Steel Making (MT410601)

Program: B.Tech.	Branch: Metallurgical Engineering
Subject: Steel Making	Semester: VI
Subject Code:	MT410601

UNIT 2

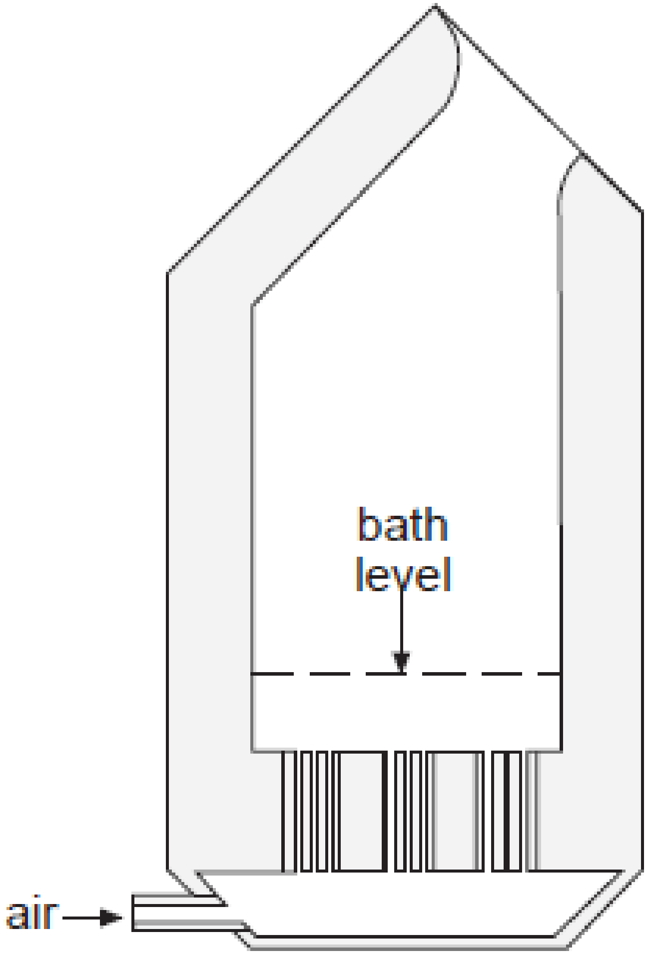
OVERVIEW OF STEELMAKING PROCESSES AND THEIR DEVELOPMENT

- Bessemer
- Open hearth
- Oxygen steelmaking
- EAF
- Induction furnace

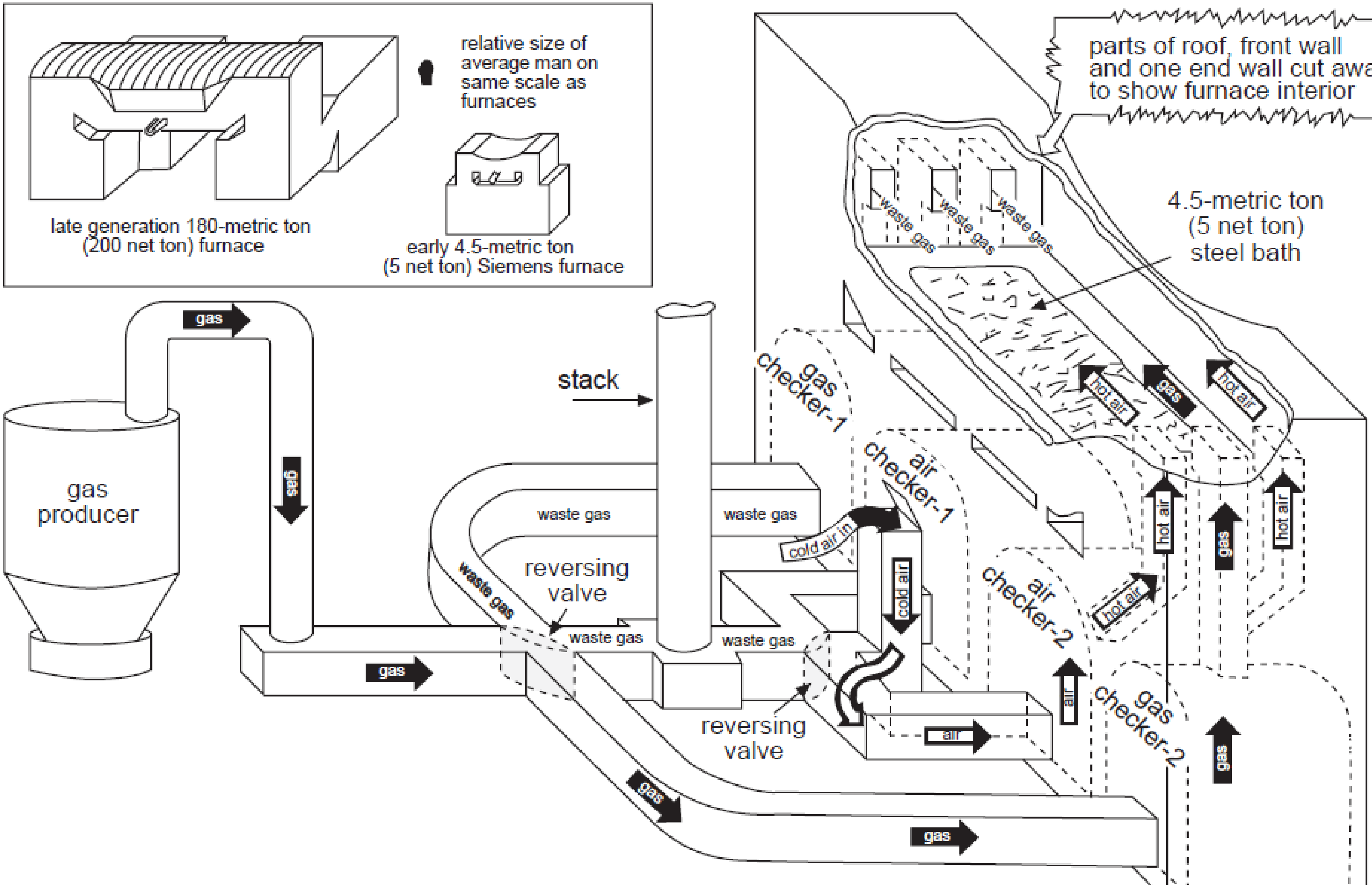
BESSEMER

- Acidic lining
  - P removal difficult
  - S removal difficult

- Basic lining
  - Basic lining
  - Addition of flux



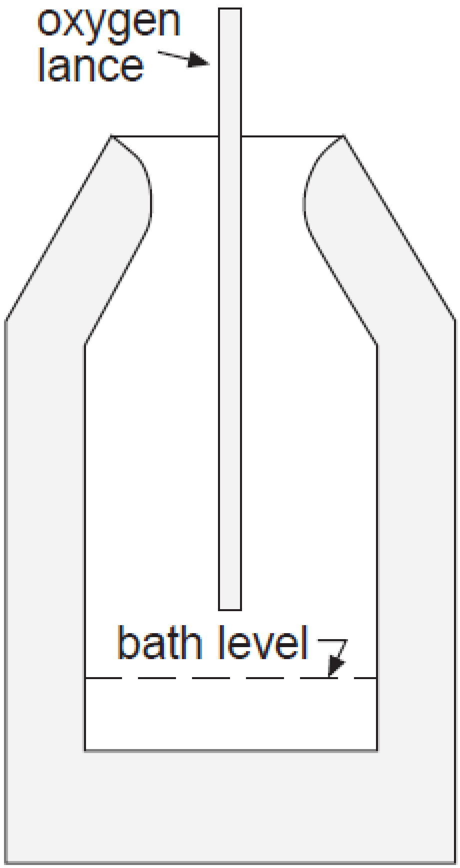
OPEN HEARTH PROCESS

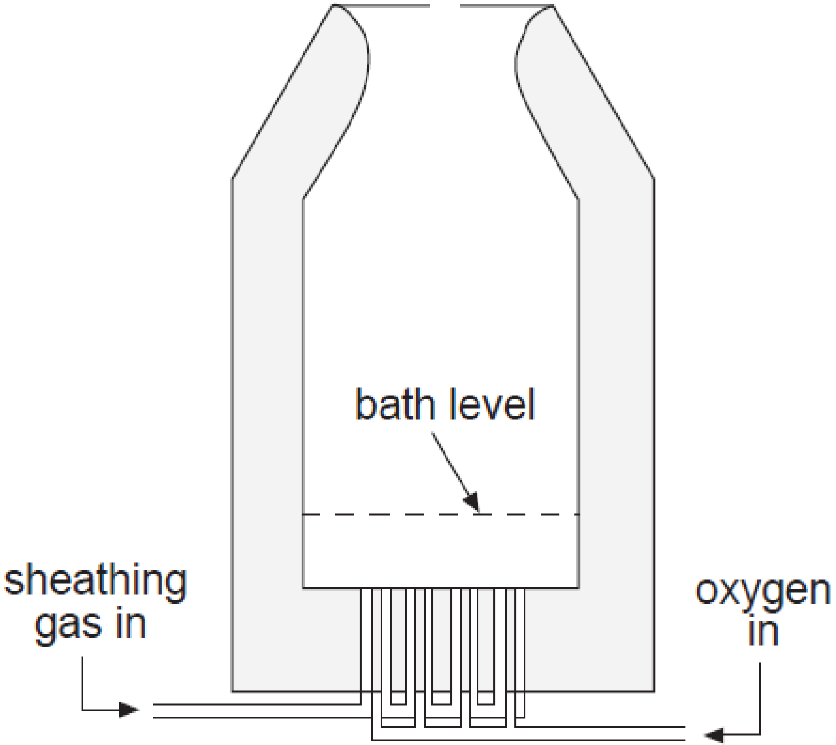


OPEN HEARTH PROCESS

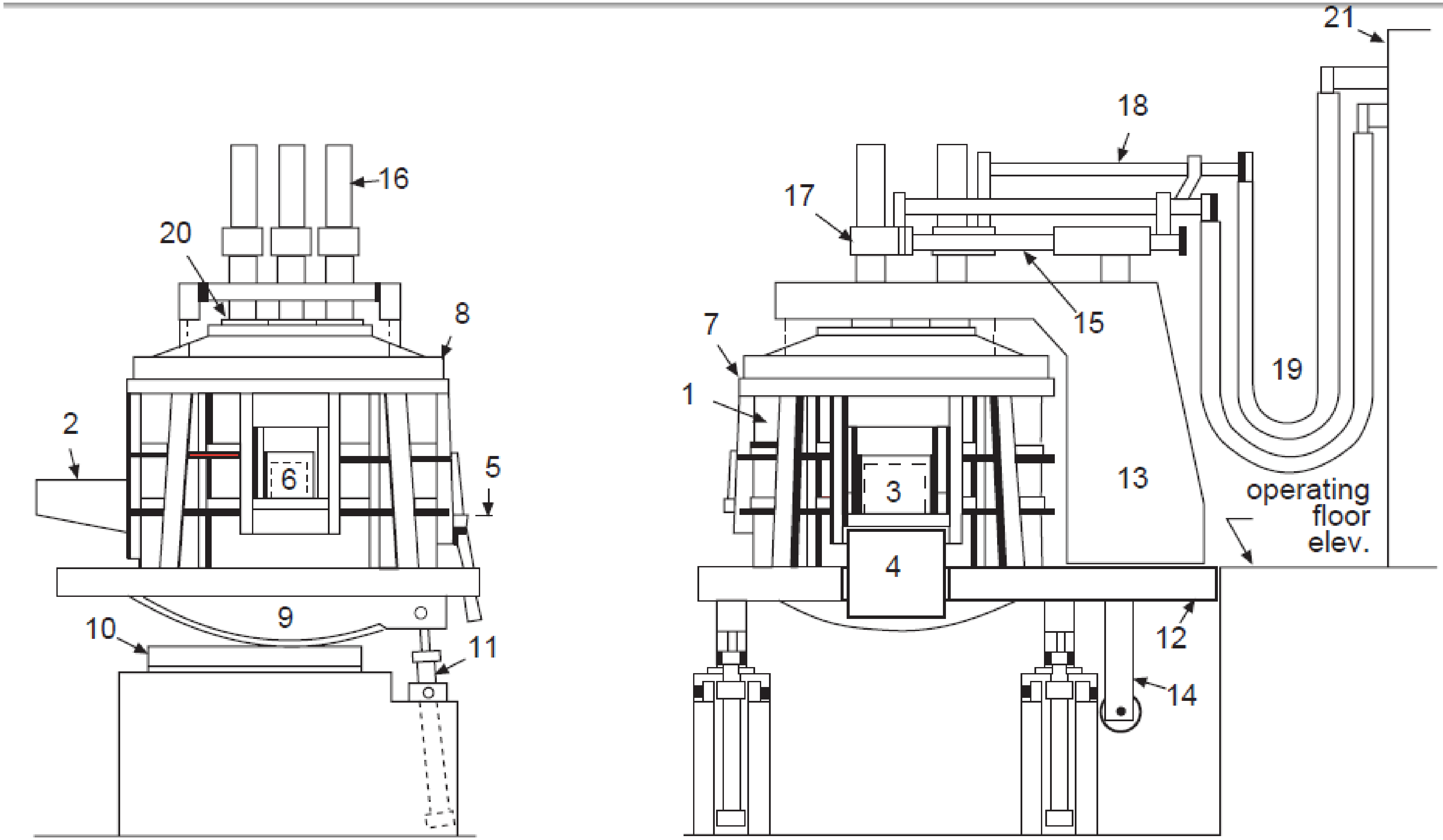
- Hot air
- Hot gas
- Use of Iron ore

OXYGEN STEELMAKING





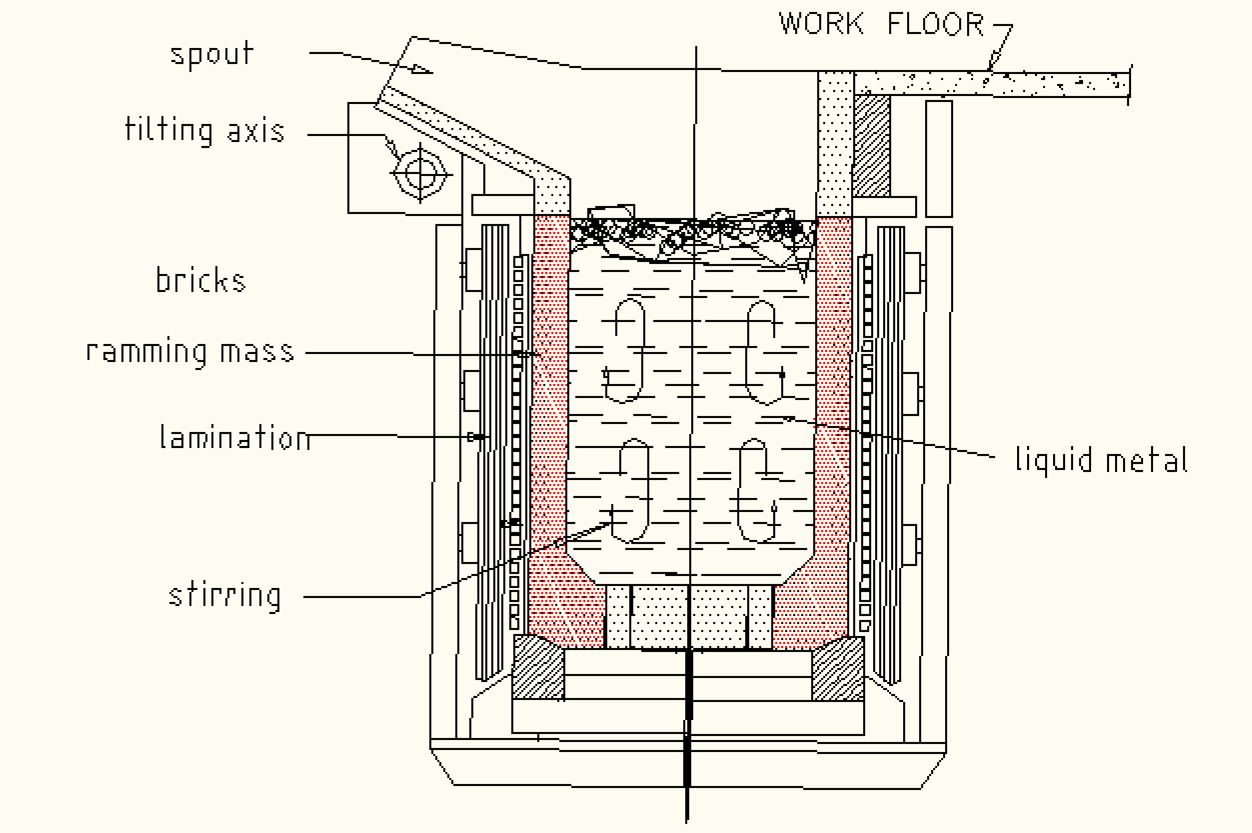
ELECTRIC ARC FURNACE



side door elevation

rear door elevation

INDUCTION FURNACE



Induction furnace

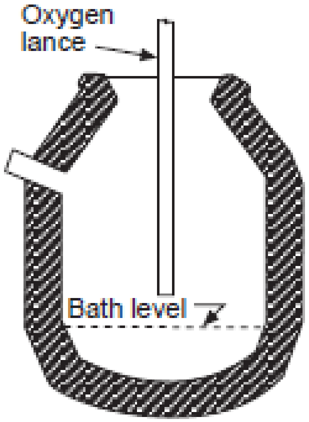
INTEGRATED STEEL PLANTS IN INDIA

1. Tata Iron and Steel Company (TISCO)
2. Indian Iron and Steel Company (IISCO)
3. The Visweswaraya Iron and Steel Ltd
4. Bhilai
5. Rourkela
6. Durgapur
7. Bokaro
8. The Salem Steel Plant
9. Vijayanagar Steel Plant
10. Vishakhapatnam Steel Plant (VSP)
11. Daitari Steel Plant
13. Dolvi Steel Plant

BASIC OXYGEN FURNACE (BOF)

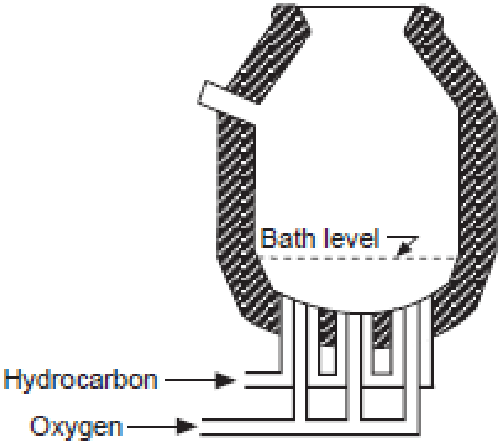
TYPES OF OXYGEN STEELMAKING PROCESSES

- There are basically three variations of introducing oxygen gas into the liquid bath. These are shown schematically in the next slide.
- The most common configuration is the **top-blown converter (BOF), where all of the oxygen is introduced via a** water-cooled lance.



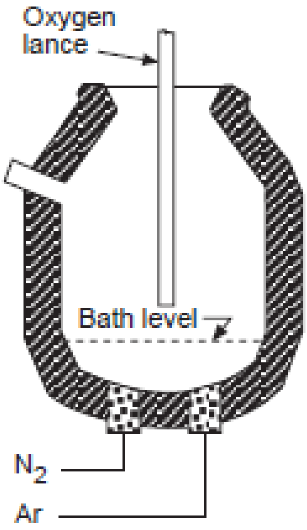
Top-blown (BOF) process

Oxygen of commercial purity, at high pressure and velocity, is blown downward vertically into the bath through a single water-cooled pipe or lance, indicated by arrow.

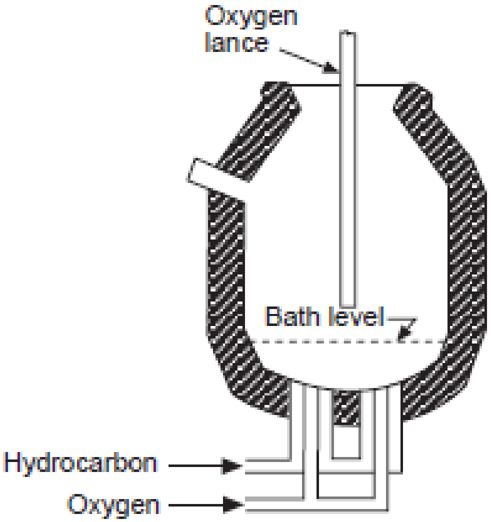


Bottom-blown (OBM or Q-BOP) process

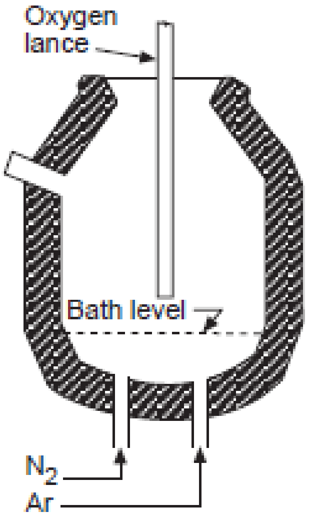
Oxygen of commercial purity, at high pressure and velocity, is blown upward vertically into the bath through tuyeres surrounded by pipes carrying a hydrocarbon such as natural gas.



