almost all the states of India produce some quantity of limestone.Over three-fourths of the total limestone of India is produced by Madhya Pradesh, Rajasthan, Andhra Pradesh, Gujarat, Chhattisgarh and Tamil Nadu.

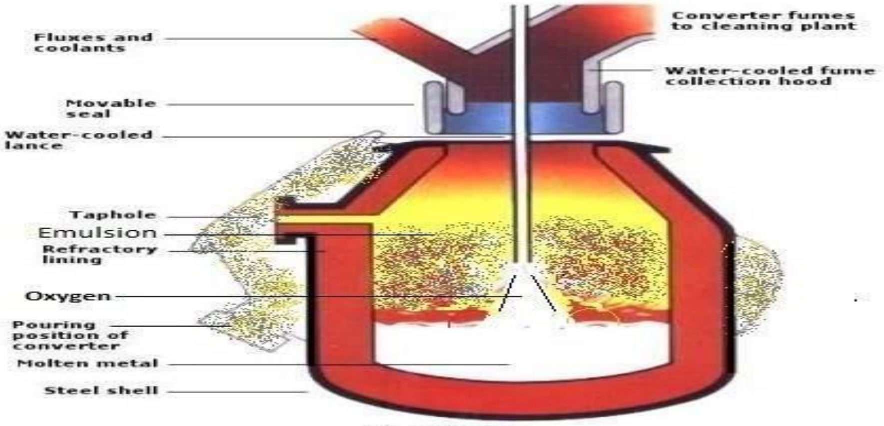
LECTURE-09

4.1 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
- 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



LD-converter

4.2 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-symetrical 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°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 1/3rd 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 .
- 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:

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

- 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)

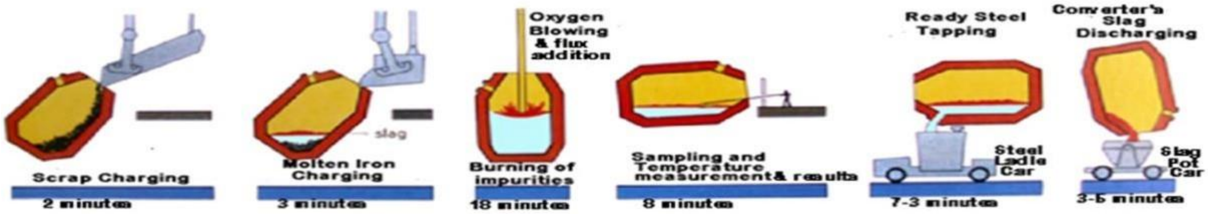
IMPURITY	REQUIRED	RANGE USED
C	4.1-4.3	4.00-4.50
P	01-0.25	0.05-0.45
Si	0.50-0.85	0.65-1.40
Mn	0.5-0.8	0.40-2.50
S	0.02-0.03	0.02-0.06

- √ 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



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)

4.3 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 trmendous increase in interfacial areas of metal slag, metal-gas and slag-gas systems.

Sequence of Impurity Eliminatio

- 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- SiO2 and the curve goes down with Silicon curve.
- Due to lime dissolution basicity increases CaO-SiO2 formed & (FeO), (MnO) rejected
- Mn reversion takes place: (MnO)+[C]={Mn}+{CO} & Curve goes up.
- At the end Carbon-Oxygen reaction decreases (FeO) increases ,oxidizes Mn again & the curve goes down again.

4.4 Steel-

- The oxygen blown steel has a very low nitrogen content (<0.004).
- Earlier soft steels (c>0.15%) were produced but now high carbon steel , alloy steel and stainless steel etc are produced .
- LD steels are characterized by their low P,N,C contents.
- Carbon content can be reduced to 0.04%.
- P 0.02 wt% , 0.2% MN ,0.015 wt% S .
- Tensile strength and yield point values very well correlate to chemical composition of LD steel.
- LD steel is superior quality in many aspects to open hearth steel .

SLAG

- BASICITY IS HIGH.
- Excess lime prolongs lining life and ensures complete dephosphorisation and the role layed by the slag in converter is very important .
- Composition

  CaO = 47.88%   FeO = 26.30%   SiO2 = 12.16%
  MnO = 0.28%   MgO = 0.82%   Al2O3 = 1.22%
  P205 = 3.33%   S= 0.28%

Advantages

4.5 LD. It's a very fast process :Heat 40-50min

- It is autogenous, or self-sufficient in energy

There is some drawback in LD process likes:
(i) more splashing and slopping,
(ii) slow slag-metal reaction,
(iii) poor bath agitation,
(iv) over oxidation of slag

Lecture-10

4.6 Oxygen Bottom blowing Process

Main advantages of BOTTOM BLOWING processes are as follows:
(i) No splashing and slopping,
(ii) Quick slag-metal reaction,
(iii) Vigorous bath agitation,
(iv) Decreasing over oxidation of slag.

There are two processes: **(i) OBM and (ii) LWS**

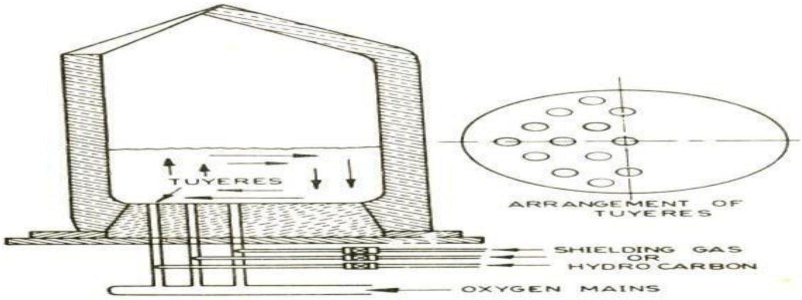
OBM

- To decease 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 drasticall in bottom blowing process.
- The problem was solved by blowing oxygen along with protective fluid (Propane/gaseous♣ Hydrocarbon) from bottom developed by the Maximillianshutte 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 os stainless steel embeded 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 turbulance, damage during charging and higher working volume

A few bigger tuyeres is better than large no of fine tuyeres w.r.t. mentainance.



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.

Main advantages of OBM process:

(i) More efficient agitation of the bath, as a result there are no temperature and concentration gradients that causes slopping,

(ii) Oxygen utilization is so efficient that very little oxygen is available for post-combustion of CO gas above the bath,

(iii) Since there is no emulsification of slag and metal, it is necessary to inject lime as a fine powder along with oxygen,

(iv) Reaction proceed more efficiently,

(v) Better iron yield

(vi) Better phosphorus and sulphur partition between metal and slag,

(vii) Higher manganese content and lower oxygen content, hence reduce ferro-alloy consumption;

(viii) Operation of the process is very near to equilibrium.

Disadvantages of OBM process:

(i) Bottom of the converter should have arrangement for injection of at least three gases (oxygen, hydrocarbon and nitrogen)

(ii) OBM converter can only be titled in one direction due to the position of tuyeres in one side of the vessel,

(iii) Nitrogen content of OBM steel is higher than LD steel,

(iv) Cost of refractory per tonne of steel in OBM is higher than LD because bottom does not give the same life of the vessel .