Top lance plus permeable elements in bottom



Top lance plus cooled bottom tuyeres



Top lance plus uncooled bottom tuyeres

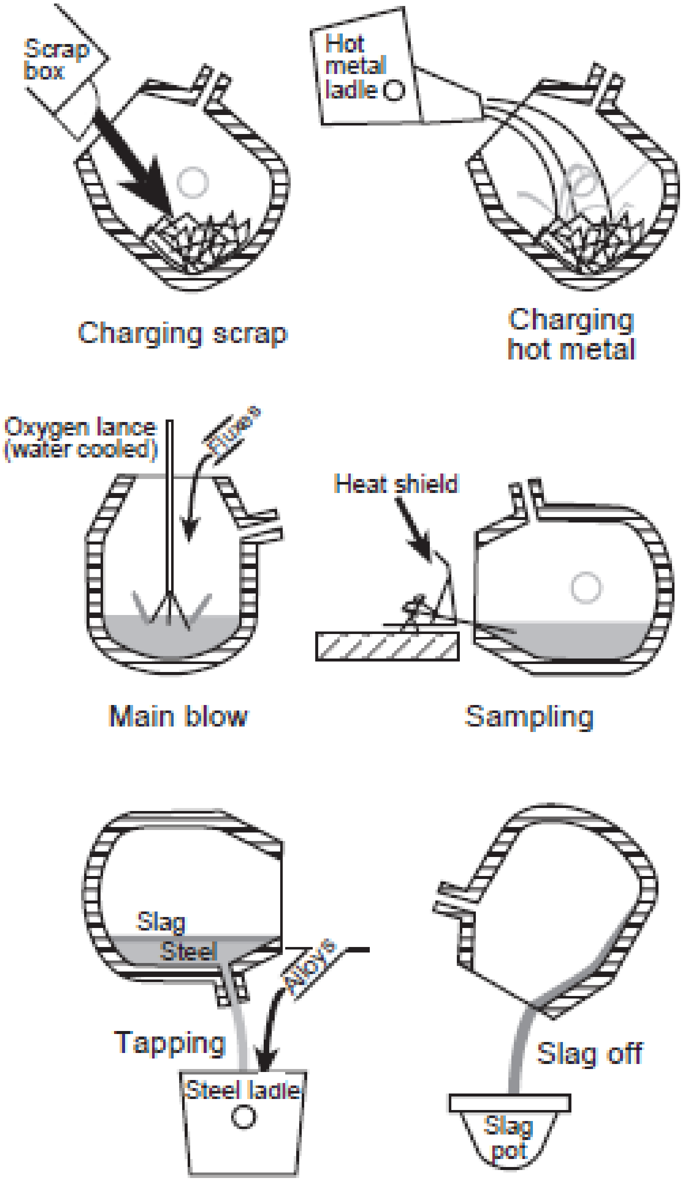
- The blowing end of this lance features three to five special nozzles that deliver the gas jets at supersonic velocities.
- In top blowing, the stirring created by these focused, supersonic jets cause the necessary slag emulsion to form and keeps vigorous bath flows to sustain the rapid reactions.
- The lance is suspended above the furnace and lowered into it.
- Oxygen is turned on as the lance moves into the furnace. Slag forming fluxes are added from above the furnace via a chute in the waste gas hood.

- In the **bottom-blown converters (OBM or Q-BOP), oxygen is introduced via several tuyeres** installed in the bottom of the vessel. Each tuyere consists of two concentric pipes with the oxygen passing through the center pipe and a coolant hydrocarbon passing through the annulus between the pipes.
- The coolant is usually methane (natural gas) or propane although some shops have used fuel oil.

- The coolant chemically decomposes when introduced at high temperatures and absorbs heat in the vicinity, thus protecting the tuyere from overheating.
- In bottom blowing, all of the oxygen is introduced through the bottom, and passes through the bath and slag thus creating vigorous bath stirring and formation of a slag emulsion. Powdered fluxes are introduced into the bath through the tuyeres located in the bottom of the furnace

- The **combination blowing or top and bottom blowing, or mixed blowing** process is characterized by both a top blowing lance and a method of achieving stirring from the bottom.
- The configurational differences in mixed blowing lie principally in the bottom tuyeres or elements.
- These range from fully cooled tuyeres, to uncooled tuyeres, to permeable elements.

PROCESS DESCRIPTION



Event	**Min.**	**Comments**
Charging scrap and hot metal	5–10	Scrap at ambient temperature, hot metal at 1340°C (2450°F)
Refining–*blowing* oxygen	14–23	Oxygen reacts with elements, Si, C, Fe, Mn, P in scrap and hot metal and flux additions to form a slag
Sampling–chemical testing	4–15	Steel at 1650°C (3000°F), chemistry and temperature
Tapping	4–8	Steel is poured from furnace into a ladle, typical size = 250 tons
Pouring *slag off* at furnace	3–9	Most slag is removed from furnace, in some shops slag is used to coat furnace walls

OXYGEN BLOW

- After scrap and hot metal are charged, the furnace is set upright and the oxygen is supplied through a water-cooled lance.
- There are two lance lift carriages above each furnace but only one lance is used at a time; the other is a spare.
- The oxygen blow times typically range from 13 to 25 minutes from one shop to another with an average of about 20 minutes.
- The oxygen is added in several batches. Each batch is characterized by a different lance height above the static steel bath and sometimes by an oxygen rate change

- The first batch lance height is very high to avoid the possibility of lance tip contact with the scrap and to safely establish the oxidizing, heat generating reactions. If the lance would contact the pile of scrap in the furnace, a serious water leak could result causing a dangerous steam explosion

- The second batch lance height is usually approximately 20 to 30 inches lower than the first batch and approximately 20 to 30 inches higher than the main batch. The purpose here is to increase the reaction rate and control the early slag formation.
- This second or middle batch generates some early iron oxide to increase proper slag formation

- The main batch is where most of the action occurs—it is by far the longest batch. The lance height is an empirical compromise between achieving faster carbon removal rates and proper slag making.

- The position of the lance is very important for proper functioning of the process. If the lance is too high, the slag will be over stirred and over-oxidized with higher FeO percentages.
- This will cause higher than normal yield losses and lower tap alloy efficiencies due to oxidation losses.
- Further, the rate of carbon removal is reduced and becomes erratic. Slag volume increases and there is an increased chance of slopping, *which is an uncontrolled slag drooling or spilling over the top of the* furnace.

- When the lance is too low, carbon removal increases somewhat, slag formation, slag reactivity, and FeO are reduced and sulfur and phosphorus removal problems often occur. If the lance is very low, then spitting of metal droplets or sparking occurs which cause severe and dangerous metallic deposits, called skulls, on the lance and the lower waste gas hood.

FLUX ADDITIONS

- Soon after the oxygen is turned on, flux additions are started and are usually completed at the end of the second batch of oxygen.
- The fluxes control the chemistry and sulfur and phosphorus capacity of the slag. The principle active ingredients from the fluxes are CaO (from burnt lime) and MgO (from dolomitic lime). The CaO component is used principally to control sulfur and phosphorous.

- The dolomitic lime is used to saturate the slag with MgO. The principle ingredient of the furnace refractories is MgO. Steelmaking slags without it are very corrosive to the lining.
- The corrosion rate is reduced dramatically when MgO is added to saturate the slag. It is much cheaper to satisfy the slag’s appetite for MgO from dolomitic lime than by dissolving it from the lining.

TAPPING

- For tapping, the furnace is rotated to the tap side and the steel flows through a taphole into a ladle sitting on a car below. The slag floats on top of the steel bath inside the furnace. Near the end of tapping (four to ten minutes) a vortex may develop near the draining taphole and entrain some of the slag into the ladle.
- There are various devices used to minimize or detect the onset of slag. Heavy uncontrolled slag entrainment into the ladle has a significant adverse effect on production costs and steel quality

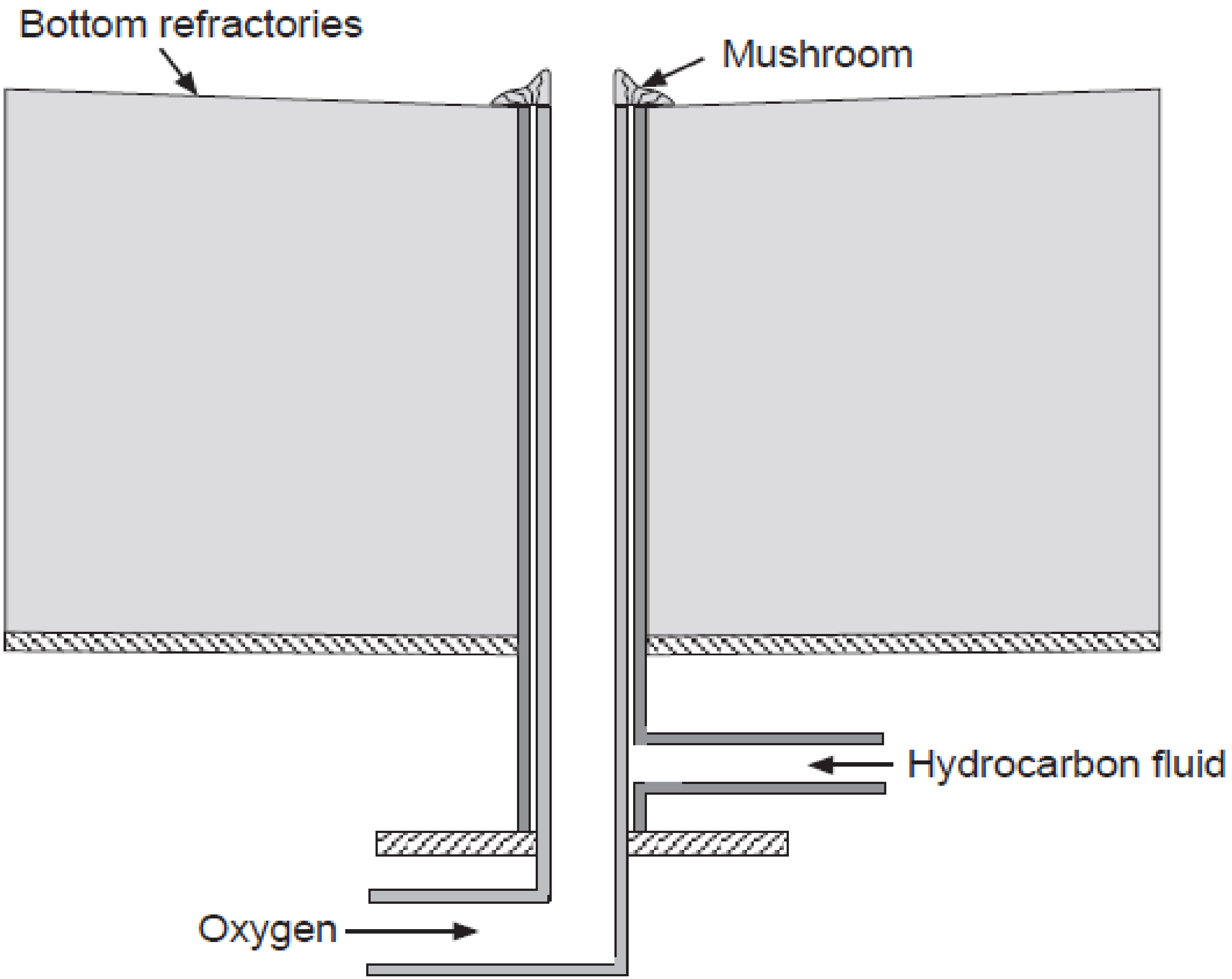
- The condition and maintenance of the taphole and the furnace wall around it can influence alloy recovery consistency and metallic yield.
- Poor taphole maintenance and practice can lead to a burnthrough in either the furnace shell or the taphole support frame. A very small taphole can significantly increase the tap time, reducing productivity, steel temperature, and nitrogen pickup in the ladle.
- A very large taphole will not allow enough time to add and mix the alloy additions in the ladle. Further, aged tapholes have ragged streams with higher surface areas that will entrain air, which in turn dissolves more oxygen and makes control of oxygen levels in the steel difficult

- A newly installed taphole yields a tap time of seven or eight minutes. Tapholes are generally replaced when the tap time falls below four minutes. A very important aspect of the melter/operator’s job is to carefully monitor the condition and performance of the tap hole.
- Steel is often lost to the slag pot, a yield loss, when a pocket or depression develops near or around the tap opening. Such a depression can prevent several tons of steel from being drained into the ladle. Again, the operator must carefully monitor yields and furnace condition and make repairs to prevent this problem.

THE BOTTOM-BLOWN OXYGEN STEELMAKING OR OBM (Q-BOP) PROCESS

- The successful development and application of the shrouded oxygen tuyere in the late 1960s led to the development of the OBM (Q-BOP) process in the early 1970s.
- Oxygen in this process is injected into the bath through tuyeres inserted in the bottom of the furnace. Each tuyere is made from two concentric tubes forming an inner nozzle and an outer annulus

- Oxygen and powdered lime are injected through the central portion of the tuyeres, while a hydrocarbon gas, typically natural gas or propane, is injected through the annular section between the two concentric pipes, as shown in Fig.
- The endothermic decomposition of the hydrocarbon gas and the sensible heat required to bring the products of the decomposition up to steelmaking temperatures result in localized cooling at the tip of the tuyere.



: Schematic drawing of an OBM (Q-BOP) tuyere.

- The localized cooling is enough to chill the liquid metal and form a porous mushroom on the tip of the tuyere and part of the surrounding refractory.
- This mushroom reduces the burn back rate of the tuyere, and the wear of the surrounding refractory.
- The injected lime provides additional cooling to the tuyere, and results in better slag refining characteristics

- Top lances in OBM (Q-BOP) furnaces have also been adopted, mainly for the purposes of increasing the post-combustion of the offgases within the furnace, and to control the buildup of slag and metal in the furnace cone area.
- Top lances used in OBM (Q-BOP) furnaces are normally stationary, since they are not used for refining purposes. Tuyeres, located in the upper cone area of furnaces with a heat size larger than approximately 150 tonnes have also been used, but typicallyresult in higher refractory wear.

- For this reason, their application has been limited to shops which require increased scrap melting capabilities (resulting in shorter lining lives), and with a heat size smaller than 150 tonnes.

SEQUENCE OF OPERATIONS

- After the steel is tapped, the furnace is rotated to the vertical position, and nitrogen is blown to splash the slag onto the furnace walls.
- This results in a coating that extends the life of the furnace barrel. The furnace is also rocked to coat the bottom with slag.
- This operation can be done with the slag as is, or with conditioned slag.

- The furnace is then ready to receive the scrap and hot metal.
- Nitrogen is injected at sonic flow to protect the tuyeres during the hot metal charge. The furnace is rotated to its vertical position, and the bottom and top oxygen blow are started.
- Burnt lime is injected with the oxygen through the bottom, and the dolomitic lime is added through the top at the beginning of the blow.

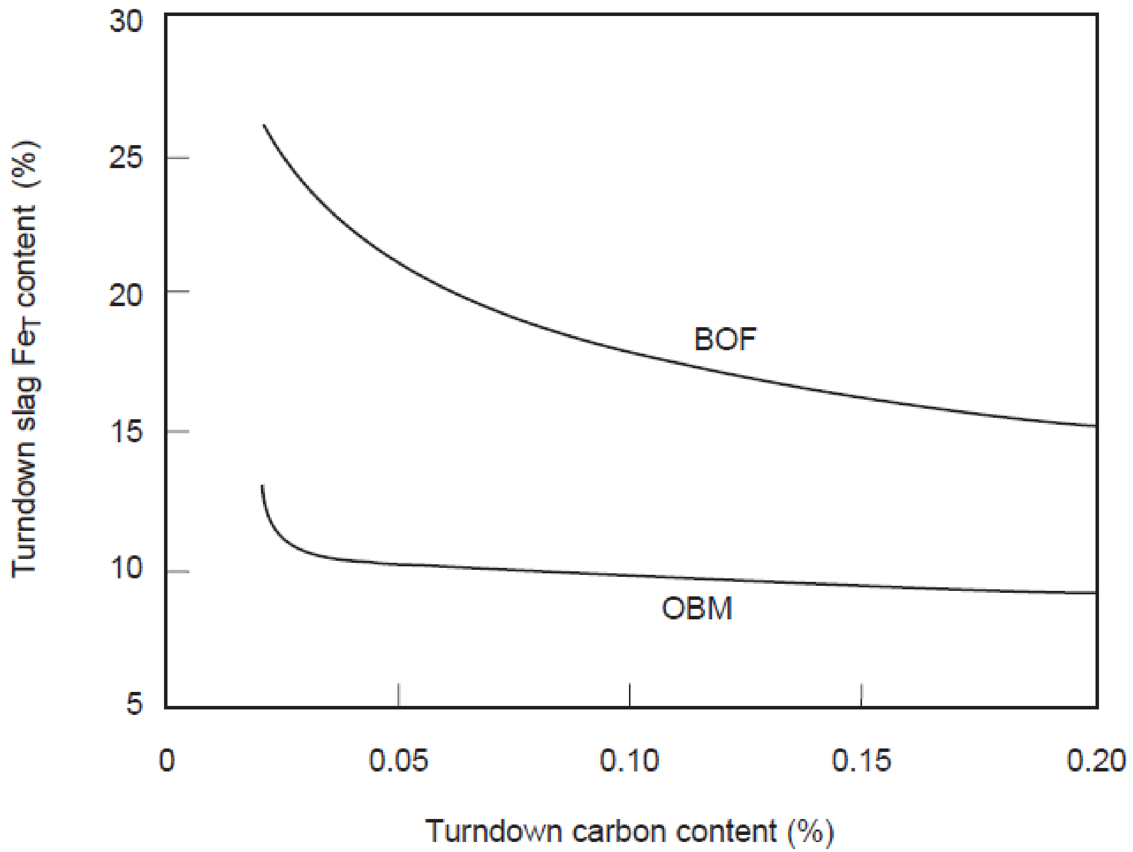
- Typically the lime is injected within the first half of the oxygen blow.
- When the calculated oxygen amount has been injected, the gas is switched to nitrogen or argon and the furnace is rotated for sampling.
- A sample for chemical analysis is taken, and the temperature and oxygen activity are measured. If the desired temperature and chemistry have been obtained, the heat can then be tapped.

- If necessary, small adjustments in temperature and chemistry can be made by injecting additional oxygen through the bottom, by injecting more lime, or by cooling the heat with ore or raw dolomite.
- Since the process is very reproducible, the heat is normally tapped after these adjustments, without making another temperature measurement or taking another sample for chemical analysis.