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 stirring10 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 coeeficient	Higher P,S partition coeeficient
12	Less Alloy recovery	Better Alloy recovery

KALDO PROCESS

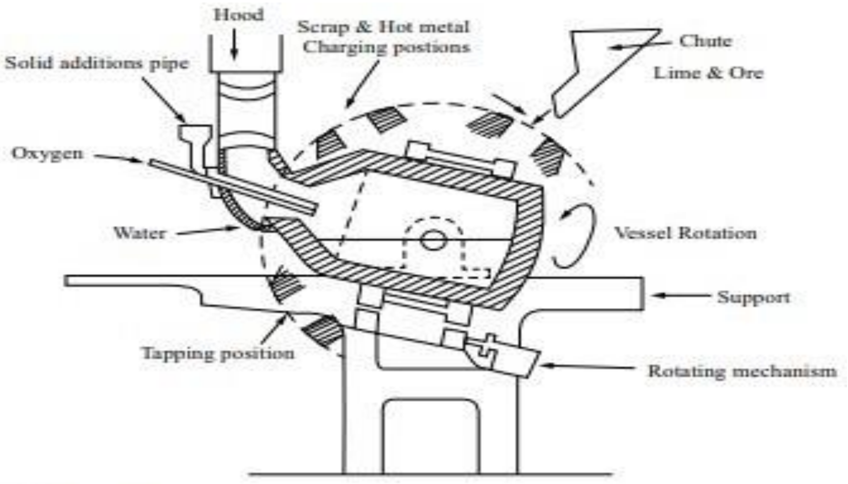
- Kaldo process was developed by Professor B. Kalling in Sweden (1954). The largest converter (8.5 m length and 5.5 m diameter, 135 t capacity) can be tilted at least 180° and usually 360°, to permit charging, tapping, etc .
- Converter is inclined during operation at 16–20° with horizontal and speed of rotation up to 25–30 rpm to its own axis. Metal slides back along the lining wall. Oxygen is injected through water-cooled lance which inclined at 22–30° to the horizontal and oscillates about 15–20 times per minutes.
- Due to slag-metal contact is very good, so reactions will be accelerated, i.e. faster
- It is possible to reduce P very low level (i.e. 0.025%) while C is 0.5% or more. At very high speed (>30 rpm), formation of cascading occurs, i.e. metal droplets fall through gaseous atmosphere and oxidized.
- Initial hot metal composition is 3.5–4.0% C, 1.8–2.0% P, 0.2–0.3% Si, 0.5% Mn, 0.05–0.06% S; after lower down speed of rotation to 10–12 rpm and decrease the angle of lance; C and P comes down to 0.4% and 0.11%, respectively .
- First slag (52% CaO, 8% SiO_2, 18% P_2O_5, 3.5% MgO and 9% FeO) is taken out. Fresh lime and iron ore are charged at low speed of rotation (6–8 rpm) and low oxygen flow rate to form second slag .
- C and P further comes down to 0.1% and 0.03%, respectively. After second slag off again fresh lime and iron ore are charged to form third slag (43% CaO, 4% SiO_2, 7% P_2O_5, 6.5% MgO and 27% FeO); C and P further comes down to 0.05% and 0.018%, respectively .
- Lime addition is 13–14% of hot metal. Lancing time is 35–40 min. Tap-to-tap time is 40–60 min.
- Converter is lined with tar bonded dolomite bricks (0.35–0.45 m thick) and lining life is only 50 heats.

Advantages:

1. High iron yield,
2. Less iron loss in the slag,
3. Low sulphur, low nitrogen and low oxygen content in steel,
4. Less blowing time, i.e. tap-to-tap time is less,
5. High amount of scrap/iron ore can be charged as coolant

Problems:

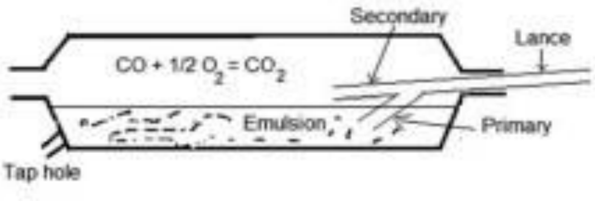
(i) lining life is relatively short (50 heats only) and
(ii) (ii) mechanical problem to rotate large furnace



Kaldo process [1]

Rotor Process

- Rotor process was developed in Germany (1952).
- 100–120 t capacity vessel has 4.5 m diameter and 15 m long.
- The speed of rotation is low (0.2–4.0 rpm).
- There are two lances: (i) water-cooled primary lance (made of copper), incline 27–45° to the bath surface, oxygen is passed at the rate of 70– 85 N m3 /min at 6–12 atm pressure; and (ii) secondary lance with 2–4 nozzles to supply oxygen for burning CO gas within the vessel and also supply lime powder (50%) .
- Dolomite/magnesite bricks are used for vessel lining, life is 400–500 heats.
- 40–45% scrap can be charged as coolant.
- Tap-to-tap time is 120–150 min (including hot repair of the furnace).
- Lining materials used for lining: (i) rammed tar dolomite, (ii) unburnt tar dolomite brick, (iii) burnt dolomite brick and (iv) magnesite ramming mass



LECTURE-11

Combined Blowing Processes

KMS Process

Technical development was done by Klockner, West Germany for using Maxshutte tuyeres to increase the scrap melting capability of the standard OBM process by modification as Klockner–Maxshutte Steelmaking or Klockner–Maxshutte Scrapmelting (KMS) process. Figure 15.26 shows KMS process.

Aim of the process:

1. Good heat transfer and energy utilization by the action of the burners to the scrap charged, by using bottom tuyeres as oxy-fuel burners for scrap pre-heating,
2. Protection of the refractory lining against high flame temperatures of burners by the scrap,
3. A low-cost method for steel production.

This process is developed to provide increased scrap melting capability through:

(i) Post-combustion of converter off-gases,
(ii) Pre-heating of scrap within the converter using the bottom tuyeres as oxy-fuel burners,
(iii) Introducing external energy by carbon injection during the process blowing,
(iv) Introducing the blowing simultaneously from top and bottom of the converter

These developments can be divided into three types:

(i) Simultaneous top and bottom blowing ! partial combustion of CO gas inside the furnace

(ii) Injection of fuel oil through bottom tuyeres (which act as burners) for pre-heating of scrap before charging hot metal to the converter ! scrap pre-heated through the bottom tuyeres, the fuel efficiency can increased more than twice ! without much oxidizing of iron in the scrap this can be achieved by pre-heating of the scrap and partial combustion of CO gas inside the converter.

(iii) Injection of carbon in the form of coke or low volatile coal into the melt during oxygen lancing ! combined with pre-heating of the scrap, partial combustion of CO gas and injection of carbon ! 50% scrap can be charged

The steps for KMS process are as follows

1. Furnace is empty, refractory is hot. All tuyeres are protected from over-heating by low flow rate of air or nitrogen gas
2. Scrap is charged in one or two baskets, furnace is turned vertically.
3. Pre-heating starts with oil and oxygen passing through the bottom tuyeres, which act as burners.
4. Pre-heating is stopped according to the calculated time (by computer) based on heat and material balance.
5. Furnace is turned horizontal to receive hot metal charge and then turned vertically after bottom tuyeres get high flow rate of nitrogen gas.
6. Blowing starts by switching over from nitrogen to oxygen gas through bottom and through side tuyeres. Natural gas (or propane) is used as protective gas for tuyeres. Powder lime is added as required with oxygen gas through the bottom tuyeres.
7. Blowing is stopped, according to computer calculated amount of total oxygen required, by switching over again to nitrogen gas and furnace is turned down for sampling

Advantages:

• It can continue steel production at a high level with scrap melting when hot metal production is reduced by unforeseen mishaps.