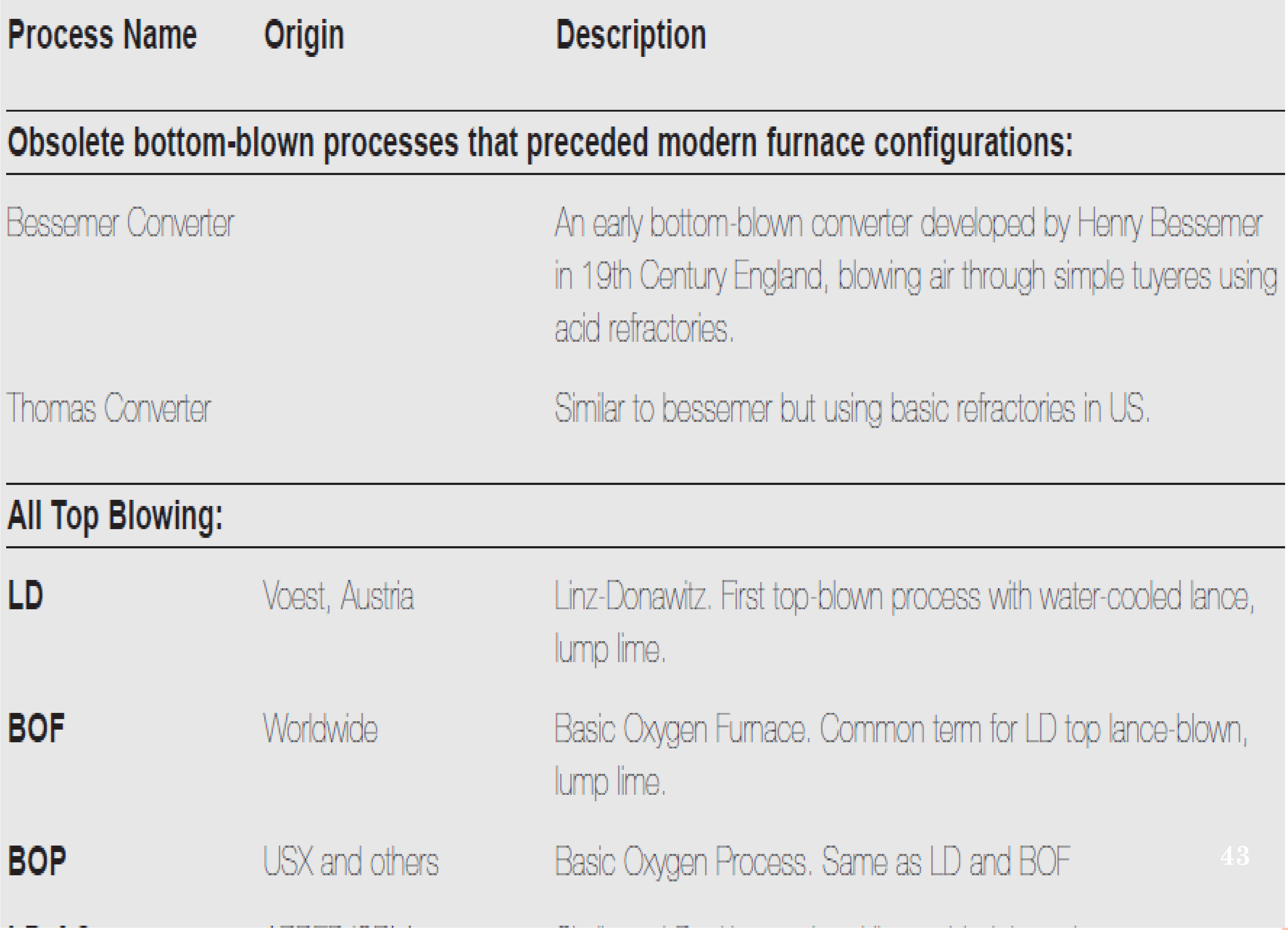
PROCESS CHARACTERISTICS

- The injection of the oxygen and hydrocarbons through bottom tuyeres results in distinct process characteristics.
- The oxygen reacts directly with the carbon and silicon in the liquid iron melt, resulting in lower oxidation levels in the metal and slag at the end of the blow.
- The bottom injection also results in very strong bath mixing. Steel decarburization is enhanced by the strong bath agitation, particularly during the last portion of the blow, when mass transfer of the carbon in the melt controls the rate of decarburization at carbon contents below 0.3%.

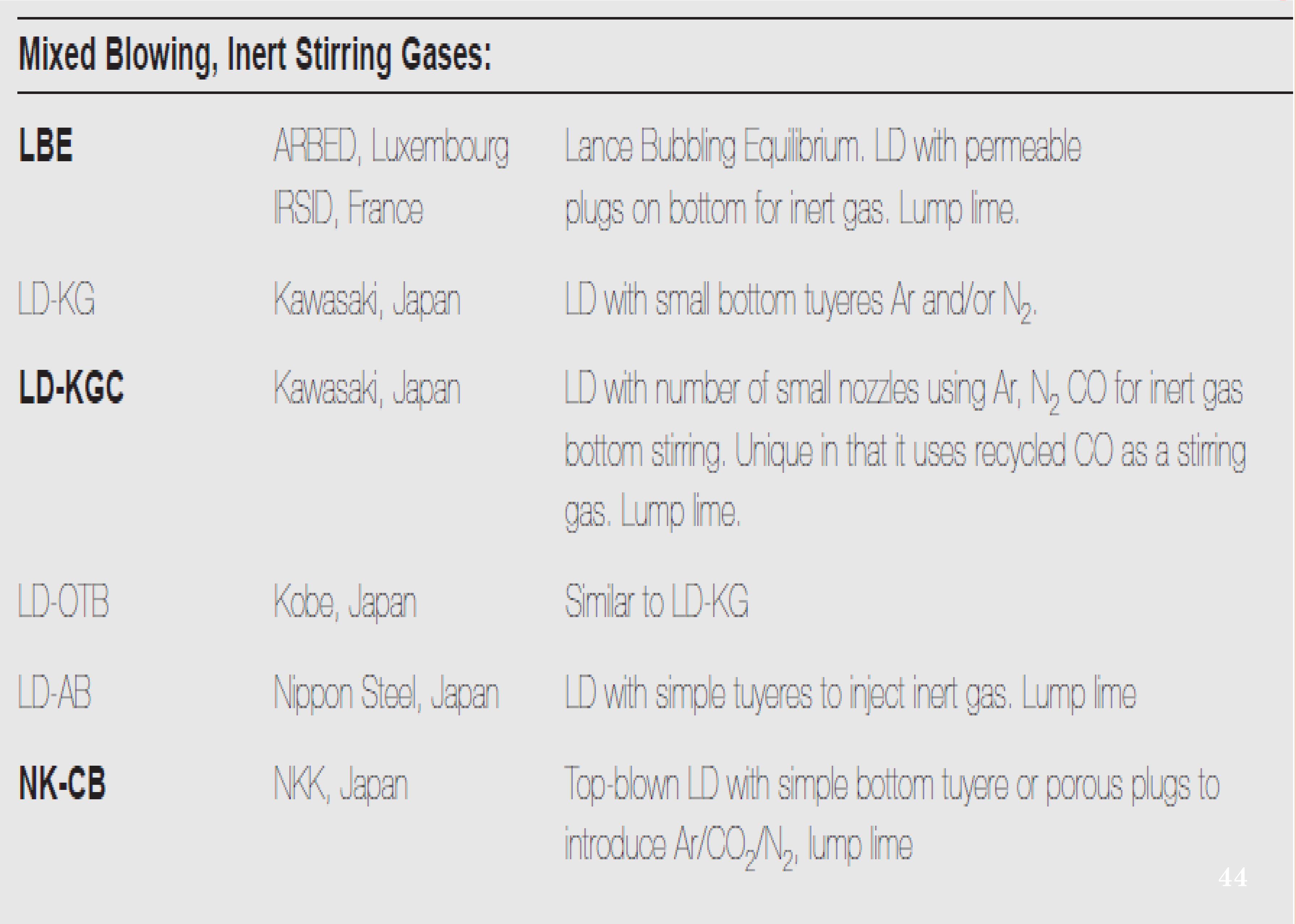
- This results in less iron being oxidized and lost to the slag, as shown in Fig.,



- The manganese content at turndown is also higher than in the top-blown vessels, due to the lower bath and slag oxidation.
- The variability in blow behavior introduced by the top lance in top-blown vessels is eliminated.
- By injecting the oxygen and lime through the bottom tuyeres in a controlled manner, a highly reproducible process control is obtained

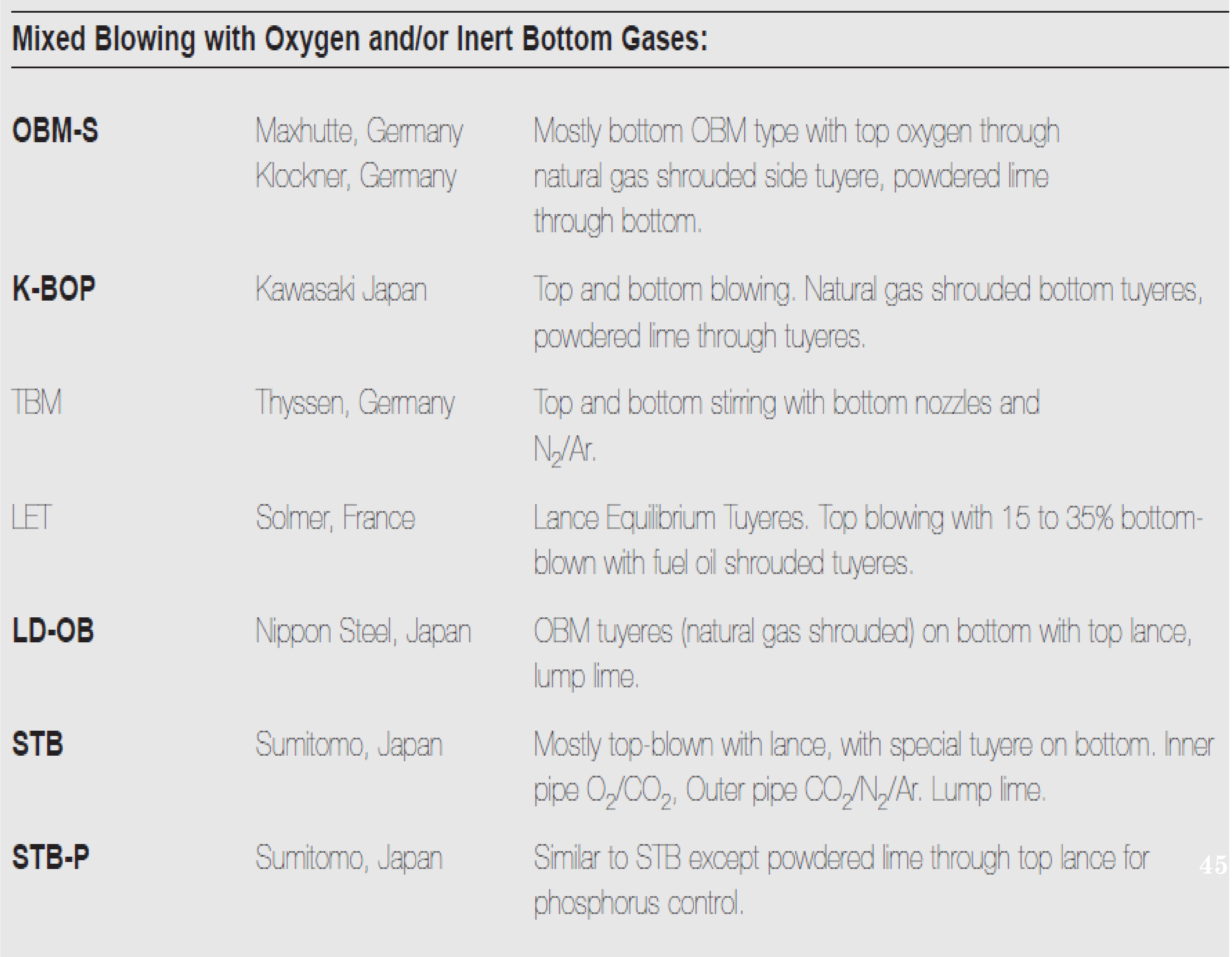


Process Name	Origin	Description
Obsolete bottom-blown processes that preceded modern furnace configurations:		
Bessemer Converter		An early bottom-blown converter developed by Henry Bessemer in 19th Century England, blowing air through simple tuyeres using acid refractories.
Thomas Converter		Similar to bessemer but using basic refractories in US.
All Top Blowing:		
LD	Voest, Austria	Linz-Donawitz. First top-blown process with water-cooled lance, lump lime.
BOF	Worldwide	Basic Oxygen Furnace. Common term for LD top lance-blown, lump lime.
BOP	USX and others	Basic Oxygen Process. Same as LD and BOF



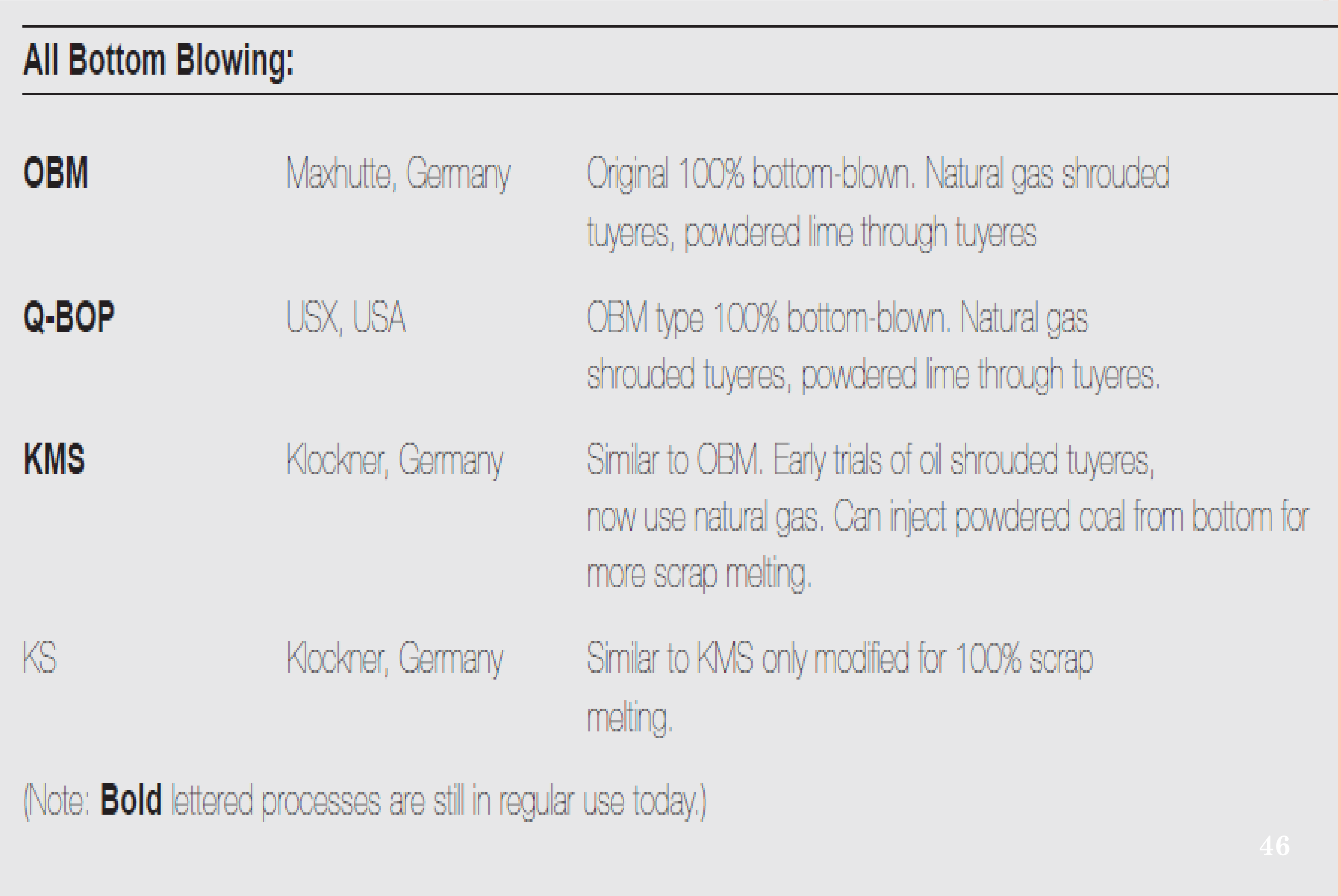
Mixed Blowing, Inert Stirring Gases:

LBE	ARBED, Luxembourg IRSID, France	Lance Bubbling Equilibrium. LD with permeable plugs on bottom for inert gas. Lump lime.
LD-KG	Kawasaki, Japan	LD with small bottom tuyeres Ar and/or N_2.
LD-KGC	Kawasaki, Japan	LD with number of small nozzles using Ar, N_2 CO for inert gas bottom stirring. Unique in that it uses recycled CO as a stirring gas. Lump lime.
LD-OTB	Kobe, Japan	Similar to LD-KG
LD-AB	Nippon Steel, Japan	LD with simple tuyeres to inject inert gas. Lump lime
NK-CB	NKK, Japan	Top-blown LD with simple bottom tuyere or porous plugs to introduce Ar/CO_2/N_2, lump lime



Mixed Blowing with Oxygen and/or Inert Bottom Gases:

OBM-S	Maxhutte, Germany Klockner, Germany	Mostly bottom OBM type with top oxygen through natural gas shrouded side tuyere, powdered lime through bottom.
K-BOP	Kawasaki Japan	Top and bottom blowing. Natural gas shrouded bottom tuyeres, powdered lime through tuyeres.
TBM	Thyssen, Germany	Top and bottom stirring with bottom nozzles and N_2/Ar.
LET	Solmer, France	Lance Equilibrium Tuyeres. Top blowing with 15 to 35% bottom-blown with fuel oil shrouded tuyeres.
LD-OB	Nippon Steel, Japan	OBM tuyeres (natural gas shrouded) on bottom with top lance, lump lime.
STB	Sumitomo, Japan	Mostly top-blown with lance, with special tuyere on bottom. Inner pipe O_2/CO_2, Outer pipe CO_2/N_2/Ar. Lump lime.
STB-P	Sumitomo, Japan	Similar to STB except powdered lime through top lance for phosphorus control.



All Bottom Blowing:

OBM	Maxhutte, Germany	Original 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres
Q-BOP	USX, USA	OBM type 100% bottom-blown. Natural gas shrouded tuyeres, powdered lime through tuyeres.
KMS	Klockner, Germany	Similar to OBM. Early trials of oil shrouded tuyeres, now use natural gas. Can inject powdered coal from bottom for more scrap melting.
KS	Klockner, Germany	Similar to KMS only modified for 100% scrap melting.

(Note: **Bold** lettered processes are still in regular use today.)

BOTTOM STIRRING PRACTICES

- Inhomogenieties in chemical composition and temperature are created in the melt during the oxygen blow in the top-blown BOF process due to lack of proper mixing in the metal bath.
- There is a relatively dead zone directly underneath the jet cavity in the BOF.

- Bottom stirring practices using inert gases such as nitrogen and argon are being used extensively to improve the mixing conditions in the BOF.
- The inert gases are introduced at the bottom of the furnace by means of permeable elements (LBE process) or tuyeres. In a typical practice, nitrogen gas is introduced through tuyeres or permeable elements in the first 60 to 80% of the oxygen blow, and argon gas is switched on in the last 40 to 20% of the blow.
- The rapid evolution of CO in the first part of the oxygen blow prevents nitrogen pickup in the steel.

SOME OF THE EFFECTS OF BOTTOM STIRRING AND THE RESULTING IMPROVED MIXING INCLUDE

- *(a)*
- *Decreased FeO content in slag. Better mixing conditions in the vessel causes the* FeO in the slag to be closer to equilibrium conditions, which results in lower concentrations of FeO in the slag.
- Plant studies have shown that for low carbon heats, bottom stirring can cause a reduction in the FeO level in slag by approximately 5%.

- This results in better metallic yield, lower FeO level in the ladle slag and reduced slag attack on the refractories. Improvements in iron yield by as much as 1.5% or more have been reported.
- Lower levels of FeO in the steelmaking slag reduces the amount of heat generated during the oxygen blow, and hence reduces the maximum amount of scrap that can be charged in a heat.