• It is the ability to reduce production costs, substituting usually more expensive hot metal with less costly scrap and oxy-fuel

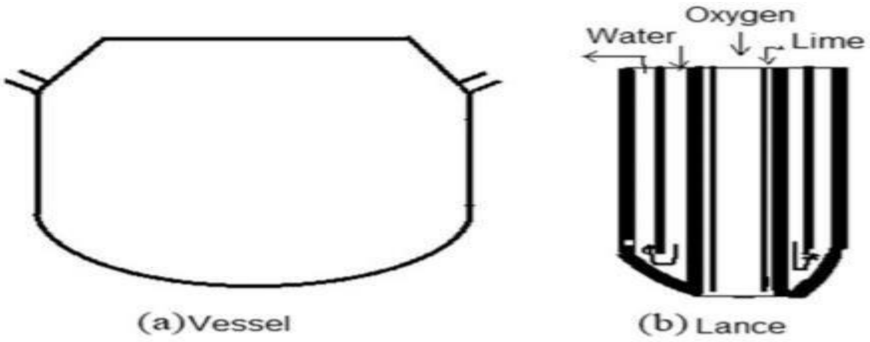
.• It is the ability to increase steel production for a given amount of hot metal

LECTURE-12

4.7 LD-AC/OLP

- LD process was originally designed to refine hot metal containing less than 0.4% phosphorus. LD Process was modified by the CNRM in Belgium to refine high phosphorus hot metal (>1.5% P), by introducing major portion of lime charge as powder through the lance along with oxygen; and this process was put into commercial practice at the works of ARBED in Luxembourg.
- Hence, the process is known as incorporating Linz-Donawitz with ARBED and CNRM (LD-AC). This process was developed for high phosphorus (1.5–2.0% P) hot metal particularly for UK and European countries; it is not applicable for Indian hot metal (0.4% P)
- Vessel shape is altered to a tulip shape (i.e. like tulip flower) with two tap holes at opposite sides vessel volume is more (20%) than LD to accommodate extra slag volume generated due to high phosphorous in hot metal.
- High phosphorous content hot metal is charged along with scrap, ore, bauxite and lump lime in the vessel. Oxygen is lancing at high velocity to the metal bath to oxidize the impurities and raising the temperature of metal and slag.
- Much of the lime (2/3rd) in finely powder (0.01–2.0 mm) form is charged along with oxygen lancing (after 5 min of oxygen lancing) to form slag quickly and to carry away the oxides from the metal. Rest 1/3rd of lime is charged as lump (40–60 mm) condition.

- Phosphorous content in hot metal too high, so phosphorous cannot remove in one stage. Phosphorous can remove in two or three stages: Hot metal: 3.8–3.5% C, >1.5% P
- First slag off (45–50% CaO, 18–20% P_2O_5, 5–8% SiO_2 and 10–11% FeO) and composition of Bath: 1.0–1.5% C, 0.2–0.3% P,
- Second slag off (50% CaO, 10% P_2O_5, 2–4% SiO_2, 20–25% FeO, few% of MnO and MgO) and composition of bath: 0.2% C, 0.04% P, 0.04% S,
- Third slag off and composition of bath: 0.05–0.1% C, 0.01% P, 0.01% S.
- Lance is then carefully lowered to control the foam of the slag, after 15 min blowing stopped and first slag is drained out (not completely), some slag keeps on the bath (this slag is known as pre-formed slag) for formation of second slag quickly after adding powder lime.
- After first slag off,carbon in metal is brought down to 1.0–1.5% and 0.2–0.3% P. The remaining C and P are removed by the second slag. This is known as double slag practice. Lime powder helps to form the second slag and shortens the lancing time. Oxygen is blown again for 5–6 min; at the end of refining sample is taken and analysed. Temperature is measured, and heat is tapped leaving second slag in the vessel for the next heat .



(a)Vessel (b) Lance

Fig. 15.17 a LD-AC vessel, b lance

LECTURE-13

5.1 Electric Furnace Processes

The main furnaces that are used to produce steel through secondary route are (1) electric arc furnaces (EAF) and (2) induction melting furnaces (IMF).

(1) Arc furnaces: Arc furnaces are two types: (i) direct arc and (ii) indirect arc.

Direct arc furnace: In a direct arc furnace, current flows from the electrode to the charge and heat is transferred directly from the arc to the charge and part of heat is also generated in the charge itself. Three electrodes arc furnace was developed by Paul Heroult (in France) for steelmaking in 1899. In an electric arc furnace, scrap and or sponge iron/DRI is melted and converted into high-quality steel by using power electric arcs formed between a cathode and anode.

There are two types of direct arc furnaces: (a) AC arc furnace and (b) DC arc furnace.

(a) **Alternate current** (AC) arc furnaces has three electrodes and they are fed from a three-phase supply input, one phase connected to each electrode and the charge is the neutral point (as shown in Fig. 16.2). There are acid lining EAF and basic lining EAF;Basic furnace is most popular due to removal of sulphur and phosphorous from the melt.

(b) **Direct current** (DC) arc furnace has only a single electrode which acts as cathode and the bottom of the vessel act as anode . These furnaces are applicable onlly in large sizes.

(ii) **Indirect arc furnace**: In an indirect arc furnace, arc is struck between two carbon electrodes and heat is transferred to the charge by radiations . Indirect arc furrnaces are of small capacities and do not developed steelmaking temperature readily. These furnaces are generally used in non-ferrous foundries for low-temperature melting.

Main Parts of EAF

1. Furnace body, i.e. shell, hearth, wall and spout, door, etc.,
2. Roof and roof-lifting arrangements,
3. Electrodes, their holders and supports,
4. Gears for furnace movements and
5. Electrical equipments, i.e. the transformer, cables, electrode control mechanism, etc.

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 is0.2 to 0.22.

Roof

The roof 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 electrode.

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 m 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.

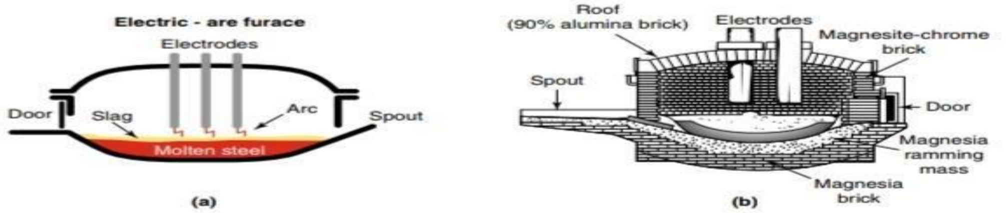


Fig. 16.6 Basic layout of an EAF [6]. **a** Halved egg shape hearth, **b** schematic diagram. (a) Permission from Dr. Dmitri Kopeliovich)

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:

1. 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.

2. 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.

3. 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.

4. 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.

5. 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.

5.2 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. Flourspar, $CaF2$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:
- $2P+5(feO)+3(CaO)= (3CaO.P2O5)$
- 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:
- $2(FeO) + (CaC_2) = (CaO) + Fe + 2[CCO$
- $(CaO) + [FeS] = (CaS) + (FeO)$
- Carbide slag tends to recarburise the bath hence not suited for low carbon heats($C<0.15\%$). So Lime slag is made with lime, Fe-Si and Aluminium,No coke added.

5.3 Advantages of EAF

1. It requires less capital investment.
2. It requires less installation period.
3. Any grade and superior quality of steels can be produced from scrap/sponge iron.
4. Increasing availability of alternate iron sources, like sponge iron, hot metal, etc.
5. Alloying elements can be added directly to the furnace with minimum loss, and hence, composition of bath can be controlled easily.
6. Temperature of the molten bath can be controlled within narrow limits.
7. Improvement in the operation, control, efficiency and high metallic yield and
8. It has readymade market and easily available of main raw material from local market .

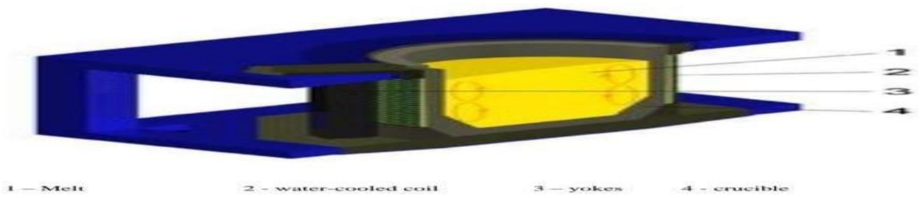
LECTURE-14

Introduction

5.4 Induction furnace

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 elments. 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 ements may be lost due to oxidation and must be re-added to the melt. Operating frequencies range from utilityfrequency (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.



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 isoften 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;iduction 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 ellectromagnetic polllution; 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 as a holding unit for high-melting-point alloys, such as cast iron.

5.5 Advantage:

- Overall heating work piece deformation is small, small power consumption.
- The pollution.
- Heating speed, the work piece surface oxidation and decarburization lighter.
- Surface hardened layer can be adjusted as needed, easy to control.
- 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.
- Hardened layer marten site smaller, hardness, strength, toughness, are higher.
- 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.

6.1. a AJAX PROCESS

- ➢ This process Was first developed in UK at Appleby Frodingham steel co, in 1957.
- ➢ The furnace is essentially a titlting open Hearth furnace .
- ➢ The end wall, ports, down takes, slag pockets and checkeres were suitably altered keeping the general design of open hearth furnace in view.
- ➢ The downtake, slag pocket and checkeres are cylindrical in shape and covered with cylindrical steel shell with appropriate opening and flanges for fastening them with each other place. The furnace campaign depended only on roof and hearth life.
- ➢ Due to a lot of fumes generates during oxygen refining led to clogging of checkers, so Gas cleaning facilities were provided .
- ➢ The furnace is fixed by coke oven gas from each side through the burners .
- ➢ One water cooled lance was provided on each side.
- ➢ It was alternatively used with the direction of fuel firing and were completely with drawn when not blowing .
- ➢ The lance angle 27-34 degree to the surface during blowing(3 nozzles).
- ➢ Oxygen was blown at 5-6 atm pressure and flow rate 30-35 m3/min .

OPERATION

- √ Scrap is charged in the furnace and was preheated by fuel firing.
- √ The hot metal was poured in andfuel supply pt off.
- √ Oxygen blowing was immediately started from or end by lowering the lance inside the furnace.
- √ At the end of usual fuel cycle time it was withdrawn and one on the other side was now inserted and lancing continued.
- √ The process was to refine Thomas grade iron .
- √ The blowing continued till carbon drops to 1% and phosphorus to 0.1-0.15%.
- √ By this time the fertilizer grade slag was ready and removed.
- √ Fresh lime and ore charged to form 2nd slag.
- √ Blowing was continued again till 0.4-0.5% and bath temperature 1570 ˚ .
- √ At this stage oxygen lancing is stopped and heat is finished as in OH practice .
- √ Tap to tap time 5-6 hrs.

ADVANTAGES

- √ **T**he process is fast and it could make a very wide range of steels.
- √ It runs on Thomas grade iron .
- √ The tilting design helps to remove slag and metal readily.
- √ The cost of production is less 60-70% of the standard OH practice .

DISADVANTAGES

- √ **T**he Fe content of slag is 10-20% as against 9-10% in standard O.H practice.

6.c . SPRAY STEEL MAKING PROCESS

- ➢ In this process the iron from blast furnace is poured through high porosity jets. The molten metal is immediately automised into a pipe spray and, in the brief period as the droplets fall into a receiver vessel, they are completely converted to steel. Lime and fluxes are continuously fed to form a slag.
- ➢ The spray of refined metal collects in a receiving ladle and slag runs off continuously.

- Before each run the receiving ladle is filled with steel scrap which acts as a coolant and also reduces the process cost (this process consumes 32-40 percent steel scrap). Since hot metal comes staight from the blast fumace runner, no heat is lost. Principle chemcial reactions take place out of contact with refractory walls of the vessel. In many ways the spray steel making gives nearly ideal conditions for refining by presenting the maximum surface of iron to the oxygen, thus enabling the maximum degree of chemical interactions to take place in the hortest possible time.

- ideally the process is carried near the blast furnace, so that no new buildings are required and no costs are involved in transporting liquid iron from one place to another.
- If for any reason the plant is situated away from the blast furnace then higher blast furnace tapping temperatures are desirable.
- The spray process is conducted in an enclosed chamber which is refractory lined and water cooled in parts. The catch ladle or receiving ladie is positioned underneath and waste gases are circulated through a main .

The speed of this reaction is such that all the undesirable elements get removed between the point of impact of the metal and oxygen and the surface of the sing below. In a Bessemer converter the maximum carbon removable rate is of the order of 0.5 percent per minute. A rough calculation indicates that the carbon removable rates in spray steel making re something 10 times greater than bessemer converter.

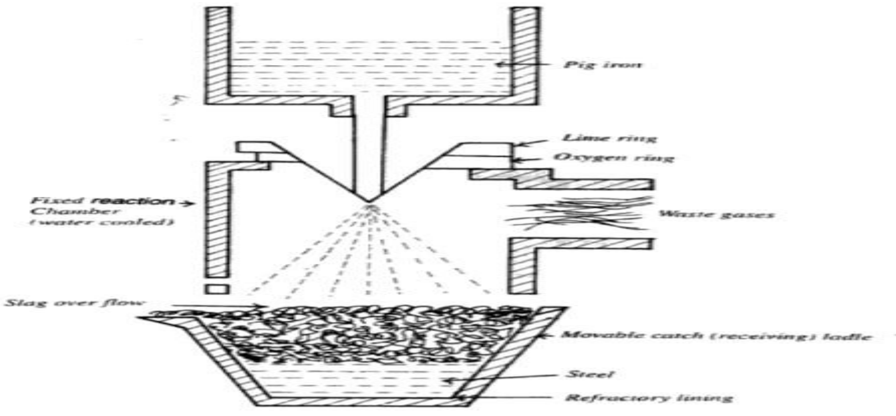


Fig. 3.8 : Spray Steel making process

LECTURE-15

Deoxidation of Steel

7.1

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 n non metallic oxide inclusion in solidified casting.
- The removal of residual oxygen content of refined steel is known as deoxidatin 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 slid 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

7.2 Difference between killed , semi-killed and rimming steel

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 outsiide.
- 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.

LECTURE-16

PIT SIDE PRACTICE

8.1 The entire processing of molten steel from the time of tapping until it is solidified including stripping from mould and reconditioning, etc. is known as casting pit practice or pit side practice .

Teeming Ladle

The ladle is lined with refractory to withstand the tapping temperature and weight of liquid metal. It is a welded or riveted steel shell, refractory lining may be bricked (most commonly adopted) or rammed. The teeming ladle has an opening in its bottom, it equipped with (i) a nozzle, (ii) a stopper rod and (iii) mechanism for raising and lowering the stopper rod to open or close the nozzle .

Teeming Methods

Teeming means pouring of liquid steel from ladle to an ingot mould. The method of teeming affects the ingot quality. A sound ingot gives high yield and less return scrap during subsequent working operations .

There are three types of teeming methods: (i) direct teeming, (ii) tundish teeming and (iii) bottom teeming

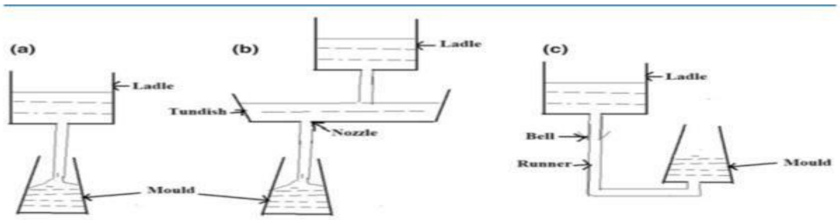


Fig. 18.8 Teeming methods: a direct teeming, b tundish teeming and c bottom teeming

Direct teeming: Direct teeming means pouring of liquid steel from ladle to an ingot mould directly.The rate of teeming increases as the nozzle diameter increases due to erosion. Magnesite and graphite nozzles are better than fireclay nozzle in this respect. Since th stream of liquid steel directly hits the bottom place of the mould, the wear of the bottom plate is quite severe in direct teeming. This method is used for rolling ingots.