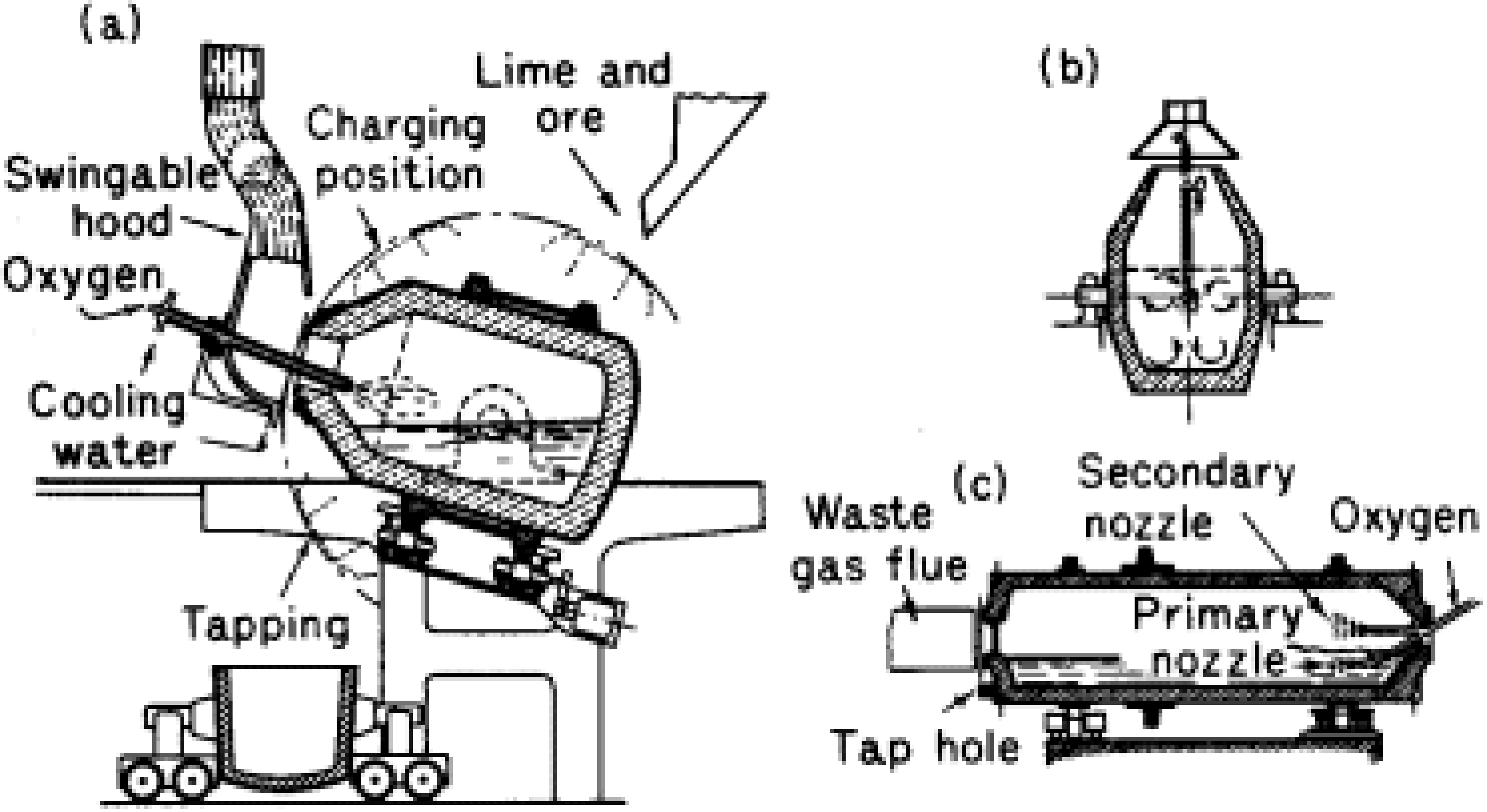
- (b)
- *Reduced dissolved oxygen in metal. A study shows that bottom stirring can reduce the* dissolved oxygen level in a low carbon heat by approximately 225 ppm.
- This lowering of dissolved oxygen leads to lower aluminum consumption in the ladle. Studies have shown aluminum savings of about 0.3 lb./ton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

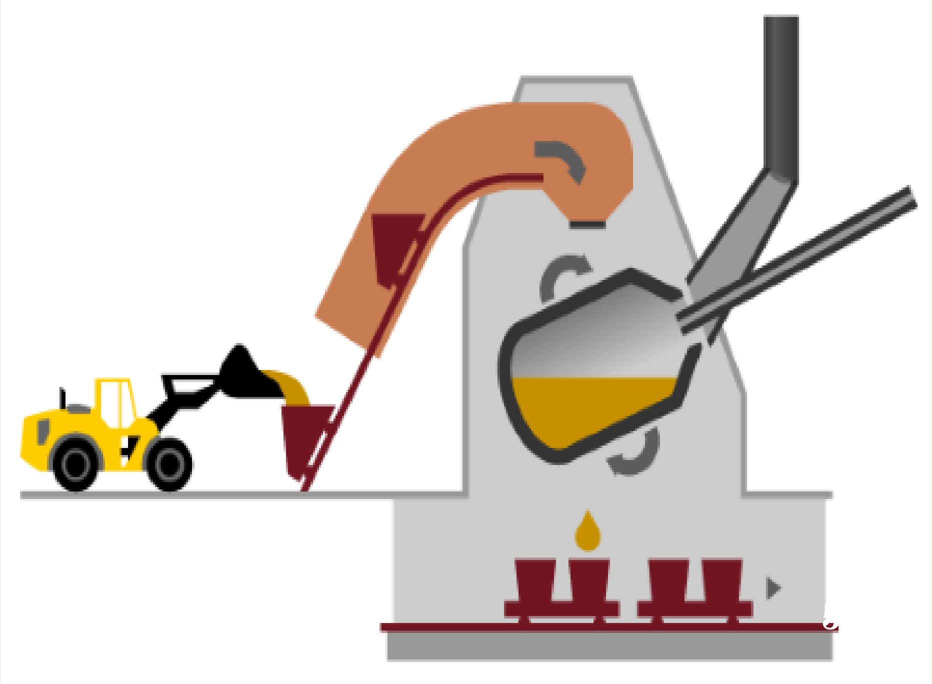
- (c)
- *Higher manganese content in the metal at turndown. An increase of approximately* 0.03% in the turndown manganese content of the metal has been shown.
- This leads to a reduction in the consumption of ferro-manganese.

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

KALDO FURNACE

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


(a)
Swingable hood
Charging position
Lime and ore
Oxygen
Cooling water
Tapping
(b)
(c)
Waste gas flue
Secondary nozzle
Oxygen
Primary nozzle
Tap hole



- In the blowing position the vessel is held at an angle of 16-20^o horizontal.
- The waste gases are carried through a water cooled hood which swings into fit over the mouth of the vessel during blowing.
- The oxygen lance is inserted through the hood into the vessel at an angle to the surface of the bath.
- A water cooled feeder is also provided besides the charging chute at the top, to make solid additions without interrupting the blow.

- The facilities required for scrap and flux charging, hot metal pouring, tapping, slagging etc. are in a way similar to the LD process.

HEAT SEQUENCE

- The hot vessel, containing some slag from the previous heat, is rotated into vertical position and it receives lime, ore and other fluxing materials.
- Scrap is charged after making the vessel nearly horizontal.
- Scrap is literally poured in the vessel. Hot metal is charges immediately after the scrap. The vessel is tilted to blowing angle of 16-20^o
- the lance is inserted through the hood at a proper angle. The rate of oxygen supply and speed of rotation of the vessel are varied during blowing.

- Blowing commences at oxygen flow rate nearly 50-60 % of the maximum allowable value. The vessel is also rotated slowly.
- Both of them are increased progressively and they attain their respective maximum values in about 5-7 min.
- Initial conditions are such that all the silicon most of the manganese and some iorn are oxidised.
- The formation of SiO2, MnO and FeO take lime in solution and form a thin, basic and oxidizing slag. The slag retained in previous heat is helpful

- Scrap : chilling effect and refractory wear due to rotation in bath.
- At the end of 18-20 minutes of blowing all the solids are completely molten. The oxygen flow rate is then decreased by nearly 50% and the speed of the rotation is reduced to about 10-12 rpm.
- the lance angle is also decreased. This is de-phosporisation period. The blow is stopped after nearly 25 minutes of blowing and the phosporic slag is removed as completely as possible.

- The slag at this stage should be thin and slightly foamy so that the metal shots do not remain entrapped and get lost along with the slag removal.
- In two slag removal almost 80% of the oxygen is blown before the removal of the first slag.
- In two slag practice the second blow continues for a pre determined time and the heat is tapped. If a very low phosporous level is to be achieved one more intermediate slag is removed and the blow is continued.

- The third blow is very short. Fresh charges of lime and ore are made before blowing. The heat is finished by withdrawing the lance and the hood.

PROBLEMS ASSOCIATED

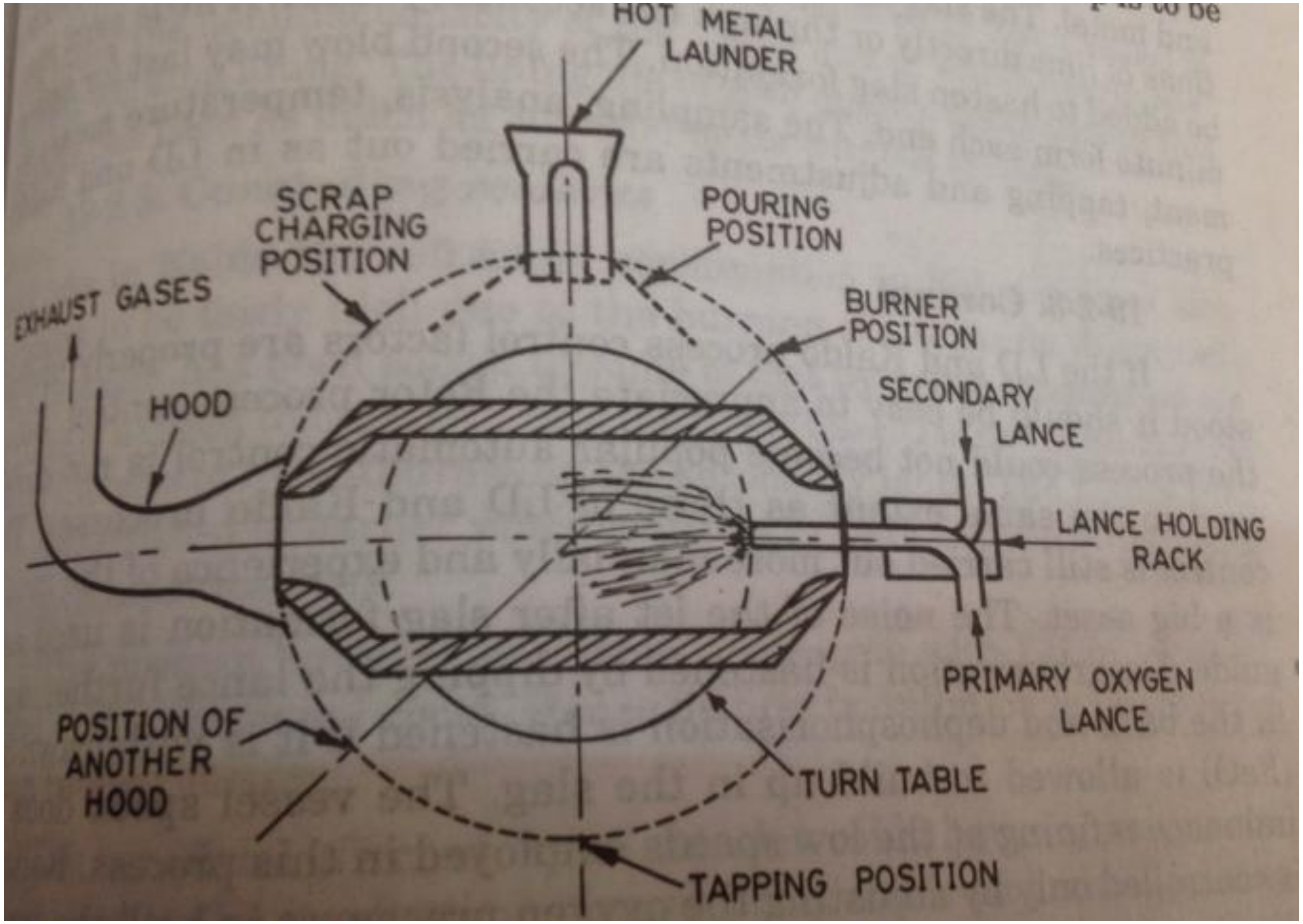
- In spite of being a very scientifically designed and developed process and hence a promising process at the beginning, it could not be widely adopted for the simple reason that the refractory consumption per tonne of steel produced is still very large in kaldo vessels.
- The lining life is nearly 60-100 heats as against 200-300 heats then for similar material in LD vessel.

ROTOR FURNACE

- A long cylindrical vessel (L=4D) is used to provide enough space for burning most of the CO evolved during refining to CO_2, and thereby utilising the heat for steel making.
- The primary oxygen lance or refining lance is dipped in the slag-metal system whereas a secondary lance is inserted well above the slag surface to burn the evolved CO to CO_2.
- The turbulence caused by the primary submerged lance and the sweeping of gases over almost the entire slag surface in the vessel causes a good proportion of heat to be released.

- The rotation of the vessel is essential to safe guard the lining from over heating and assist in heat transfer.

PLANT DESIGN



- For 100-120t: 15m Long and 4.5m Dia with nearly 1-1.2m openings at both ends.
- The vessel is rotated around its own axis in horizontal plane at a fixed speed of 0.2-4 rpm.
- The vessel is mounted on a turntable of about 8m diameter and which can be rotated on a horizontal plane.
- The arrangements around the table are such that the lance and gas-offtakes are located at diametrically opposite points .

- The table has tapping and de slagging positions, the vessel can be raised in a vertical plane upto 90^0.
- For tapping as inclination of few degrees is given.
- The lining is much similar to LD and Kaldo vessels.

OPERATION

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

- The vessel is moved to blowing position. The lances are inserted and blowing started.
- Simultaneously the vessel is also rotated.
- The primary oxygen flow is nearly constant throughout the blow at about 70-85 m3/min.
- The secondary lance is put-on a little after the primary is put-on and it blows air as per the design.
- It is also equipped to feed lime powder if required. The vessesl is blown for half the time from each end to even out the lining wear over the entire length of the vessel

ELECTRIC ARC FURNACE

ELECTRIC ARC FURNACE:

An **Electric Arc Furnace** (**EAF**) is a furnace that heats charged material by means of an electric arc.

Arc furnaces range in size from small units of approximately one ton capacity (used in foundries for producing cast iron products) up to about 400 ton units used for secondary steelmaking

TEMPERATURE RANGE

- Industrial electric arc furnace temperatures can be up to 1,800 ℃, (3272 ℉) while laboratory units can exceed 3,000 ℃. (5432 ℉)
- Arc furnaces differ from induction furnaces in that the charge material is directly exposed to an electric arc, and the current in the furnace terminals passes through the charged material.

HISTORY

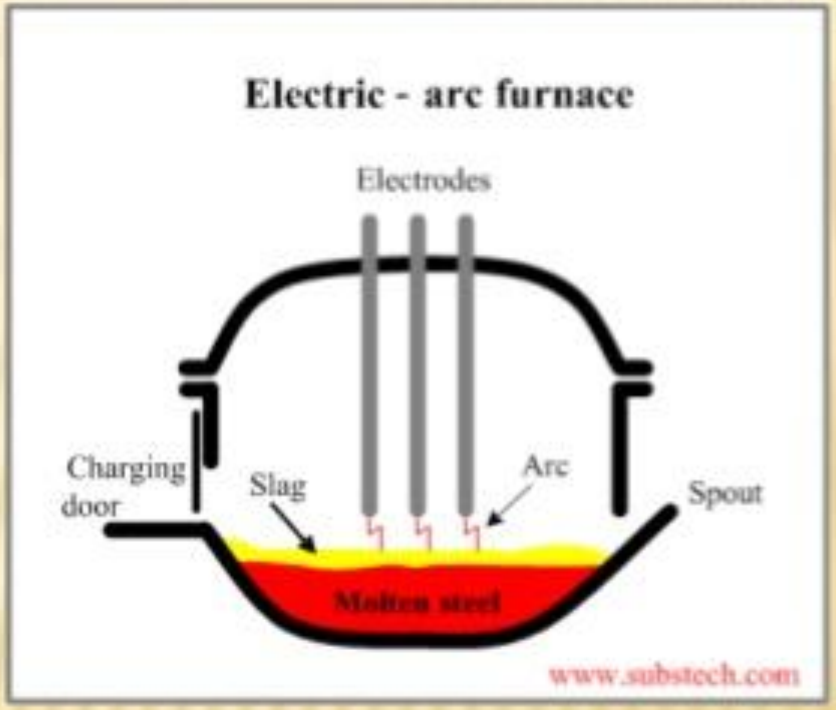
- The first electric arc furnaces were developed by Paul Héroult, of France, with a commercial plant established in the United States in 1907.
- The Sanderson brothers formed The Sanderson Brothers steel Co. in Syracuse, New York, installing the first electric arc furnace in the U.S.
- This furnace is now on display at Station Square, Pittsburgh, Pennsylvania.

TYPES OF EAF

- Two kinds of electric current may be used in Electric Arc Furnaces:
- direct (DC) EAF
- alternating (AC) EAF
- Three-phase AC Electric Arc Furnaces with graphite electrodes are commonly used in steel making.

CONSTRUCTION

- The furnace consists of a spherical hearth (bottom), cylindrical shell and a swinging water-cooled dome-shaped roof.
- The roof has three holes for consumable graphite electrodes held by a clamping mechanism.
- The mechanism provides independent lifting and lowering of each electrode.


Electric - arc furnace
Electrodes
Charging door
Slag
Arc
Spout
Molten steel
www.substech.com

- The charge door, through which the slag components and alloying additives are charged, is located on the front side of the furnace shell.
- The charge door is also used for removing the slag (de-slagging).

REFRACTORY LINING OF AN EAF

- Refractory linings of Electric Arc Furnaces are made generally of resin-bonded magnesia-carbon bricks.
- When the bricks are heated the bonding material is coked and turns into a carbon network binding the refractory grains,preventing wetting by the slag and protecting the lining the from erosion and chemical attack of the molten metal and slag.

OPERATION/WORKING

- The scrap is charged commonly from the furnace top.
- The roof with the electrodes is swung aside before the scrap charging.
- The scrap arranged in the charge basket is transferred to the furnace by a crane and then dropped into the shell.

- Lower voltages are selected for this first part of the operation to protect the roof and walls from excessive heat and damage from the arcs.
- Once the electrodes have reached the heavy melt at the base of the furnace and the arcs are shielded by the scrap,
- the voltage can be increased and the electrodes raised slightly, lengthening the arcs and increasing power to the melt.

CHEMICAL AND PHYSICAL PROCESSES IN AN EAF

- *Melting*
- Melting process starts at low voltage (short arc) between the electrodes and the scrap.
- The arc during this period is unstable.
- In order to improve the arc stability small pieces of the scrap are placed in the upper layer of the charge.
- The electrodes descend melting the charge and penetrating into the scrap forming bores.

- The molten metal flows down to the furnace bottom.
- When the electrodes reach the liquid bath the arc becomes stable and the voltage may be increased (long arc).
- The electrodes are lifting together with the melt level. Most of scrap (85%) melt during this period.

Temperature of the arc reaches 6300ºF (3500ºC).

OXIDIZING STAGE

- At this stage excessive carbon, phosphorous, silicon and manganese oxidize.
  The process is similar to that in Basic Oxygen Furnace.
- Basic oxidizing slag composed of lime (CaO) and ion ore (FeO) is used during the oxidizing period.
  Gaseous oxygen may be blown into the melt for additional oxidizing.

REDUCING STAGE

- New slag composed mainly of lime (CaO), CaF2 (as slag fluidizer) is added at this stage for formation of basic reducing conditions.
- The function of this slag is refining of the steel from sulfur and absorption of oxides, formed as a result of deoxidation ("killing").
- The excessive oxygen dissolved in the melt during oxidizing period is removed by metallic deoxidizersMn, Si, Al:

$$[Mn] + [O] = (MnO)$$

$$[Si] + 2[O] = (SiO_2)$$

$$2[Al] + 3[O] = (Al_2O_3)$$

Basic reducing slag is favorable for desulfurization in accordance to the reaction:

$$[S] + (CaO) = (CaS) + [O]$$

Oxide and sulfide non-metallic inclusions are absorbed by the slag

- Iron oxide causes increase of Oxygen content in the molten steel according to the reaction:
  (square brackets [ ] - signify solution in steel, round brackets ( ) - in slag, curly brackets {} - in gas)

  $(FeO) = [Fe] + [O]$

  Oxygen dissolved in the melt oxidizes carbon, phosphorous, silicon and manganese:

  $[C] + [O] = \{CO\}$

  $[Si] + \{O_2\} = (SiO_2)$

  $[Mn] + 1/2\{O_2\} = (MnO)$

  $2[P] + 5/2\{O_2\} = (P_2O_5)$

  Carbon monoxide partially burns in the atmosphere:

  $\{CO\} + \{O_2\} = \{CO_2\}$

ADVANTAGES OF ELECTRIC ARC FURNACE

- The use of EAFs allows steel to be made from a 100% scrap metal feedstock.
- This greatly reduces the energy required to make steel when compared with primary steelmaking from ores
- . Another benefit is flexibility: while blast furnaces cannot vary their production by much and can remain in operation for years at a time,

- EAFs can be rapidly started and stopped, allowing the steel mill to vary production according to demand.
- During the peak of global financial meltdown in 2009, an estimated quantity of only 1 million tonne was produced in USA employing EAF technique.
- Although steelmaking arc furnaces generally use scrap steel as their primary feedstock,

- if hot metal from a blast furnace or direct-reduced iron is available economically, these can also be used as furnace feed.
- A typical steelmaking arc furnace is the source of steel for a mini-mill, which may make bars or strip product. Mini-mills can be sited relatively near to the markets for steel products, and the transport requirements are less than for an integrated mill, which would commonly be sited near a harbour for access to shipping.

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- Steelmaking in electric arc furnace has emerged as an important steelmaking process in recent years.
- The flexibility and easy adoptability of EAF steelmaking to accommodate the fluctuating market demand have evolved into the concept of mini steel plants to produce different grades of finished products (long or flat or mixed) of plain carbon or alloy steels from scrap and other metallic charge materials.