Tundish teeming: Tundish teeming means pouring of liquid steel from ladle to tundish and then tundish to ingot mould . A tundish is inserted between the ladle and the ingot mould to ensure uniform rate of metal stream. The tundish has its own nozzle to regulate the flow. The tundish nozzle size is slightly bigger than the nozzle of ladle. Tundish with one or more, up to eight, nozzles are used to distribute the liquid metal evenly for all moulds at a time. This method reduces the total teeming time of a ladle, and the available super-heat in the metal can be utilized fully. This method is used for teeming forging and special alloy steel ingots.

Bottom teeming: Bottom teeming means pouring of liquid steel from ladle to a riser and at the bottom of the riser is connected with moulds; pouring of liquid steel is from riser to moulds . This is also known as uphill or indirect teeming. Liquid steel is teemed into a vertical runner which is connected at the bottom to the moulds. The top of the vertical runner is shaped like a bell to make teeming easy. The height of the runner is more than that of the moulds to ensure complete filling of the moulds. In general, one vertical runner is used to feed at least two or as many as twelve moulds (Fig. 18.9). The quality of the bottom teemed ingot is much superior, and the bottom plate wear is much less as compared to top teemed ingots. Use ofbottom teeming is economically justified only if the superior quality of the ingot is required.

Lecture -17

Ingot mould

Earlier molten steel is poured into permanent moulds to produce ingots for rolling, forging, etc.,except in steel foundry. The moulds are themselves massive cast iron castings of uniform shapes with a cross section like square,rectangular, round, polygonal, etc.

Types of ingot moulds:

(I) Narrow-end-up (NEU),

(II) Wide-end-up (WEU).

(I) **Narrow-end-up (NEU)**: NEU moulds can be lifted from the lugs to strip the ingot off the mould easily and efficiently. This is commonly used to produce rimming and semi-killed steel ingots for rolling .

ii) **Wide-end-up (WEU**): WEU moulds cannot be stripped off without the aid of additional mechanical arrangement. This is now to produce forging ingots of killed steels .

Hot Top

Fully de-oxidized or killed steel shrinks deeply on solidification and may lead to the formation of ingot pipe. Use of hot top (height 30–60 cm) acts as a reservoir to liquid metal to the main part of the ingot and avoids the formation of such a pipe which otherwise leads to excessive loss of ingot yield during working. The shrinkage cavity is than mainly confined to the hot top region. Hot top is also called a feeder head . Hot top is a cast iron box which is lined from inside with fireclay bricks and is generally placed on top of the wide-end-up (WEU) moulds

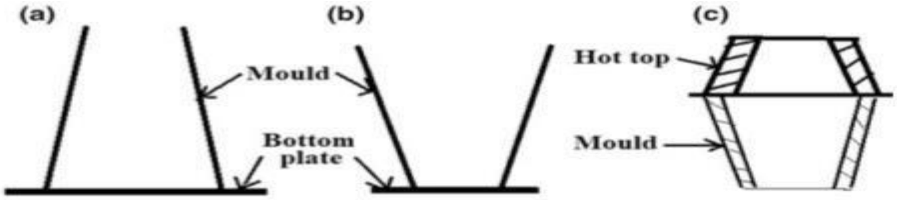


Fig. 18.2 Types of ingot mould: **a** narrow-end-up (NEU), **b** wide-end-up (WEU) and **c** WEU with hot top

8.2 INGOT DEFECTS

1. **Pipe formation or piping,**
2. **Blow holes**
3. **Columnar structure,**
4. **Segregation,**
5. **Non-metallic inclusions,**
6. **Internal rupture and hairline cracking and**
7. **Surface defects.**

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. 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.

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.

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 = (concentration of solute in solid/ concentration of solute in solid in liquid)

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.

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 $Al2O3$ are undesirable.

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

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 -18

9.1 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 saviing**.**

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.

- 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.

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 rant and superheat which is required for stand 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.

3. **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 sped 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.

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 product 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.

9.2 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.

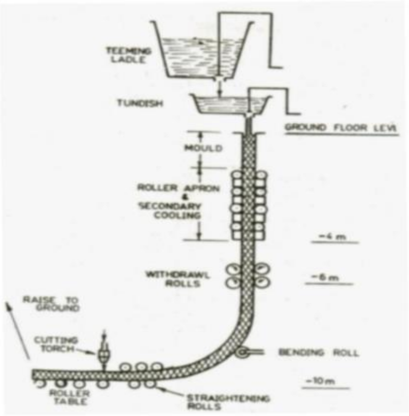
The Vertical-Mould Horizontal Discharge Type

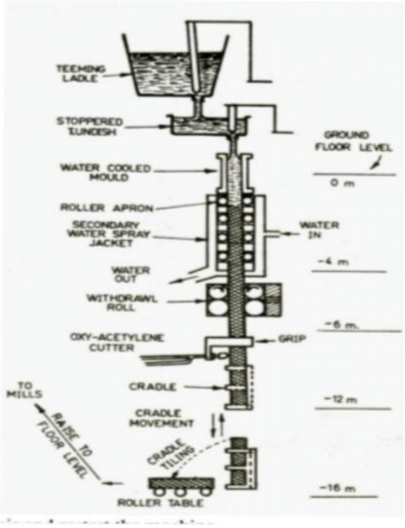
√ This is a modification over the earlier vertical design to reduce the overall height of the machine. The mould, roller apron and the pinch rolls are similar in design to those of vertical machine.

√ 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.

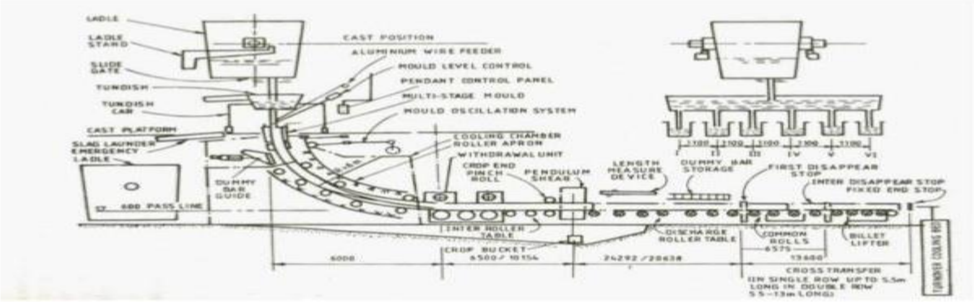
√ It is popular for small and medium sized cross-sections





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



9.3 Mould Maintenance

Mould powder of continuous casting is used primarily to facilitate the smooth passage of casting through the mould. It is also known as casting powder and mould flux . Mould powder plays an important role in the continuous casting of liquid steels. It is one of the most critical and influential factors for smooth casting of the liquid steel. The functions of a mould powder in continuous casting are as follows:

(a) To insulate the surface of the mould and stop any freezing,
(b) To prevent re-oxidation of cast surface in the mould,
(c) To achieve a uniform heat transfer between the solidifying cast shell and the water-cooled surface of the mould,
(d) To act as a lubricant and reduce the friction between mould and cast shell and
(e) To absorb inclusions from the molten steel

9.4 Advantages Os Continuous Casting

1. The yield improves by 10–20% than that of ingot practice.
2. Concast gives saving in energy due to elimination of ingot reheating, primary rolling, etc.
Energy requirement for: (a) coke oven ! BF ! BOF ! Concast is 26.14 GJ/t of billet;
3. The quality of concast product is better than conventionally cast ingots. Concast have favourable grain size, less segregation and more homogeneous chemical composition due to rapid cooling.
4. The caster can be operated most effectively by online computer control.
5. Concast technique has much higher productivity and is comparatively less expensive over a long run.

9.5 Near-Net-Shape (NNS) Casting

The NNS casters are further classified into four different types depending on the thickness of slab or strip produced. These types are as follows

(i) Thin slab caster: It produces slabs of about 20–70 mm thickness and 1000–2000 mm width which can directly be taken to finishing stand of hot strip mill without any conditioning.

(ii) Strip caster: It produces strips of about 5–20 mm thickness which need some conditioning in the form of limited hot rolling to avoid cracking before further cold rolling.

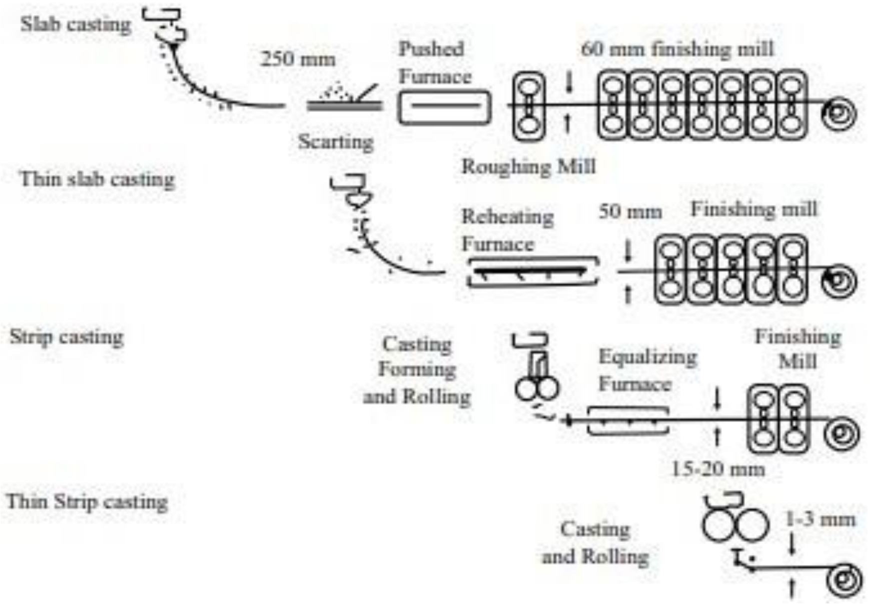
(iii) Thin strip caster: It produces strips less than 5 mm thickness which can directly be taken to cold rolling mill. (iv) Foil caster: It produces strips of about 0.02–0.5 mm thickness which can directly be used without further working.

The developments in concast technology to shorten the process route are shown in Fig..

One of the important types of NNS casters is round continuous caster to produce a cast product of round cross section to produce seamless tubes.

The advantages of NNS casters are as follows:

- Comparatively lower capital investment operational and production cost,
- Improved quality of the product (i.e. minimization of segregation and uniform chemical composition of the cast), • Uniform physical and mechanical properties of the finish product
- Greater flexibility of production,
- Less energy consumption to produce steel strip or sheet.



NEAR NET SHAPE CASTER

LECTURE-19

10.A Degassing Practices

- ➢ During the primary steelmaking process, gases like oxygen, hydrogen and nitrogen are dissolved in the liquid steel. These gases have a harmful effect on the mechanical and physical properties of steel. Dissolved oxygen [O] from liquid steel cannot be removed as molecular oxygen {O2}, and it removal is termed as de-oxidation.
- ➢ The term de-gassing is used for the removal of dissolved hydrogen [H] and nitrogen [N] gases from liquid steel as molecular hydrogen {H2} and nitrogen {N2}. Since the de-gassing process of liquid steel is carried out in teeming ladles under vacuum, it is also known as vacuum de-gassing of liquid steel.

There are 3 methods of degassing which are in practice

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

Ladle De-gassing

A ladle de-gasser is used to reduce the concentrations of dissolved gases (H_2, N_2, O_2) in the liquid steel; homogenize the liquid steel composition and bath temperature; remove oxide inclusions from the liquid steel; and provide the conditions that are favourable for final de-sulphurization.

Vacuum De-gassing is practised in steel works to achieve the following main objectives

- To remove gases, such as hydrogen, nitrogen and oxygen from the steel,
- To produce steels of low to ultra-low carbon content (<30 ppm C),
- To produce steels within close chemical composition ranges,
- To improve steel cleanliness by removing part of the oxygen through vacuum de-oxidation and by the agglomeration and floating of non-metallic inclusions,
- To control pouring temperatures, especially for continuous casting operation.

Vacuum Arc De-gassing (VAD) Process

Vacuum arc de-gassing (VAD) process (Fig. 17.8) is a chamber de-gassing process with electrodes added for reheating the liquid steel. This is a single unit process in which the ladle sits in a vacuum chamber and is stirred by inert gas through porous plug at the bottom with provision for heating through electrodes and alloying additions. After addition of lime to the liquid steel in the ladle, arcing is carried out at a pressure of 250–300 mm Hg to raise the temperature and fuse the lime followed by short duration de-gassing, additions for chemistry adjustment and deep de-gassing to pressures as low as 1 mm Hg. Argon stirring is continued in all the operational steps, and the adjustment of flow rate is done for different operations being carried out during the VAD process. The heating rate is around 3–4 °C/min, and during heating, the rate of argon gas flow is kept on the lower side. In this system, under vacuum, carbon–oxygen reaction under the high-temperature arc is of great help in achieving low [O] content without any solid reaction product. Removal of [H] depends on

(i) argon flow rateon
(ii) pressure of vacuum chamber and (iii) initial [H] content. H_2 levels as low as 1.5 ppm are achieved caused by intense mass transfer by argon and low partial pressure of hydrogen gas because of dilution of liberated carbon monoxide gas.

The main advantage of this process is the high degree of de-sulphurization as high as 80% for production of steels with sulphur levels as low as 0.005%. VAD is now a widely used process to produce clean steel

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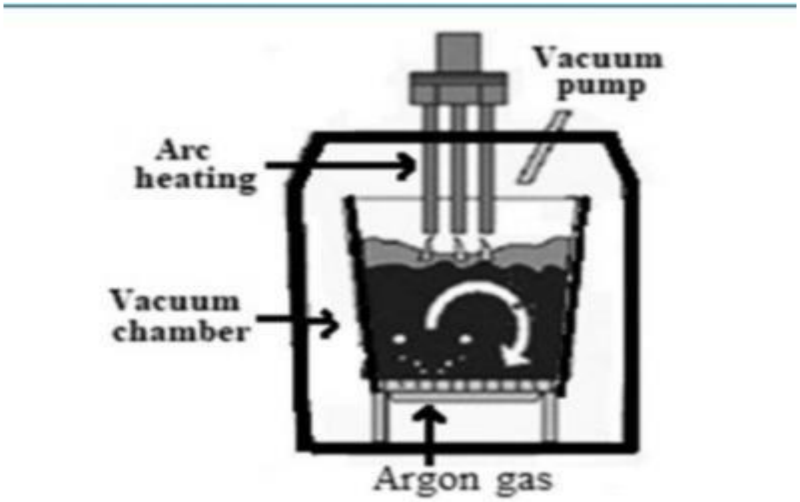


Liquid steel is held in a ladle which is put inside a vacuum chamber. Ladle is not filled completely, up to 30% of the total volume (i.e. ¼ height) should be provided free board; else liquid metal may spill over the edges. Steel may be stirred by bubbling an inert gas or by an electromagnetic stirrer while being exposed in vacuum. The teeming ladle, after tapping, is kept in a vacuum chamber which is then evacuated. Metallurgical reactions such as de-gassing, de-oxidation, de-carburization, de-sulphurization as well as alloying take place under vacuum conditions. The ladle is removed after a predetermine time when the correct teeming temperature of steel is reached. Teeming is carried out in open atmosphere. As the pressure fails (in vacuum), the vigorous in the ladle increases and the bath appears as if it is boiling.