- Although scrap is the preferred raw material but sponge iron and iron carbide are being used regularly in most plants because of shortage of steel scrap and to dilute the concentration of tramp elements.
- Several developments in the design and operation have made EAF steelmaking to contribute significantly to the overall total production of steel in the world.
- According to an estimate, the proportion of electric steel is around 40 to 45% in the total world steel production.
- It must be noted that EAF consumes lot of electric energy and hence the cost and availability of electrical power are important issues in electric steel development.

TYPE OF ELECTRIC FURNACES

- In principle an electric arc is formed between the electrode and the metallic charge and charge is heated from the arc radiation.
- Electric arc furnaces are of two type (a) alternating current and (b) direct current.
- In alternating current, furnace operates by means of electric current flowing from one electrode of three to another through the metallic charge.
- In direct current, the current flows from carbon electrode, which acts as cathode, to an anode embedded in the bottom of the furnace.

CONSTRUCTION OF AC ELECTRIC ARC FURNACE

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

HEARTH

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

ROOF

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

ELECTRODE

- A typical alternating current operated EAF has three electrodes.
- Electrodes are round in section, and typically in segments with threaded coupling, so that as the electrodes wear, new segments can be added.
- Graphite electrodes are preferred over carbon electrodes because of better electrical conductivity.
- The electrodes are automatically raised and lowered by a positioning system.

- Electrode consumption depends on
  - Oxidation of the surface of the electrode
  - Mechanical losses due to fracture
  - Dissolution in slag during carbon boil
- The diameter of the electrode should correspond to the current supplied; if current density is excessively high, electrodes will be heated and oxidized vigorously.
- The electrode current could vary from 12 to 16Acm2⁄ 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 centers of electrodes is called the diameter of the electrode spacing.
- If the electrodes are placed close to each other and far from furnace walls, the charge at the furnace banks will be heated belatedly.
- With large spacing diameter, electric arcs will burn near the walls, which will result in rapid wear of the lining.

- The electrode spacing diameter for the bath diameter could be 0.45 for small furnaces, 0.35 for medium- sized and large furnaces, and still lower for super- powerful furnaces.
- For a bath diameter of 5560 mm of a 100 ton furnace the electrode spacing diameter would be 0.35×5560=1900mm.

SIDE 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.
- The side wall thickness is usually 450 to 500mm for 10 to 50 ton furnaces and 550 to 650mm for 100 to 200 ton furnaces.

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 with the refining period.

- In small furnaces, the power consumption for melting is about 600kWh/ton and it falls to 450kWh/ton in big furnaces.
- Additional 150 to 400 k Wh/ton power is required during refining depending on the practice.

- Large transformers are required to run electric arc furnaces.
- During melting more power is required than during refining.
- The transformer capacity is designed to suit melting requirements.
- The capacity of the transformer is usually 470-650 KVA per tonne of furnace capacity.
- In terms of hearth area, the transformer capacity is in the range of 750-900 KVA per square meter

CHARGING MATERIALS

- Steel scrap is the principle 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.

PLANT LAYOUT

- Layout of an electric arc furnace steelmaking shop varies from plant to plant due to difference in the quality of the product and the scale of production.
- Some plants have just one EAF while others have two.
- The variation is also due to whether the shop is provided with oxygen lancing and carbon injection facilities, gas cleaning equipments and finished castings or ingots.

BROADLY ELECTRIC FURNACE STEELMAKING SHOP COMPRISES OF THE FOLLOWING:

a) Electric furnace
b) Transport facilities for ladle
c) Scrap charging
d) Auxiliary injection facilities
e) Electrode movement mechanism
f) Charging of raw materials and weighing system
g) Slag disposal.

In an ideal layout, all the above facilities should be arranged so as to ensure smooth input and output of materials.

ARC FURNACES OPERATION

- It consists of charging, melt down period and refining. The large baskets containing heavy and light scrap are preheated through the exit gas.
- Burnt lime and spar are added to help early slag formation. Iron one or mill scale may also be added if refining is required during melt- down period.
- The roof is swung off the furnace, and the furnace is charged. Some furnaces are equipped with continuous charging. Hot metal is also charged as per the requirement.

- In the meltdown period, electrodes are lowered and bored into the scrap.
- Lower voltages are selected in order to protect the roof and walls from excessive heat and damage from the arcs.
- Once the arc is shielded by scrap, voltage is increased to form molten metal pool to reduce the meltdown period.
- During meltdown period, silicon, manganese and carbon oxidizes.
- Also oxidizing and limy slag is produces which promotes dephosphorization as well.

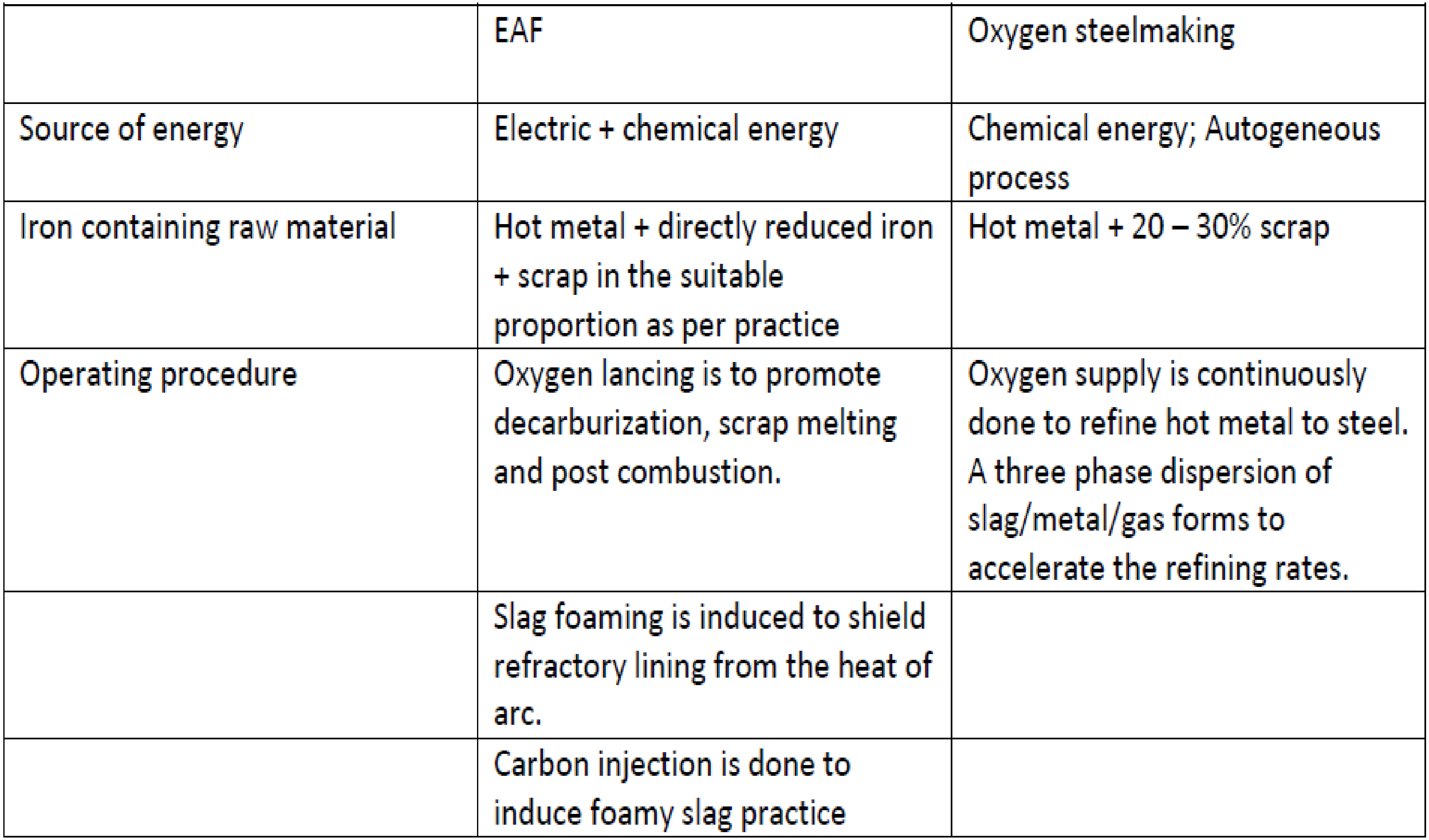
MELT- DOWN TIME DEPENDS ON

  - Arc conditions: larger arc requires lower current and lower heat losses
  - Deep or shallow bath: deep bath shortens the meltdown period.
- Refining continues even during melting. Removal of phosphorus must be complete before the rise in temperature and carbon boil.

- The single oxidizing slag practice is employed when removal of sulphur is not required.
- When both P and S are required to be removed double slag practice is used.
- In double slag practice, oxidizing slag is removed and reducing slag is formed after deoxidation with ferrosilicon or ferromanganese or aluminum.

- Reducing slag helps to avoid loss of alloying elements
- Once the bath chemistry and its temperature are attained, heat is deoxidized and finished for tapping

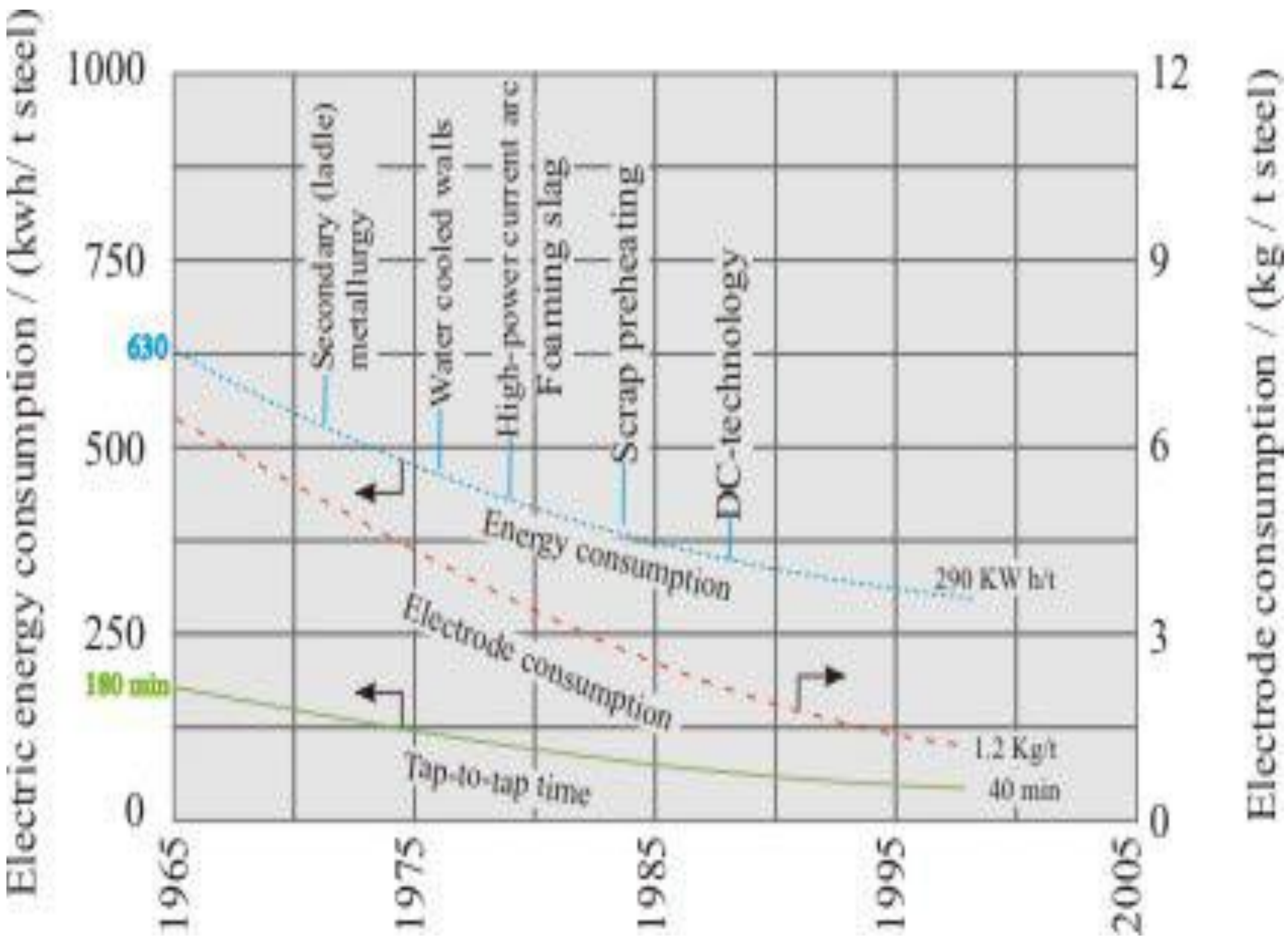
COMPARISON WITH OXYGEN STEELMAKING



	EAF	Oxygen steelmaking
Source of energy	Electric + chemical energy	Chemical energy; Autogeneous process
Iron containing raw material	Hot metal + directly reduced iron + scrap in the suitable proportion as per practice	Hot metal + 20 – 30% scrap
Operating procedure	Oxygen lancing is to promote decarburization, scrap melting and post combustion.	Oxygen supply is continuously done to refine hot metal to steel. A three phase dispersion of slag/metal/gas forms to accelerate the refining rates.
	Slag foaming is induced to shield refractory lining from the heat of arc.	
	Carbon injection is done to induce foamy slag practice	

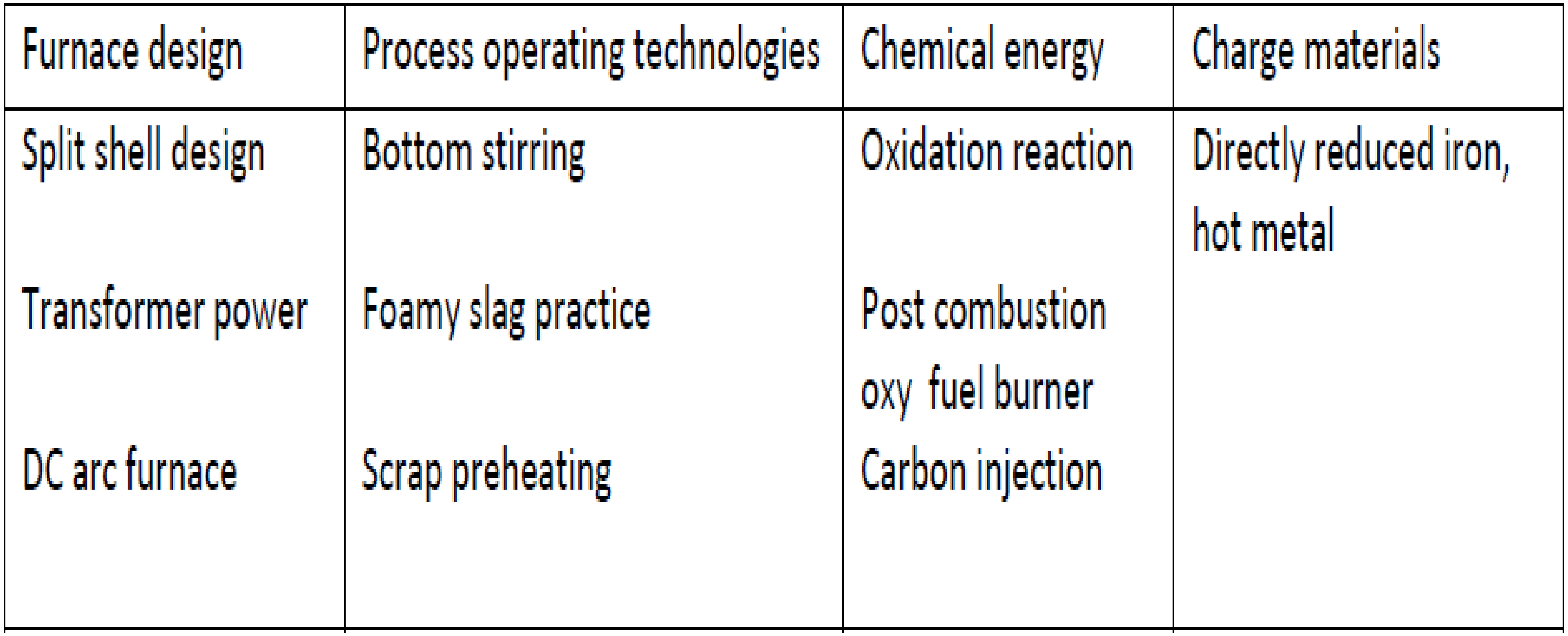
MODERN DEVELOPMENTS IN ARC FURNACE

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


Electric energy consumption / (kwh/ t steel)
Electrode consumption / (kg / t steel)
1000
750
500
250
0
630
180 min
12
9
6
3
0
1965
1975
1985
1995
2005
Secondary (ladle) metallurgy
Water cooled walls
High-power current arc
Foaming slag
Scrap preheating
DC-technology
Energy consumption
290 KW h/t
Electrode consumption
1.2 Kg/t
Tap-to-tap time
40 min

- Figure shows the developments in electric steelmaking technologies.
- Developments in EAF technologies are strongly supported by secondary steelmaking. One can note in the figure that the power consumption has decreased from 630
- Kwh/ton of steel to 290kWh/ton. Similarly tap tp tap time has decreased from 180 minutes to 40 minutes and electrode consumption has decreased from arounf 6.2 kg/ton to as low as 1.2 kg/ton within the periods of representation in the figure.
- This became possible with the several simultaneous developments in the secondary steel-making method. Table shows the various developments

DEVELOPMENT IN EAF



Furnace design	Process operating technologies	Chemical energy	Charge materials
Split shell design	Bottom stirring	Oxidation reaction	Directly reduced iron, hot metal
Transformer power	Foamy slag practice	Post combustion oxy fuel burner	
DC arc furnace	Scrap preheating	Carbon injection	

FURNACE DESIGN (1)

- Construction of hearth and lower side section of the shell of larger diameter than the top opening. This leads to increase in shell volume which results in larger tonnage charge, lower heat losses and improved thermal efficiency.

(2)

- In the split shell design, shell structure is constructed in two sections: lower section which contains hearth and free board allowance for slag, and upper section containing side wall and roof. The two sections are coupled such that the upper section can be repaired easily. This reduces the downtime and increases furnace availability.

(3)

- High powered transformers are the current trends. Most modern furnaces operate at 500k VA/ton and the trend is towards ultra high power ranging in between 700k VA/ton to1000k VA/ton.
- Developments are in progress to install transformer with 1500k VA/ton capacity.
- It is claimed that a 120 tons operating at 180 MVA transformer capacity and by using refining combined burner technology through oxygen gas and carbon injection, it is possible to increase capacity by up to 50%.
- The largest transformer in AC EAF corresponds to a rated power 0f 240 MVA for 300 ton furnace.

(4)

- Eccentric bottom taping reduces tap times, temperature losses and slag carry over into ladle. The strip producing plants are equipped with eccentric bottom tapping in electric arc furnaces.