From the small ladle, liquid stream is allowed to fall into a ladle which is evacuated. Ladle is closed from top with a special cover which contains exhaust opening. Liquid steel (with 25–30 °C super-heat) is tapped into ladle. Liquid steel flows down in the form of a stream from the furnace or ladle to another ladle or mould during its exposure to vacuum, i.e. molten steel is exposed to vacuum in the form of a stream of metal flowing from one vessel to another. Rapid rate of de-gassing take place due to large increase in surface area of steel in the form of falling droplets. The steel is poured either from a teeming ladle, a pony ladle or a tundish. It is received either in a ladle or in a mould kept inside a vacuum chamber.

LECTURE-20

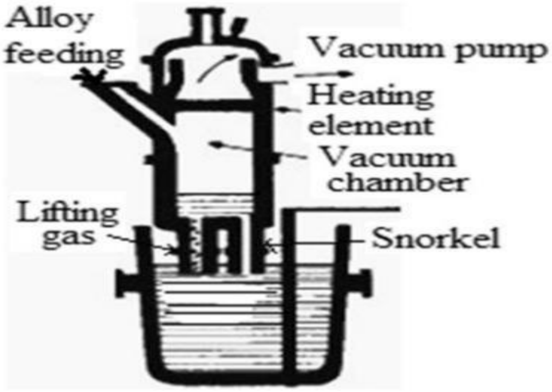
CIRCULATION DEGASSING

In the recirculation de-gassing practice, liquid steel can circulate in the vacuum chamber continuously by special arrangement. In this process, a vacuum chamber is positioned above the ladle possessing a snorkel or snorkels which are dipped into the liquid steel bath. Liquid steel is either continuous or intermittently circulated during its exposure to vacuum. There are two types of circulation de-gassing processes: (a) RH process and (b) DH process.

RH De-gassing Process

- RH process was developed by Rheinstahl Heinrich Shutte at Germany in 1957. The chamber is a cylindrical steel shell with two legs, called snorkels, openings at the top to provide for exhaust, alloy additions, observation and control .
- Circulation is carried out in a refractory lined chamber equipped with two snorkels which are immersed in the steel bath.
- By reducing the system pressure and by injecting inert gas into the up-leg snorkel, the liquid steel rises into the vacuum chamber where de-carburization and other reactions take place. The steel then recirculates back into the ladle through the down-leg snorkel.
- In this way, the entire heat can be rapidly treated. Cylindrical shell is lined with fireclay bricks in the upper portion and alumina (Al_2O_3) bricks in the lower portion to sustain high temperature.

- ➢ The legs are lined with Al_2O_3 refractories. Argon (Ar), the lifter gas, is injected at the inlet snorkel to increase the liquid steel velocity entering inlet snorkel.
- ➢ The diameter of up leg is greater than of the down leg to increase circulation rate . It is lined with fireclay bricks in the upper portion and high alumina bricks in the lower portion which directly meets liquid steel during de-gassing. The snorkels are lined with higher quality of Al_2O_3 bricks from both sides since they are dipped in liquid steel.



RH de-gassing

The operation of RH de-gasser includes as the following

- Heating of the cylindrical chamber to the desired temperature (varies in between 900 and 1500 °C),
- Lowering of the chamber into liquid steel up to a desired level,
- Evacuation of the chamber so that liquid begins to rise in the chamber,
- Introduction of the lifter gas which expands and creates a buoyant force to increase the speed of liquid steel rising into the inlet snorkel,

- De-gassing of the liquid steel in the chamber takes place and it flows back through the other snorkel into the ladle. This de-gassed steel is slightly cooler than steel in the ladle. Buoyancy force created by density difference (density of cooler liquid steel is more than the hot steel) stirs the bath.
- Rate of circulation of liquid steel in cylindrical chamber controls the de-gassing. Circulation rate depends upon amount of lifter gas and the degree of vacuum. Average rate of circulation of steel is nearly 12 t/min, and nearly 20 min are required to treat 100 t of steel to bring down the gas contents to the desired levels. The specific consumption of Ar is around 0.075 m^3/tonne.
- Additions of ferro-alloys can be made at the end of de-gassing depending on the ssuper-heat

RH process has several advantages which include

i)heat losses are relatively low,

(ii) alloy additions can be adjusted more closely and

(iii) small vacuum pumping capacity is adequate since smaller volume is to be evacuated as compared with ladle to ladle or stream de-gassing.

The technology of oxygen lancing into the RH vessel is developed by Kawasaki Steel, Japan known as KTB system. Oxygen is blown into the vacuum chamber through a water-cooled top lance, on the surface of the molten steel toaccelerate de-carburization as well as to generate heat by post-combustion of the CO gas evolving from the bath.

$\{CO_g\}+1/2O_2 = \{CO_2\}$

LECTURE-21

DH De-gassing Process

In Dortmund-Horder (DH) de-gassing process, a small portion, 10–15% of the total steel in the ladle, is treated at a time under vacuum. DH de-gassing process has a single snorkel and operates by repeatedly sucking the liquid steel into the vacuum chamber and then releasing it back into the ladle. The process is repeated until required de-gassing is achieved. It is also known as a lifter de-gassing Process. The vacuum chamber has one long leg (i.e. snorkel) to be dipped in the liquid steel. The arrangement of a vessel and the ladle is somewhat like RH process except that in DH de-gassing process the cylindrical vessel has one snorkel. The DH chamber is equipped with heating facility, alloying addition arrangement and exhaust system. Bottom of the cylindrical vessel is provided with a snorkel which can be dipped into the liquid steel (Fig. 17.12). Chamber is lined with fireclay bricks in the upper portion and high alumina bricks in the lower portion. The snorkel is lined with higher quality of Al2O3 bricks from both sides since it is dipped in liquid steel. The length of the snorkel is sufficiently large to realize the effect of atmospheric pressure on rise of steel in the snorkel.

The following are the important steps for operation the DH de-gassing process

- DH chamber is pre-heated and lowered in the ladle so that snorkel tip dips below the liquid steel surface.

- The evacuated chamber is moved up and down so that steel enters the chamber.

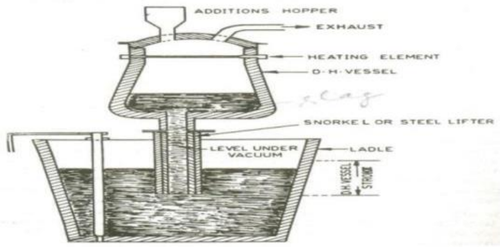
- The chamber is moved 50–60 cm with a cycle time of 20 s.

- Adequate de-gassing is possible in 20–30 cycles.

- A layer of slag is kept in the ladle to minimize heat losses.

- The DH de-gassing process can operate with lower super-heats compared with RH de-gassing

Since DH unit has heating facility.