(5)

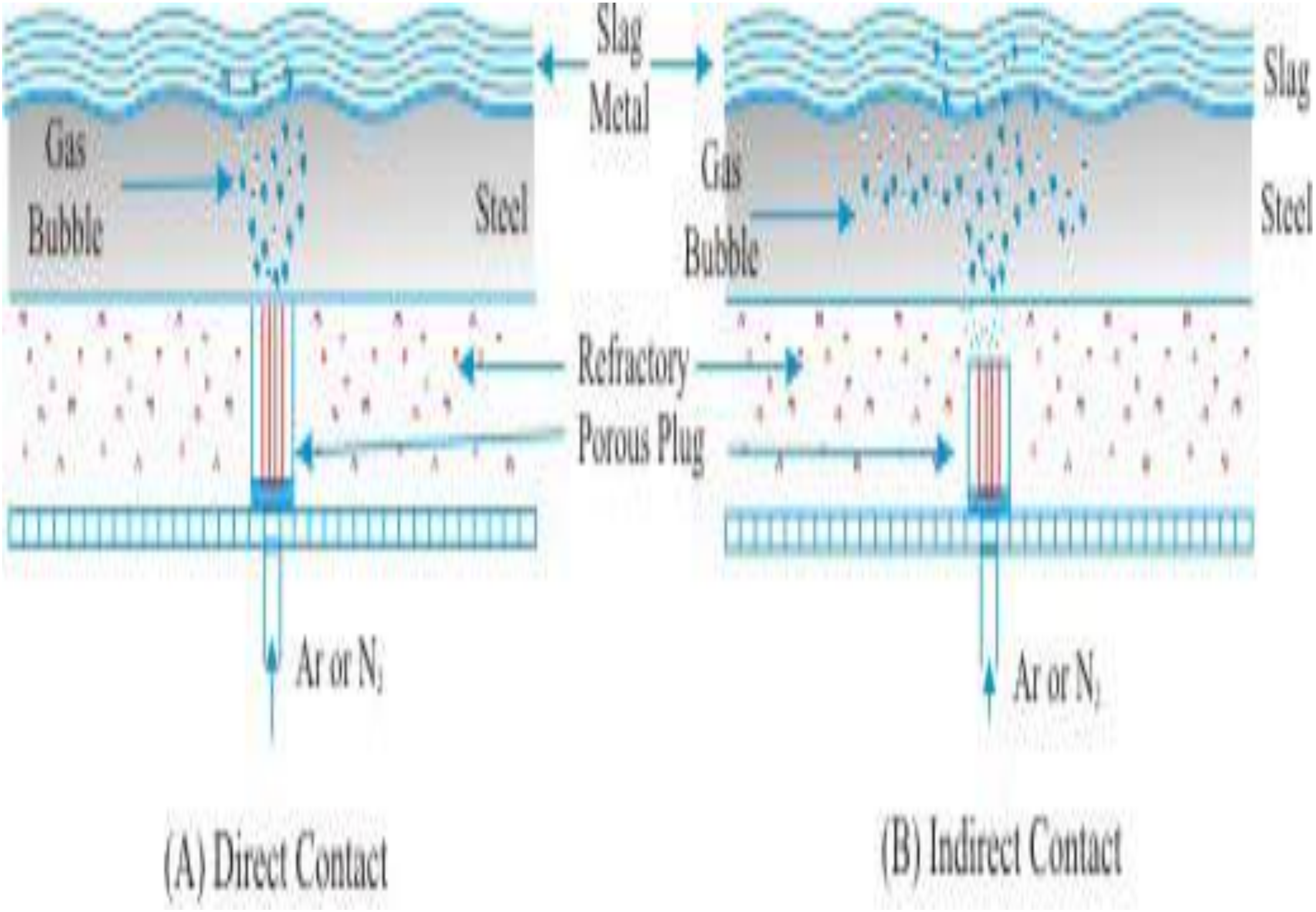
- DC (direct current) arc furnaces represent a different concept in arc furnace design.
- Most DC furnaces are with single electrode where current flows down from the carbon electrode to an anode mounted in the bottom of the furnace.
- Reduced electrode consumption of the order of 50 to 60 % is the major benefit of a dc furnace compared to a convectional three- phase arc furnace.

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

PROCESS OPERATING TECHNOLOGIES

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

- i) Bottom stirring
- In convectional arc furnaces there is little natural electrical turbulence within the bath. Due to absence of stirring large piece of scrap can take a long time to melt and may require oxygen lancing. Argon or nitrogen stirring
  - Eliminates temperature and concentration gradients
  - Shortens tap-to-tap times
  - Reduces refractory, electrode and power consumption and
  - Improves yield of iron and alloys


Slag
Metal
Gas
Bubble
Steel
Gas
Bubble
Slag
Steel
Refractory
Porous Plug
Ar or N_2
Ar or N_2
(A) Direct Contact
(B) Indirect Contact

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

II) FOAMY SLAG PRACTICE

- In EAF steelmaking, progressive melting of scrap increases the irradiative heat transfer from arc to the side walls of the furnace. By covering the arc in a layer of slag, the arc is shielded and more energy is transferred to the bath. The foaming slag during this period is beneficial.
- The effectiveness of slag foaming depends on slag basicity, FeO content of slag, slag temperature and availability of carbon to react with either oxygen or FeO of slag.

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

a) Reaction between FeO of slag with carbon

- $(FeO) + C = [Fe] + \{CO\}$ ------------------------(1)

b) Between carbon and oxygen dissolved in metal

- $[C] + [CO] = \{CO\}$ ----------------------------------(2)

c) Between chromium oxide and carbon:

- $Cr_2\,O_3 + 3C = 2Cr + 3CO$ ------------------------(3)

- Reactions 1 and 2 are important in carbon steelmaking whereas reaction 3 is important in stainless steel making.
- Injection of carbon and oxygen at several places in the bath assures slag foaming practice, when carbon content of the bath is insufficient.
- Typically carbon injection rates for slag foaming are 2.5 to 5 kg/ ton of steel. In high powered furnaces carbon injection is 5-10 kg/ton of steel.

SCRAP PREHEATING

- Preheating of scrap brings thermal energy into the furnace. Preheating of scrap to 540℃ brings 81kwh/ton of additional energy. Scrap preheating gives the following advantages:
  - Reduction in energy consumption by 40-60 kwh/ton depending on the scrap preheat temperature
  - Electrode consumption reduces by 0.3 to 0.36 kg/ton
  - Refractory consumption decreases by 0.9 to 1.4 kg/ton
  - Tap to tap time reduces by 5 to 8 minutes.

- It is important to note that scrap preheating technology needs to be developed. Thermal energy is required to preheat the scrap and is economical only when the waste heat from the furnace is utilized.

FUTURE OF EAF STEELMAKING

- The EAF needs a metallurgical reactor that has the largest growth potential both in terms of production capacity and technology evolution.
- Future EAF will be equipped with all modern technologies- like Ultra high power input (up to1500 kVA/t), latest oxygen and carbon injection technology and design features- like ultra high shell design, heavy mill type components

- This combination leads to an Electric Arc Furnace where the tap to tap times can be extremely short and the corresponding productivity reaches the level of larger furnace sizes or converter plants.
- The two main reasons for this are:
  - The possibility of a higher electrical power input and
  - A far higher efficiency of chemical energy, decarburization and scrap preheating compared to the same size (tap weight) standard furnace.

IT IS INTERESTING TO COMPARE A CONVENTIONAL 120TON EAF WITH THE ULTIMATE 120 TON EAF.

Conventional 120 ton EAF	Ultimate 120 ton EAF
2- bucket charge Scrap bucket 130 m^3 Furnace volume 145 m^3	1-bucket charge Scrap bucket 185 m^3 Furnace volume 210 m^3
Transformer design upto 1,000kVA/t, 120MVA for 120 ton tapping weight, Secondary voltage up to 1,200V	Transformer design upto 1,500kVA/t, 180MVA for 120 ton tapping weight, Secondary voltage up to 1,500V
Utilization of chemical energy 3 oxygen gas burners 3 refined combined burners (RCB) 2 carbon injectors	Utilization of chemical energy 3 oxygen gas burners 5 refined combined burners (RCB) 4 carbon injectors 4 post combustion injectors

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

UNIT 3

QUALITY STEEL MAKING

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

- Inclusions are of two types:
  - Indegenious: Those arising in the course of steelmaking.
  - Exogenous: Those arising from mechanical erosion of contacting refractory lining.
- Indegenous inclusions comprise of deoxidation products like oxides, oxy-sulphides or precipitates like sulphides, carbides, nitrides etc.
- Almost all sulphur is precipitated in form of iron sulphide or manganese sulphide, the best way is to keep sulphur as low as possible to avoid formation of inclusions.

- Oxide inclusions can be kept at a minimum by suitable deoxidation practice. Enough time is allowed for them to rise to the surface in the ladle.
- Alternatively, if economically permissible, vaccum treatment may be adopted to decrease the oxygen content of steel.

- Nitrides form only if dissolved nitrogen level is high. Addition of Zr, Ti and V form stable nitrides.
- Titanium carbide may act as an inclusion
- In general proper care during refining and more particularly during deoxidation can minimize the indigeneous inclusions.

- The exogenous inclusions arise from the mechanical erosion of refractory lining with which metal comes in contact during its processing.
- In particular the erosion of ladle and more so of the refractories used in the assembly of the mould contributed most to the formation of exogenous inclusions.
- The best way to keep them down is to use minimum of such refractory channels through which metal has to flow before solidification.

- Use of strong refractory for such places is definitely beneficial.
- Inclusions are not always undesirable.
- These are purposefully introduced to gain certain desirable effects.
- For example sulphur inclusions when form mangenese sulphides improves machinability.
- Exogenous inclusions are used for dispersion strengthening of steels.
- Stable nitrides are useful since the ill effects of dissolved excess nitrogen is thereby eliminated.

SULPHUR IN STEELS

- S is an element which is always present in steel in small quantities. S in steel is introduced through iron ore and fuel (coal and coke).
- The removal of S during steel making is a tedious and difficult process.
- S is normally regarded as an impurity in steel and is required to be reduced to the limits of practicality.

- However steels which are to be machined need a certain minimum S content for proper chip formation.
- Where machining constitutes a major fraction of the end products cost, many types of steel (carbon, alloy, and less often stainless) are intentionally resulphurized just for this reason.

- Except in those cases where it is added for machinability, or where residual S content of around 0.040 % maximum is tolerable, the usual aim during iron and steel making is to reduce S to low levels, consistent with mechanical property requirements.
- For high strength (HS) steel plates and for some special bar quality (SBQ) steel products, this may mean removing the S to a level of 0.005 % maximum.

- There are several methods which are widely used for achieving this level of S.
- Further, efficient removal of S from liquid steel or iron depends on specific metallurgical and thermodynamic conditions.
- Though these conditions may vary with the type of S removal system, most of them require reducing conditions (low FeO level).

- Also, it is important that slag, and therefore refractory conditions be basic (having high basicity ratio).
- Also the temperature preferably be high since the process of S removal is normally endothermic.
- While S can be removed anywhere between the blast furnace and the steel teeming ladle, it is now generally established that larger cost benefits are obtained when desulfurization is performed at the hot metal stage.

DESULPHURISATION

- Removal of sulphur from hot metal is called desulphurization of hot metal. Sulphur is a desirable element in steel when good machinability is required from the steel product.
- However it is an unwanted element in most of the applications of steel due to the following reasons.

- Sulphur affects both internal and surface quality of steel
- Sulphur contributes to the steel brittleness and when it exists in sulphide phase it acts as a stress raiser in steel products.
- It forms undesirable sulphides which promotes granular weakness and cracks in steel during solidification.
- It has adverse effect on the mechanical properties.
- It lowers the melting point and intergranular strength and cohesion of steel.

- Unlike other impurities which are removed from the hot metal by oxidation in the oxygen converter, the most economic method of removing sulphur from the hot metal is by reduction either in the transfer ladle or in the charging ladle, before it is charged in the converter.

- A number of technologies have been developed for the external desulphurization of hot metal but all of them have the basic requirement of a reagent and a method of mixing.
- The difference between the technologies used is the properties of the reagents, the effectiveness of the reagent to remove sulphur and the effectiveness of the mixing method to get the reagent into solution. .

- Also the effectiveness of hot metal desulphurization is inversely proportional to the desulphurization reagent injection rate.
- The most popular desulphurizing process today is deep injection of desulphurizing agent in the hot metal.

DESULPHURIZATION PROCESS

- Dip lance process is the most economical, effective and reliable method of desulphurization hot metal.
- It consists of pneumatic injection of fine grained desulphurization reagent into the hot metal with high dosing precision via a dispensing vessel and a refractory lined lance.
- For each reagent, one separate dispensing vessel is used.
- All the vessels are identical.
- Nitrogen gas is normally used as a carrier gas for the desulphurization reagent.
- The reagent transfer in the injection line is under dense flow conditions.

- The dense flow conditions maximize reagent delivery as well as reduce abrasion wear of injection lines.
- The injection of desulphurization reagents through deeply submerged lance causes an intimate mixing of the desulphurization reagent with the hot metal.
- The process allows the use of several desulphurization reagents, such as lime, calcium carbide and magnesium, which remove the sulphur in the hot metal by chemical reaction and convert it to the slag.

- Sulphur rich slag generated during the process is removed immediately after completion of the reagent reaction.
- The most common method is to tilt the ladle and rake the slag off with the help of a slag raking machine.

- Hot metal sulphur content is reduced in charging ladle or transfer ladle worldwide by this method.
- For controlling the operating cost, a combination of dip lance method with mathematical process control and flexible control of the desulphurization plant is adopted.
- This combination provides a range of possible process technological variations.

- One of these possibilities is to vary the injection rate (kg/min.) to suit the production requirements.
- Another possibility is to inject different desulphurization reagents during the process of desulphurization.
- The desulphurization reagents can be injected singly, simultaneously or with a time lag.
- Accordingly the process variations are known as mono injection, co injection or multi injection.
- Dip lance method can reliably reduce the sulphur content of hot metal to figures as low as 0.001 %.

DESULPHURIZING REAGENTS

- The most commonly used desulphurizing reagents are lime (CaO), calcium carbide (CaC2) or magnesium (Mg).
- There are some important issues with respect to the desulphurizing reagents. All desulphurizing reagents are not equal in their ability to remove sulphur. Magnesium although more expensive, has approximately 20 times the capacity of removing sulphur as lime.

- Calcium carbide has eight times more potential to remove sulphur than lime.
- However, if injected into hot metal on its own, it must be blended with volatiles in order to increase the agitation of the bath.
- Pre blending of different desulphurizing reagents such as magnesium-lime or magnesium- calcium carbide is not useful since blended reagents are prone to segregation during transport and storage besides individual injection rates of desulphurizing reagents gets sacrificed

PHOSPOROUS IN STEEL

- P is normally considered an undesirable impurity in steels. It is present in varying concentrations in iron ore, is retained in hot metal, but is eliminated early in the steelmaking process.
- P oxidizes readily and is removed from steel as P_2O_5, which is taken up by the oxidizing slag, before the oxidation of carbon takes place. Carryover of any P_2O_5 containing oxidizing slag can result in P reversion to the steel in subsequent steelmaking operations.

- In normal commercial steels, residual P content is usually at a level of 0.05 % max, but concentrations as low as 0.005 % are not unusual. P is readily removed only in basic steelmaking processes.
- Detrimental effects of P in steel include various forms of embrittlement which reduce the toughness and ductility.
- The most familiar example in this category is the classic phenomenon of temper embrittlement in heat treated low alloy steels resulting from segregation of phosphorus and other impurities at prior austenite grain boundaries.

GASES IN STEEL (NITROGEN)

- Except a small proportion of steel wherein the hardening influence of extra nitrogen content is made use of in developing

GASES IN STEEL (OXYGEN)

- Oxygen is supplied for refining iron and hence, a certain fraction is inevitably left over as dissolved oxygen in liquid steel at the end of refining.
- Several useful deoxidisers have been found to effectively deoxidise liquid steel is to obtain sound ingots on solidification.
- The use of deoxidisers, unless it forms gaseous product of deoxidation reaction, tends to decrease cleanliness of the steel.

- Where cleanliness is of prime importance and where oxygen is to be reduces to a lower level than that attainable by normal deoxidation practice, liquid steel has to be treated under vaccum prior to solidification.

DEOXIDATION: INTRODUCTION

- Refining of hot metal to steel is done under oxidizing atmosphere.
- During refining oxygen dissolves in steel.
- Solubility of oxygen in steel is negligibly small.
- During solidification of molten steel, excess oxygen is rejected by the solidifying steel.
- This excess oxygen produces defects like blow holes and non- metallic oxide inclusion in solidified casting.
- Defects have considerable effect on mechanical properties of steel.

- Therefore, it is necessary to remove oxygen from steel; removal of oxygen is called Deoxidation.

- **Sources of oxygen in steel**
  - Rust on steel
  - Oxygen blowing
  - Steelmaking slag
  - Atmospheric oxygen dissolved in steel during teeming
  - Oxidizing refractories

- At 1600°C solubility of oxygen in liquid steel is 0.23% which deceases to 0.003% in solid steel during solidification. According to the degree of deoxidation, carbon steels may be subdivided into three groups:

i. Killed steel: Oxygen is removed completely. Solidification of such steels does not give gas porosity (blow holes).

ii. Semi –killed steel: Incompletely deoxidized steels containing some amount of oxygen which froms CO during solidification.

iii. Rimming steel: Partially deoxidized or non-deoxidized low carbon steels evolving sufficient CO during solidification. These steels have good surface finish.

DEOXIDATION OF STEEL

- Deoxidation can be carried out either by single element such as Si,Al,Mn etc or by mixture of elements such as Si+Mn,Ca–Si–Al etc.
- De oxidation by single element is known as simple deoxidation, whereas deoxidation by a mixture of elements is known as complex deoxidation.

- In both simple and complex deoxidation, oxide is formed; hence it is also termed precipitation deoxidation.
- Deoxidation is also carried out by carbon under vacuum; which is called vacuum deoxidation.
- Elements are added in the form of Ferro-alloys Fe− Si,Fe−Mn or Fe Si + Fe Mn etc.

- Simple deoxidation can be represented by

$$a[M]+b[O]=(M_a\ O_b)\ \text{------}(1)$$

- If deoxidation product is pure then activity of $(M_a\ O_b=1)$ and if elements are in dilute solution

$$[W_M]^a[W_O]^b=K_m\ \text{---------}(2)$$

- Where K_M is deoxidation constant and equals to $1/KM_1$ where KM_1 is equilibrium constant.

$$\log K_M=-X/T+Y\ \text{----------}(3)$$

- Where X and Y are constants and T is temperature. Increase in T increases K_M.
- Using equations 2 and 3 one can calculate the variation of W_O with W_M when W_M is in small quantity.
- In complex deoxidation where a mixture of Si+Mn,Ca+Si,Ca+Si+Al is used, the following advantages are reported as compared with simple one:
  - The dissolved oxygen is lower.
  - Due to formation of liquid deoxidation product agglomeration of the product into large size can be obtained easily and can be floated easily.

- According to equation 2

$$[W_O]^b = K_M[W_M]^a \text{ ----------(4)}$$

- Equation 4 indicates that weight percent oxygen in steel depends on value of K_M for small concentration of deoxidizers. At 1600°C the value of Km is 2.4×10^{-5} for the reaction
- $Si+O_2=SiO_2$ and for the reaction

- 2 Al+3O=Al_2O_3 the value of $K_M=3.32\times10^{-14}$.

- Similarly for the reaction Ca+O=CaO, $K_M=9.84\times10^{-11}$.
- The value of K_M indicates the deoxidizing ability of an element.
- For the above reaction, calcium is the most efficient deoxidizer and Si is not so efficient as compared to calcium. Aluminum is also a strong deoxidizing element when compared with silicon.

- Though calcium and aluminum are very efficient deoxidizers, but they oxidize very fast and moreover, their density is much lower than steel.
- Also Ca has a boiling point 1485°C which means calcium is gaseous phase at the steelmaking temperature. Suitable injection methods or addition methods are to be developed.

KINETICS OF DEOXIDATION

- Total oxygen in steel equals to dissolved oxygen + oxygen present in deoxidation products (SiO_2,Al_2O_3,MnO etc). Even if the dissolved oxygen is low, deoxidation products (also called inclusions) have to be removed, otherwise steel is not clean (clean steel refers to number and size of inclusions in steel). Kinetics of inclusion is concerned with deoxidation reaction and separation of deoxidation products as well.

THE DEOXIDATION PROCESS CONSISTS OF THE FOLLOWING STEPS

- Dissolution and homogenization of de oxidizer. Mechanism of dissolution depends on melting point. Ferro alloys melt at around 1500°C. Aluminium is expected to melt faster due to its much lower point. Intensity of agitation will govern the homogenization of deoxidizer in steel melt for faster kinetics of reaction between oxygen and deoxidizer.
- Nucleation of solid product becomes easier if interface is present. Deoxidation by Al produces solid Al_2O_3 and as such Al_2O_3/steel interface is useful for nucleation.

- Growth of the de oxidation product: It depends on the state of the product. A liquid product can coalesce easily as compared with the solid product. Deoxidation with single elements like Al,Si etc. produce solid deoxidation product at the steelmaking temperature. Deoxidation with ferro silicon+ ferro manganese produces liquid deoxidation product. Boron, titanium zirconium are also quite effective deoxidizers. Manganese and silicon are used in the ratio 7:1 to 4:1 in order to obtain a thin liquid slag.

- Removal of deoxidation product: Removal of de oxidation product is equally important. It is achieved by floatation and absorption into a slag. Following steps are important for removal of de oxidation products from steel:

  i. Growth of de oxidation product
  ii. Movement through molten steel to surface
  iii. Absorption of inclusion by a suitable designed synthetic slag.

- Floatation of an oxide product depends among physical properties of steel, on the size of the product. The rate of rise of a spherical particle in a quiet fluid or in a fluid of laminar flow (i.e. at very low Reynold's number) can be described at steady state by Stoke's law :

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

- Where,

- Vt= terminal velocity (m⁄s)of the inclusion,
- g is acceleration due to gravity (m⁄s^2),
- Δρ= differnce in density of steel and deoxidation product and
- η is viscosity of steel (kg/m.s).

- Deoxidation products are lighter than steel; hence they move up.
- According to Stokes equation the rising velocity is proportional to square of the size of the deoxidation product.
- Larger sizes move faster. Moreover different sizes of de oxidation product will move with different velocities.
- During their movement, they may collide with one another. Stirring of melt may help floating of de oxidation products.