LECTURE-22

10.1 Argon–Oxygen–De-carburization (AOD)

Argon–oxygen–de-carburization (AOD) process is developed at Linde Division of Union Carbide, USA, on the principle reducing the partial pressure of CO by injecting inert gas argon. More than 75% of stainless steel produced worldwide by this process. The development of argon–oxygen– De-carburization (AOD) process revolutionized stainless steelmaking. The process based on the dilution principle, i.e. decreasing partial pressure of CO gas by argon–oxygen gas mixture, allowed steelmakers to use lower-cost raw materials and to shorter the steelmaking times compared to the other processes.
Stainless steel production process mainly has two stages:
(i) melting and (ii) refining.

Meltdown of the charge materials, such as scrap and process alloy, takes place in an EAF which achieves highest energy density and short meltdown time. Carbon in melt should be maintained 0.7–0.8% for good carbon boil during refining.

Refining is carried out in a converter which has solid bottom with side tuyeres for blowing argon–oxygen gas mixture.
In the AOD process, the heat is treated under atmospheric conditions, top and side/bottom oxygen blowing techniques are applied. Inert gas is injected into the melt through side/bottom tuyeres to reduce the system partial pressure. This step drastically reduces chromium oxidation during de-carburization.
Oxygen blowing from top in AOD has the greatest impact on reducing process cost and increasing productivity. 75–90% of available heat energy from the combustion reactions is transferred to the molten bath, which decreases the consumption of ferrosilicon, increases the amount of cold charge and/or to reduce the EAF tap temperature.

The chromium is getting back from slag to metal by Fe–Si, 97% recovery take placed. The consumption of argon gas is 18–20 Nm3/t. Argon gas can be substitute by nitrogen gas in the initial stage of refining, due to higher cost of argon; at the end of refining, nitrogen can be replaced by argon.

The consumption of argon gas comes down to 8–10 Nm3/t. But nitrogen in stainless steel is increased from 50 to 1000 ppm. Nitrogen is austranite stabilizer, to replace nickel, it is used in 200 series(which contain: 17–19% Cr, 4–6% Ni, 9% Mn, 0.15% C and 0.25% N). Good de-sulphurization occurs by using Ar gas stirring at the end of refining. Total time taken for AOD is two hours, and lining life is 80 heats.

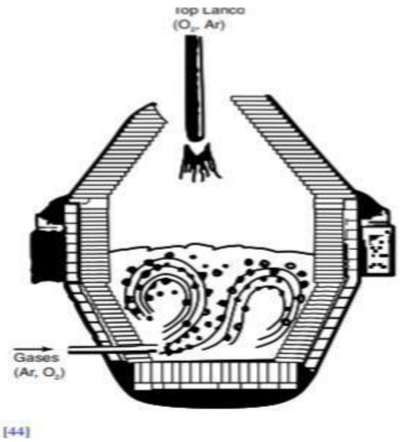


Fig. 16.33 AOD converter [44]

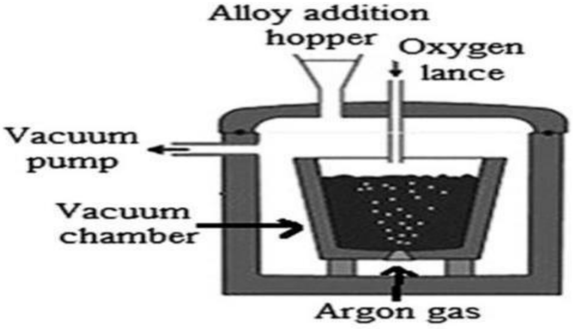
Major attributes of AOD process are as follows:

(i) Raw materials and processing flexibility, using low cost alloys,
(ii) Rapid de-carburization rate, i.e. high productivity,
(iii) Slag handling capability,
(iv) Scrap melting capability,
(v) Optimization of the melting furnace operation and cost,
(vi) Ease maintenance,
(vii) High product quality, low residual gas content.

LECTURE-23

10.1 Vacuum–Oxygen–De-carburization (VOD)

- In the vacuum process, the partial pressure of CO is kept low during refining at a markedly reduced pressure. Initially, charge is melted in an EAF, carbon in melt should be maintained 0.7–0.8% for good carbon boil during refining.
- Refining of the melt and subsequent reduction of chromium oxide takes place in a VOD vessel inside a vacuum chamber (Fig. 16.34). Oxygen is introduced by a lance that passes through a vacuum seal at the top of the vacuum vessel.
- At the same time, argon is injected through a porous plug from the bottom of the vessel to stir the bath. Refining is controlled by varying the distance between oxygen lance and top of bath, evacuation and purging rates.
- By continually lowering the chamber pressure down to less than 1l bar, the CO gas partial pressure can be reduced to a great extent than AOD process.
- 18% Cr is equilibrium with 0.45% C at 1600 °C and 1 atm pressure. Hence, lower carbon levels up to 0.02% can be successfully achieved, with 15–18% Cr at 1600 °C and low pressure, a comparatively reduced loss of chromium to the slag.
- Argon stirring is necessary; otherwise de-carburization reaction would be delayed due to lack of mass transfer of carbon from bottom to the surface where C–O reaction would be feasible.
- With the help of synthetic slag (2–3% weight of metal charge) and argon purging, 80% sulphur in metal is removed; and finally, metal contains 0.01% S. Argon gas consumption is 1 Nm3/t and time required for VOD is 2–2.5 h.chromium recovery is 97%. End of refining, vacuum is broken, and the bath is de-oxidized with Al or Fe–Si.



LECTURE -18

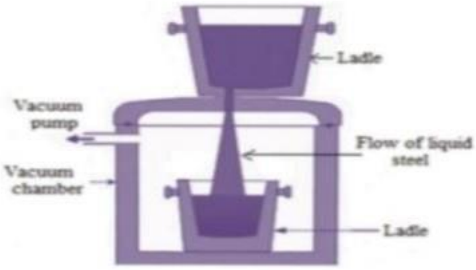
10.2 STREAM DEGASSING

In stream de-gassing, liquid steel is poured into another vessel which is under vacuum. Sudden exposure of liquid stream in vacuum leads to very rapid de-gassing due to the increased surface area created by breakup of stream into droplets. This process helps the hydrogen dissolved in steel, to be evacuated by a vacuum pump. The major amount of de-gassing occurs during the fall of liquid stream. The height of the pouring stream is an important design parameter.

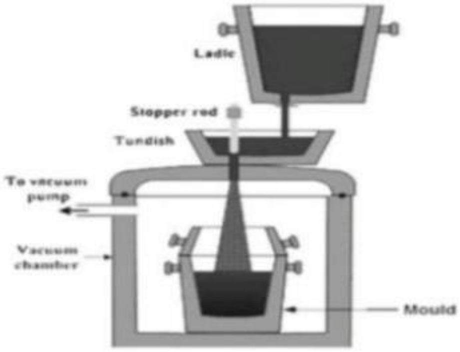
Stream de-gassing technology has the following variants in the practice.

- ***Ladle-to-mould de-gassing****:* Pre-heated ingot mould with hot top is placed in vacuum chamber. Above the chamber a tundish is placed. Liquid steel tapped in the ladle is at super-heat equivalent of 30 °C. The ladle is placed above the tundish. Bottom pouring of liquid steel is into the tundish which is desirable.

- ***Ladle-to-ladle de-gassing*****:** In ladle-to-ladle de-gassing, a ladle with the stopper rod is placed in a vacuum chamber. Ladle containing liquid steel from primary steelmaking furnace is placed on top of the vacuum chamber, and the gap is sealed by aluminium foil. Alloy additions are made under vacuum. Stream is allowed to fall in the ladle where liquid steel is de-gassed . Alloy additions are made under vacuum.



Ladle-to-ladle de-gassing



Schematics of ladle-to-mould de-gassing [1]