- Degree of stirring in the melt is important. Vigorous stirring may not be of much help since deoxidation product may be circulated in the liquid.
- For the removal of deoxidation product, equally important is the design of synthetic slag to absorb the deoxidation product

DEOXIDATION PRACTICE

- Deoxidation can be carried out during tapping, in ladles runners and even in moulds. Bath stirring is important.
- During tapping, bath is stirred due to potential energy but this subsides towards the end. When deoxidation is carried out in ladle, it is called ladle deoxidation in industrial practice.
- Depending on the extent of deoxidation, killed, semi killed and rimming steels are produced. For carbon content less than 0.15% and enough oxygen in steel, rimming steel can be produced.
- Alloy steels are fully killed to obtain maximum recovery of alloying additions.

DEGASSING PROCESSES

- There are 3 methods of degassing which are in practice:
  - Ladle degassing
  - Stream degassing
  - Circulation degassing

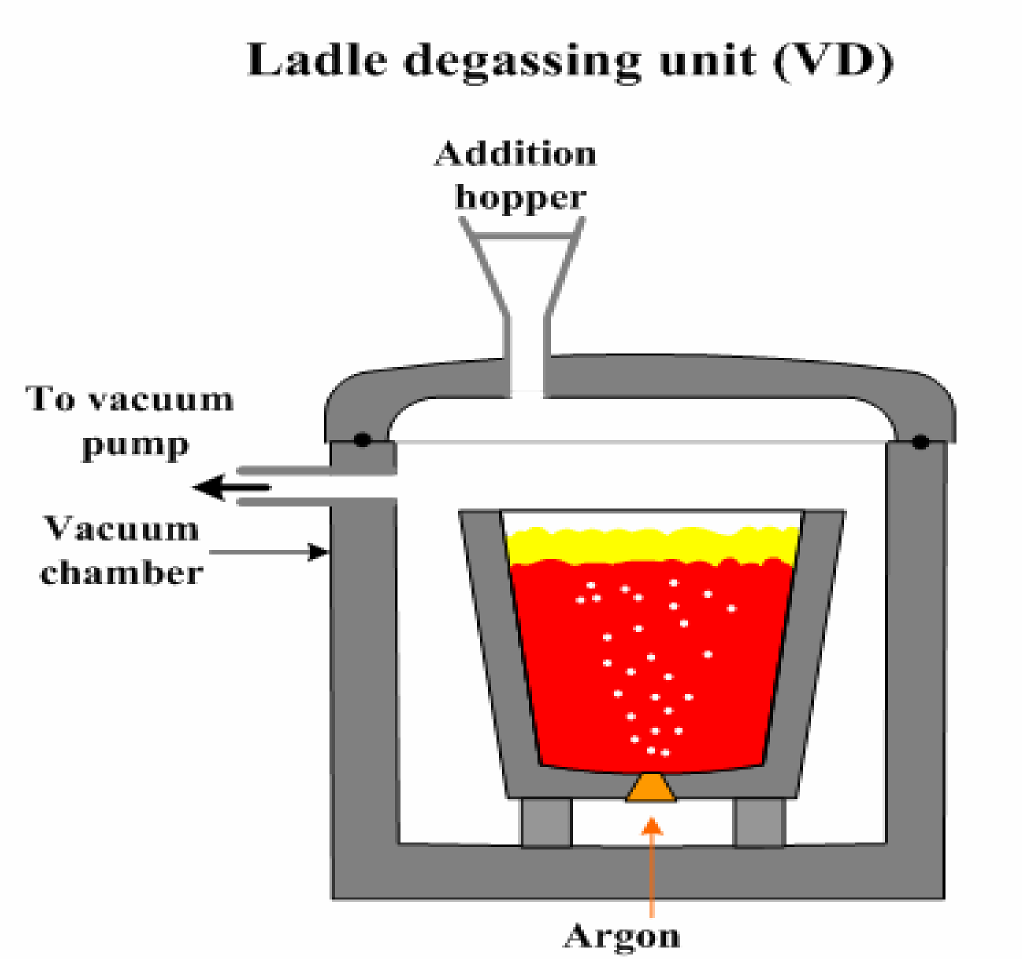
- All these processes are carried out in ladles.

- i) Ladle degassing : Liquid steel is held in a ladle which is put inside a vacuum chamber. steel may be stirred by bubbling an inert gas or by an electro-magnetic stirrer while being exposed to vacuum.

- ii) Stream degassing : Liquid steel flows down in the form of a stream from the furnace or ladle to another ladle or mould during its exposure vacuum.

- iii) Circulation degassing : Liquid steel is either continuously or intermittently circulated during its exposure to vacuum.

LADLE DEGASSING



- Ladle containing molten steel is placed in a chamber which is then evacuated. After a determined time ladle is removed from the chamber and is teemed for casting. Fig. shows ladle degassing unit.

- Ladle is provided with a porous plug at its bottom to purge argon gas as shown in the figure. In a vacuum chamber the ladle is placed.
- The vacuum chamber is equipped with a hopper so as to make additions of elements as and when it is needed.
- For effective degassing of fully killed steel, it is necessary to purge argon through the bottom of the ladle. Stirring the bath enhances rate of gas removal.

- Vigorous removal of gases causes metal splashing too. Therefore ladle is not filled completely and about 25% of its height is kept as freeboard to accommodate the splashed metal droplets.
- Pressure is maintained in between 1mmHg to 10mm Hg for effective degassing. During degassing additions are made for deoxidation and alloying.

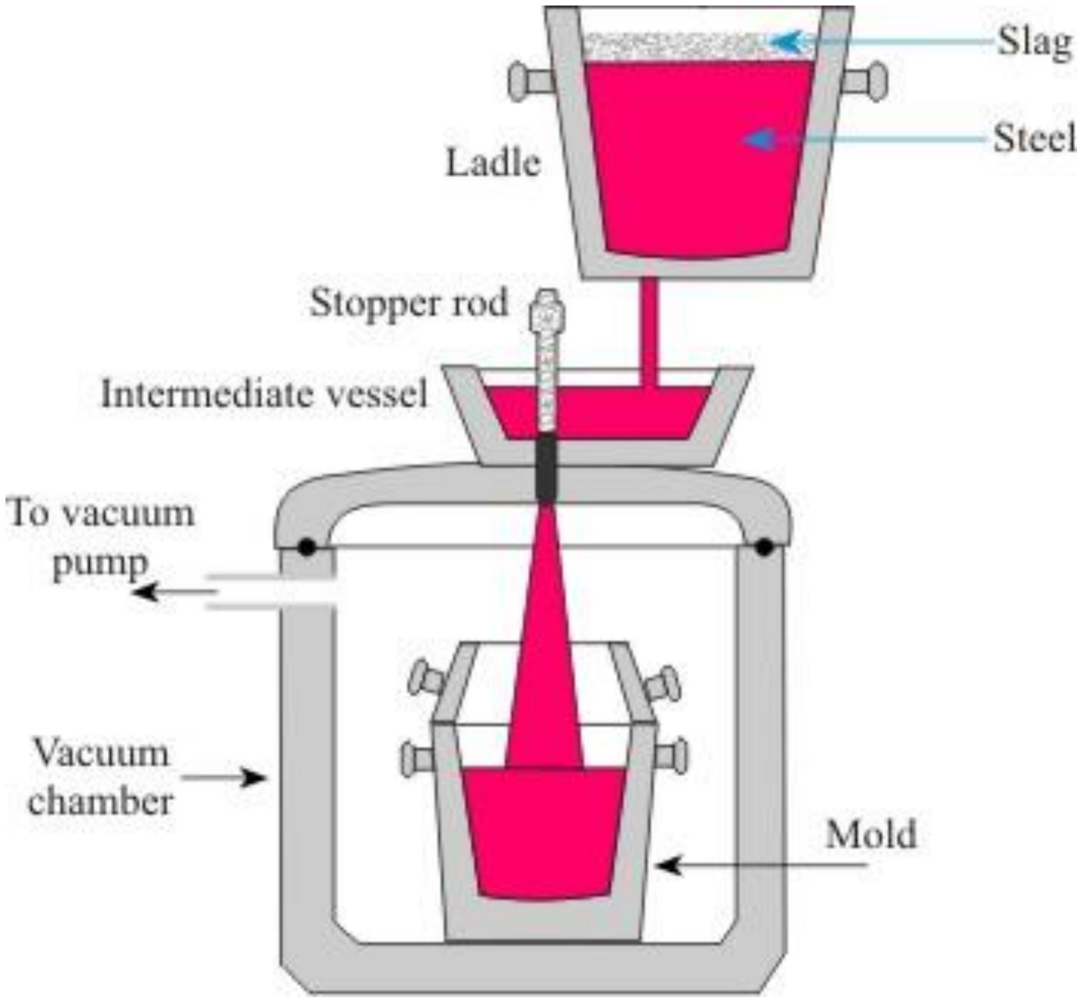
- In certain cases ladle is heated to compensate for the loss of heat during degassing.
- For the effectiveness of degassing , it is necessary that carry-over slag either from BOF or EAF should be as low as possible.
- Carry-over slag contains FeO and since oxygen content of steel is in equilibrium with FeO content of slag, oxygen content of steel increases.

- Stirring gas is introduced either from top through the roof by a submerged refractory tube or through the porous plug fitted at the bottom of the ladle.
- Electromagnetic stirring is employed for degassing. For this purpose ladle has to be made of non magnetic austenitic stainless steel or stainless window could be provided.
- For certain grades of alloy steels, both induction stirring and arc heating are employed for degassing.

- The final content of gas in steel depends on degree of vacuum and time of treatment. Hydrogen is generally reduced to below 2ppm from 4 to 6ppm, nitrogen content of steel is also reduced. The pick-up of nitrogen from the atmospheric air may occur during open pouring of steel, which must be controlled.
- Ladles are generally lined with high alumina bricks at upper part of the ladle while the lower portion is lined with fireclay.

STREAM DEGASSING

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


Slag
Steel
Ladle
Stopper rod
Intermediate vessel
To vacuum pump
Vacuum chamber
Mold

STREAM DEGASSING TECHNOLOGY HAS FOLLOWING VARIANTS IN THE PRACTICE

i. Ladle to mould degassing

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

II. LADLE TO LADLE DEGASSING

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

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

RECIRCULATION DEGASSING

- In the recirculation degassing technology, molten steel is allowed to circulate in the vacuum chamber continuously by special arrangement.
- In RH degassing technology a cylindrical refractory lined shell with two legs (also called snorkel) is designed such that steel is raised in one leg and falls back into the ladle after degassing through the second leg.
- Top side of the cylindrical shell is provided with exhaust, alloy additions, observation and control window.

- Cylindrical shell is lined with fire bricks in the upper portion, and alumina bricks in the lower portion in order to sustain high temperature.
- The legs are lined with alumina refractory.
- A lifter gas argon is injected at the inlet snorkel in order to increase the molten steel velocity entering into inlet snorkel.
- Figure shows a schematic sketch of a RH degassing unit.

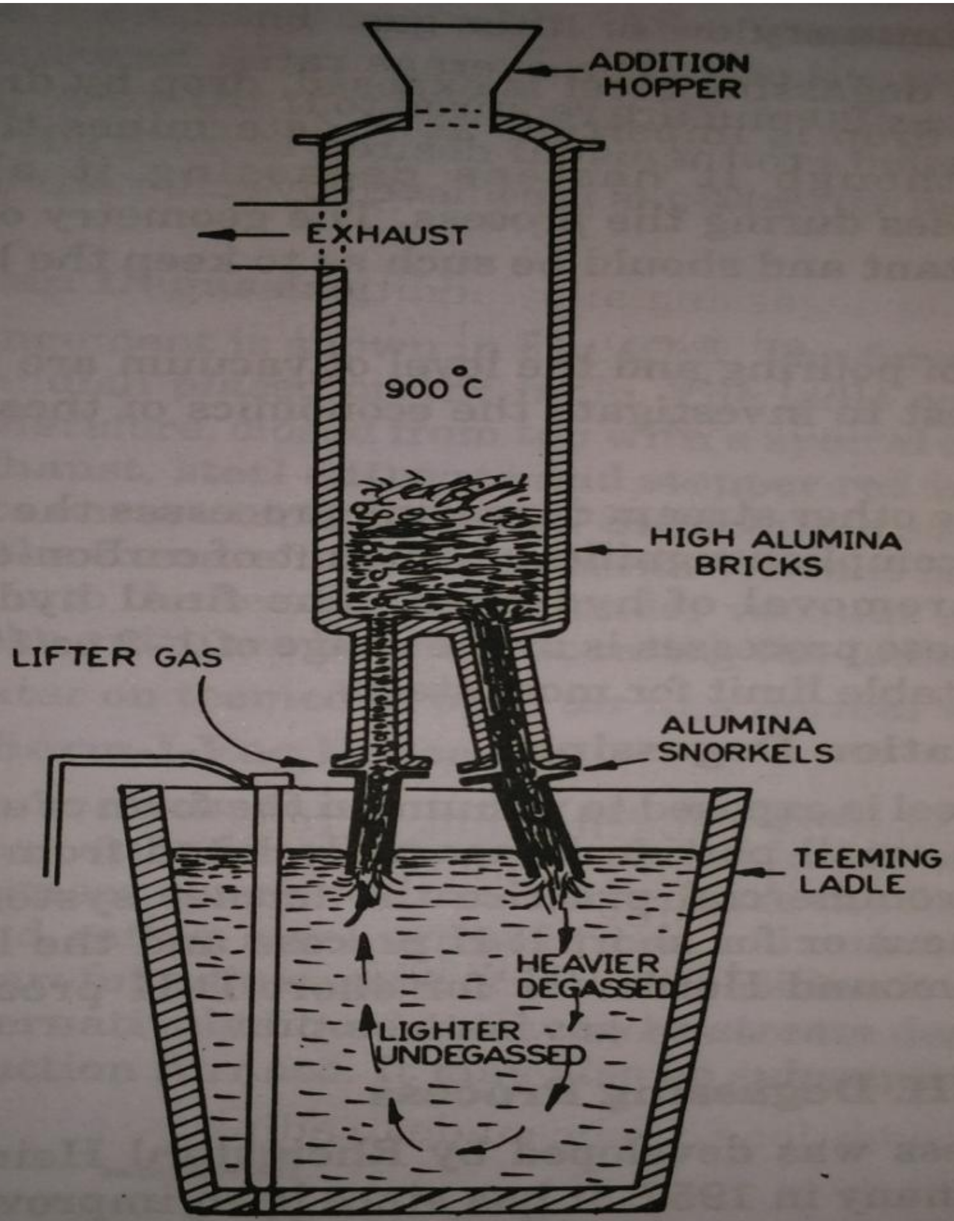


Fig. 27·7. R.H. process of degassing.

THE OPERATION OF RH DEGASSER IS AS FOLLOWS

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

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

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

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

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

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

vii) Process has several advantages like

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

DH DEGASSING

- In DH degassing, a small amount 10-15% of the total mass of steel is degassed at a time. The process is repeated until required level of degassing is achieved. The arrangement of a vessel and the ladle is somewhat similar to figure except the following:
  - In DH unit, the cylindrical vessel has one snorkel .
  - Cylindrical vessel has heating facility.

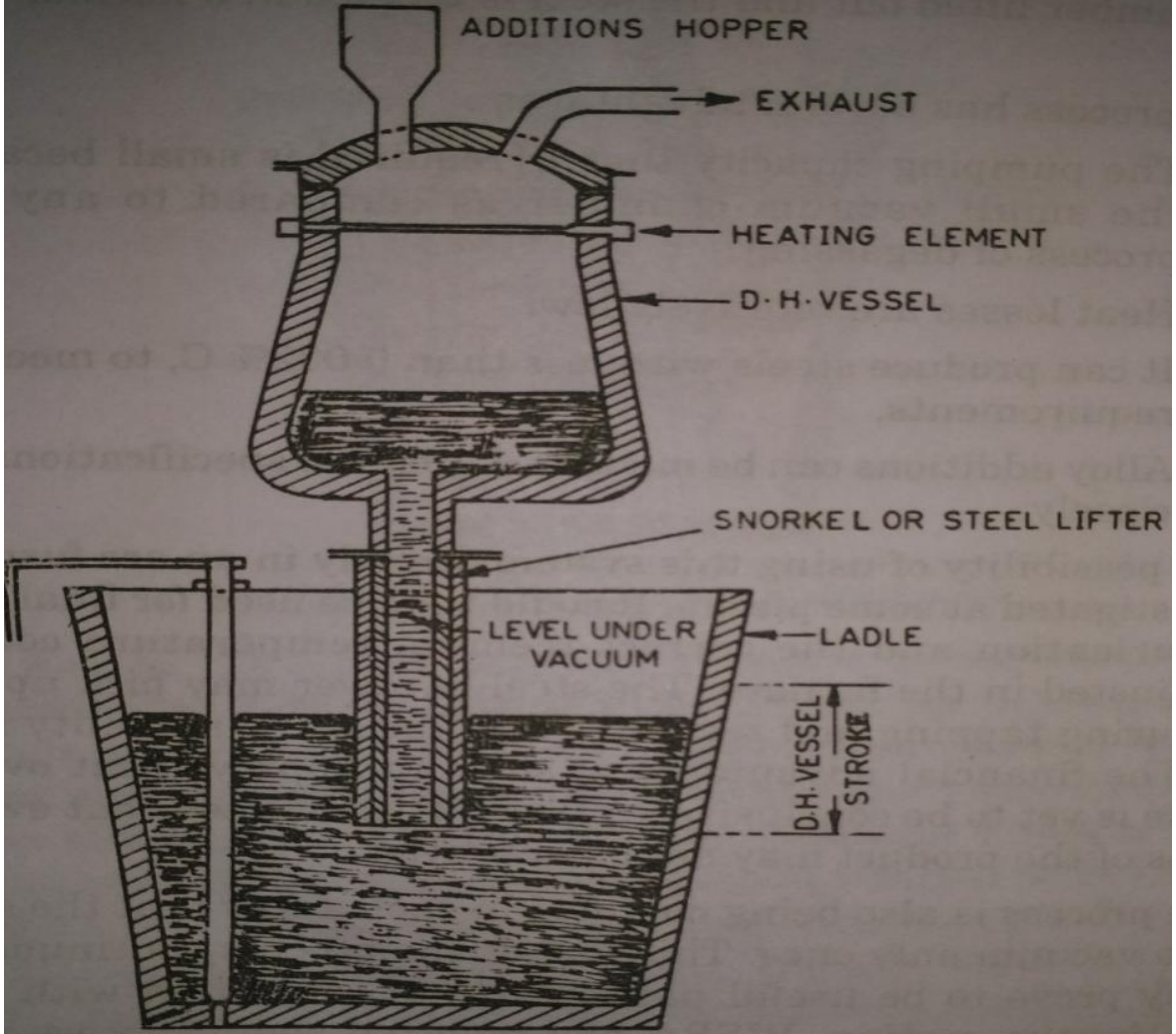


Fig. 27·8. D-H process of degassing.

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

THE FOLLOWING STEPS MAY BE NOTED FOR OPERATION

i) DH vessel is preheated and lowered in the ladle so that snorkel tip dips below the molten steel surface

ii) The evacuated chamber is moved up and down so that steel enters the chamber

iii) The chamber is moved for 50-60 times with a cycle time of 20 seconds.

iv) Adequate degassing is possible in 20 -30 cycles.

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

vi) The DH degassing unit can operate with lower superheats compared with RH since DH unit has heating facility

SECONDARY STEEL MAKING

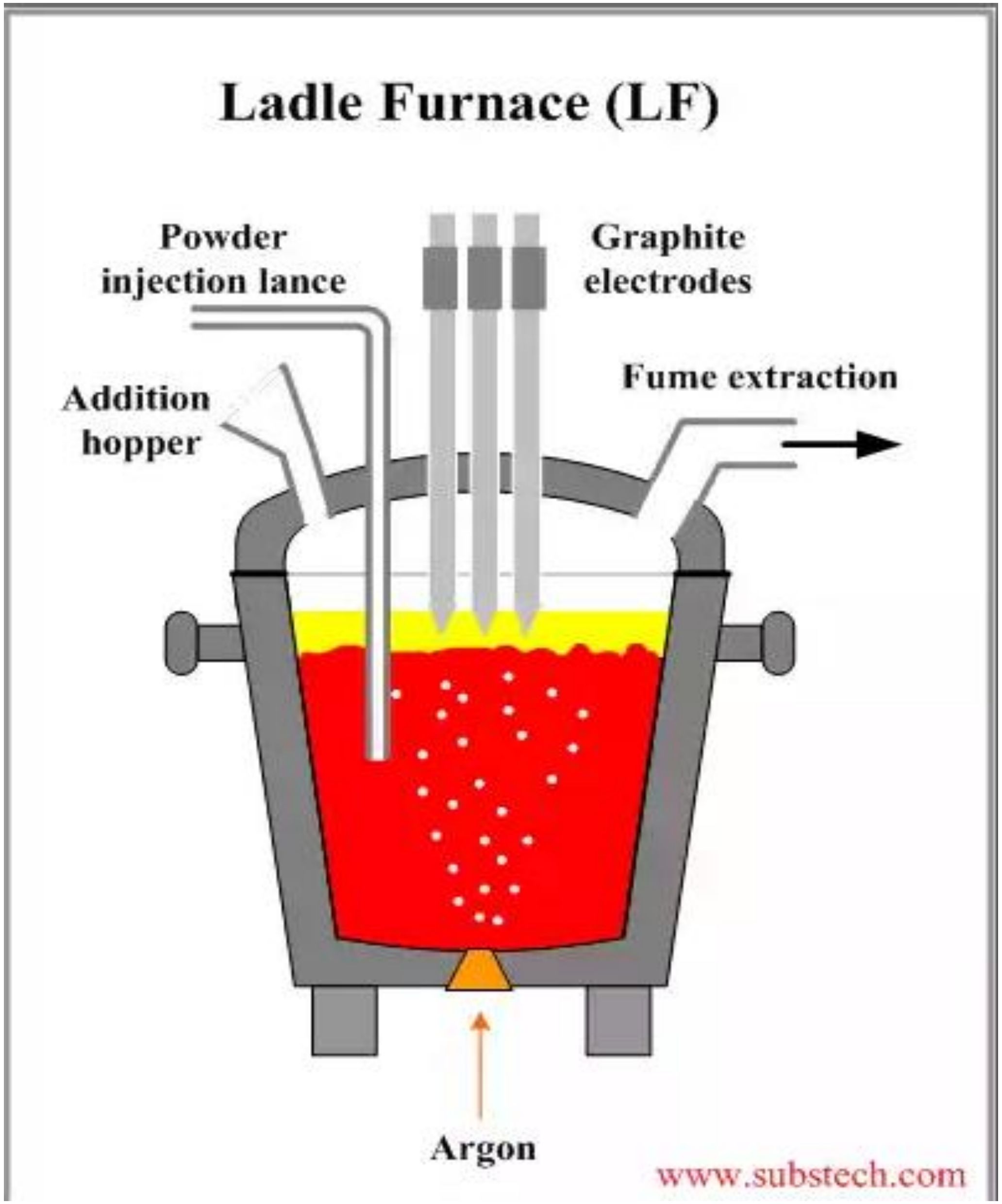
- Secondary steel making is resorted to achieve one or more of the following requirements:

1. Improvement in quality.
2. Improvement in production rate
3. Decrease in energy consumption
4. Use of relatively cheaper grade or alternatively raw materials.
5. Use of alternate sources of energy
6. Higher recovery of alloying elements.

LADLE FURNACE

- Non-metallic inclusions are naturally occurring and typically undesired products that are formed into various types depending on their favourable thermodynamic conditions in almost all treatment practices involving molten steels.
- The equipment and processes are equally varied. Secondary Refining processes are performed at atmospheric pressure or under a vacuum, with or without heating, solids and/or gas injection, and stirring.
- The purposes of secondary refining are many: temperature homogenization or adjustment; chemical adjustments for carbon, sulphur, phosphorus, oxygen and precise alloying; inclusion control; degassing, and others.

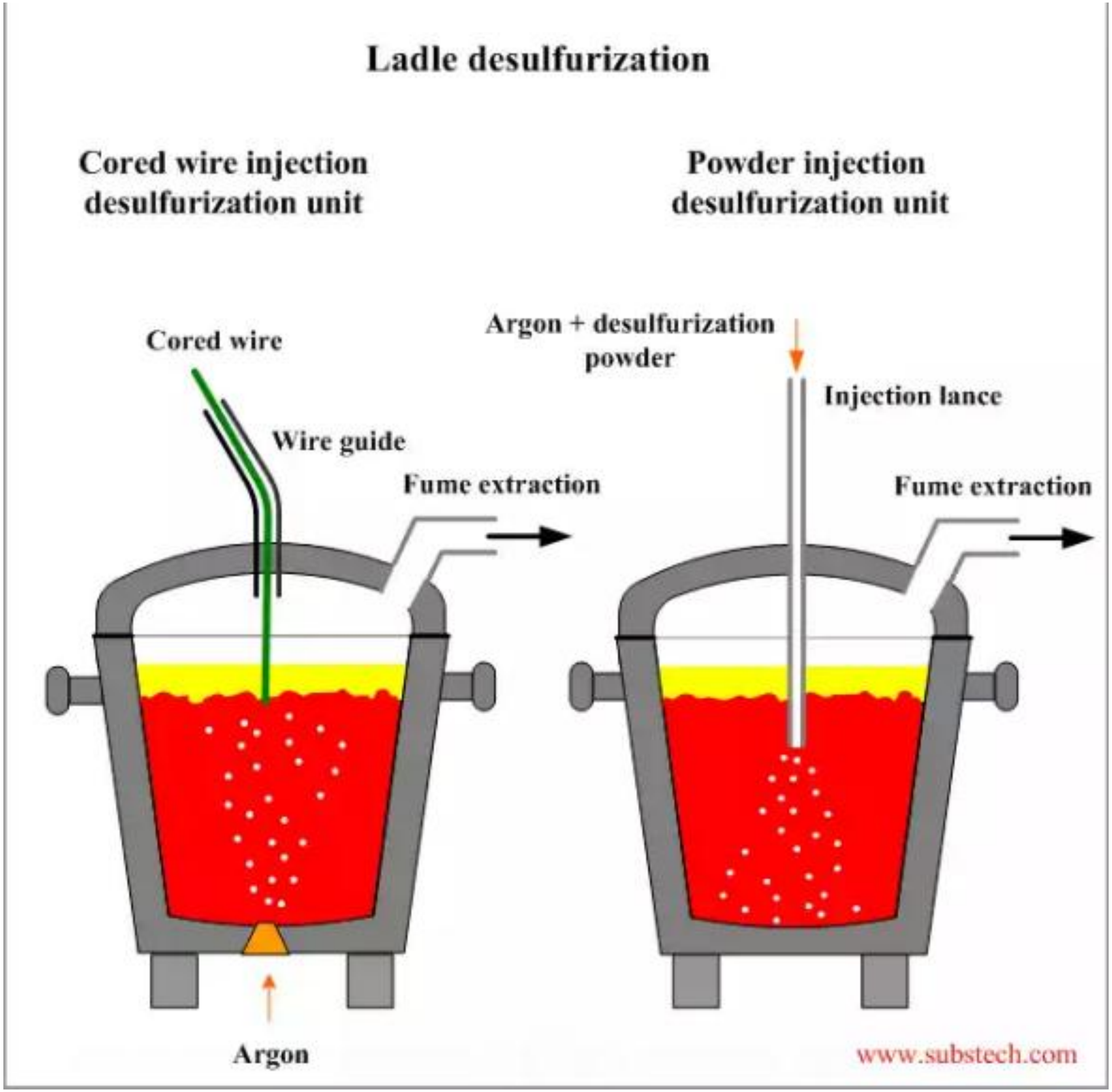
- After tapping from electrical arc furnace, the ladle furnace is put on LF refining position.
- LF refining is conducted through arc heating and argon blowing.
- During this process, the steel deoxidization, desulfurization, the adjustment of steel temperature and chemical composition are completed.
- In primary slag, there is no vacuum function in LF, but room of vacuum device may be obligated in LF zone for future development.


Ladle Furnace (LF)
Powder injection lance
Graphite electrodes
Addition hopper
Fume extraction
Argon
www.substech.com

- A Ladle Furnace is used to relieve the primary melter of most secondary refining operations, and its primary functions are:
  - Reheating of liquid steel through electric power conducted by graphite electrodes
  - Homogenization of steel temperature and chemistry through inert gas stirring
  - Formation of a slag layer that protects refractory from arc damage, concentrates and transfers heat to the liquid steel, trap inclusions and metal oxides, and provide the means for desulphurization

SECONDARY FUNCTIONS

- Alloy additions to provide bulk or trim chemical control
- Cored wire addition for trimming or morphology control
- Provide a means for deep desulphurization
- Provide a means for dephosphorization
- Act as a buffer for down stream steelmaking equipment


Ladle desulfurization
Cored wire injection desulfurization unit
Powder injection desulfurization unit
Cored wire
Wire guide
Fume extraction
Argon
Argon + desulfurization powder
Injection lance
Fume extraction
www.substech.com

SPECIFICATION OF THE LF

- LRF of liquid metal is a proven technology to produce high quality steel. Also used to raise the temperature and adjust the chemical composition of molten metal.
- LRF are used to desulphurise steel, remove other impurities and hold the molten steel for casting operations.
- Costs of extended furnace time, refractory wear and power/fuel consumption can all be reduced using LRFs to perform holding and refining.

- Reduced scrap melting capacity in BOF is another disadvantage of higher tap temperatures. LRFs also acts as a buffer between BOF and EAF and the Continuous Caster, reducing casting costs and allowing greater flexibility in steel making operations.

WORKING OF LRF

- The function stirring of molten metal is to promote homogenization. Normal stirring operations are performed by percolating argon gas through a purge arrangement in the bottom of the ladle.
- A top lance mechanism serves as a back up means for bath stirring in the event the plug circuit in the ladle is temporarily inoperable.
- The gas supply connection to the ladle is automatically when made the ladle is placed on the transfer car.

- Fumes and particulates generated during heating and alloying operations at the LF will exit the water-cooled ladle roof through the various openings in the roof.
- The ladle roof is typically a water-cooled design with a refractory center or delta section and is configured to coordinate with existing ladles such that roof will completely cover the top portion of the ladle when in operating position.

LRFs ARE USED FOR THE FOLLOWING REFINING PROCESS:

- Homogenization
- Inclusion Flotation
- Desulphurization
- Vacuum degassing

ESR (ELECTRO SLAG REFINING)

- ESR has been known since the 1930s, but it took approx 30 years before it became an acknowledged process for mass production of high-quality ingots. The ESR technology is of interest not only for the production of smaller weight ingots of tool steels and super alloys, but also of heavy forging ingots up to raw ingot weights of 165 tons.

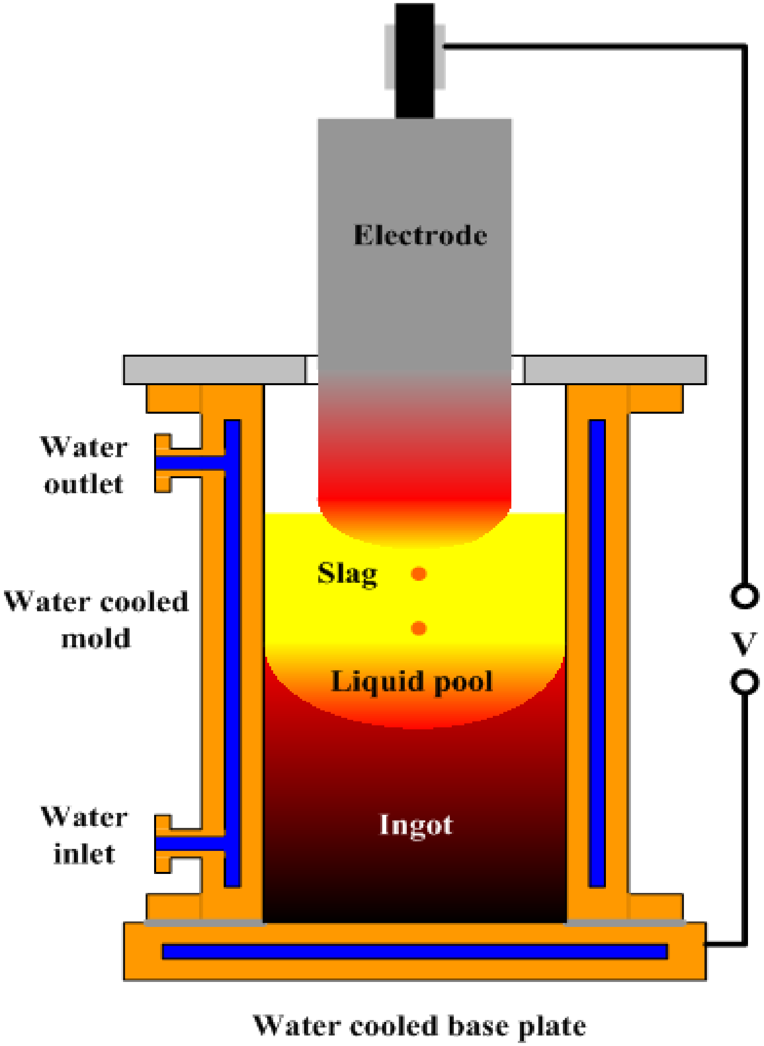
- It is a process of remelting and refining steel and other alloys for mission-critical applications in aircraft, thermal power stations, nuclear power plants, military technology.

- The consumable electrods are as cast or forged cylindrical parts made of an alloy to be remelt.
- An electroslag remelting process (ESR) starts when the lower tip of a consumable electrode is immersed into a pool of molten slag.
- The premelted slag possessing electrical conductivity is located on the water-cooled mold base connected to a power supply.
- The electric current (commonly AC) passing through the the slag keeps it at high temperature, which is about (200°C) higher than the melting point of the remelted metal.

- The electrode tip is heated by the hot slag and starts to melt forming droplets of liquid metal, which disconnect from the electrode and sink through the slag layer.
- The slag composition is based on calcium fluoride (CaF_2), lime (CaO) and alumina (A
- The molten steel in form of both liquid film on the electrode tip and descending droplets contacts with the slag and get refined due to desulfurization and removal of non-metallic inclusions (Sulfides and Oxides). l_2O_3).

- The droplets enters the molten steel pool, bottom of which is progressively solidifying. The water-cooled copper mold provides relatively high gradient of temperature resulting in high solidification rate. Solidification front is moving upwards (unidirectional solidification) forming sound homogeneous metal structure.
- The ingot has a good surface quality due to a thin slag film covering it.

Electroslag remelting



THE SLAG COMPOSITION PROVIDES THE FOLLOWING PROPERTIES:

- Melting point lower than that of the remelted alloy.
- Required level of viscosity.
- Required level of electrical conductivity.
- High solubility of sulfur.
- Capability to adsorb non-metallic inclusions.

METALLURGY OF THE ESR

Slags for ESR are usually based on calcium fluoride (CaF_2), lime (CaO) and alumina (Al_2O_3). Magnesia (MgO), titania (TiO_2) and silica (SiO_2) may also be added, depending on the alloy to be remelted. To perform its intended functions, the slag must have some well-defined properties, such as:

- Its melting point must be lower than that of the metal to be remelted;
- It must be electrically efficient;
- Its composition should be selected to ensure the desired chemical reactions;
- It must have suitable viscosity at remelting temperature.

INERT GAS MELTING

A new trend is emerging in ESR melting that involves melting of Oxygen and Nitrogen sensitive alloys under an inert gas enclosure. The major benefits of the inert gas melting system, besides very low oxygen and nitrogen levels, are as follows:

- The system is fully enclosed preventing the possibility of contamination from the melt shop during melting.
- Different slags can be used because the oxidation of the slag is no longer a concern
- No deoxidant is required. Deoxidant has been shown to be a principal source of inclusions in ESR ingots.

ADVANTAGES

- Deep desulfurization.
- Refining non-metallic inclusions.
- Homogeneous distribution of non-metallic inclusions.
- Fine Grain structure.
- No Shrinkage defects.
- Low macrosegregation.
- Good surface quality.
- Controllable process.

APPLICATIONS

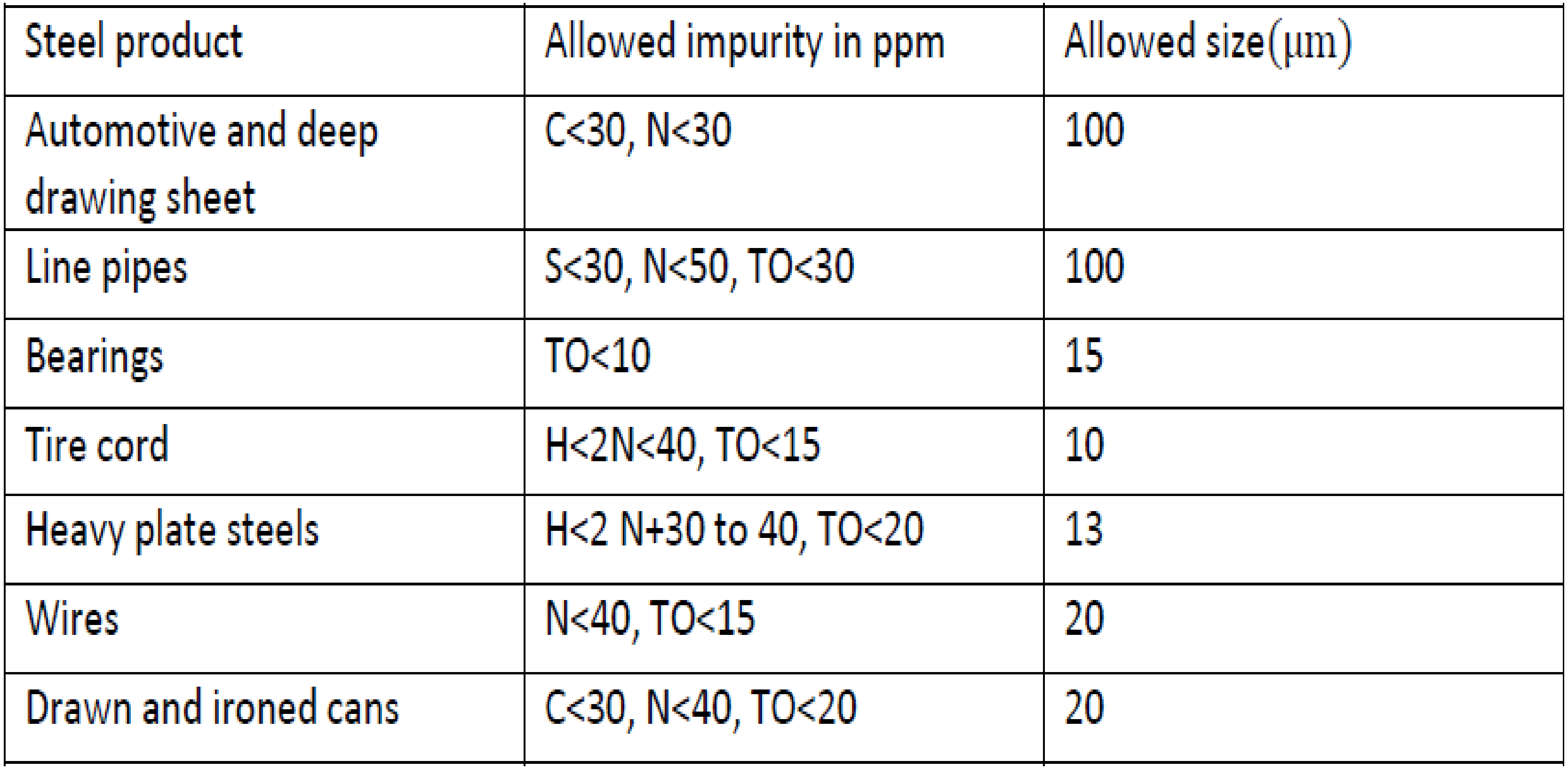
- Tool steels for milling cutters, mining, etc.
- Die steels for the glass, plastics and automotive industries.
- Ball-bearing steels.
- Steels for turbine and generator shafts.
- Superalloys for aerospace and power turbines.
- Nickel-base alloys for the chemical industry.
- Cold rolls.

UNIT 4

CLEAN STEEL

- Clean steel refers to steel which is free from inclusions. Inclusions are non metallic particles embedded in the steel matrix.
- Practically it is not possible to produce steel without any inclusion.
- Therefore we can talk about cleaner steel.
- Which steel is clean would depend on the applications.
- In this connection it is important to know that there is a limiting size below which inclusion does not affect mechanical property.

TABLE LISTS SOME APPLICATIONS WHICH CAN TOLERATE SOME MINIMUM INCLUSIONS SIZE:



Steel product	Allowed impurity in ppm	Allowed size(μm)
Automotive and deep drawing sheet	C<30, N<30	100
Line pipes	S<30, N<50, TO<30	100
Bearings	TO<10	15
Tire cord	H<2N<40, TO<15	10
Heavy plate steels	H<2 N+30 to 40, TO<20	13
Wires	N<40, TO<15	20
Drawn and ironed cans	C<30, N<40, TO<20	20

TYPES OF INCLUSIONS:

- Inclusions are chemical compounds of metals like (Fe, Mn, Al, Si, Ca etc) with non metals (O, S, N, C, H).
- Different types are:
  - Oxides:FeO,Al_2O_3,SiO_2,MnO,$Al_2O_3.SiO_2$,$FeO.Al_2O_3$,$MgO.Al_2O_3$,$MnO.SiO_2$
  - Sulphides: FeS,CaS,MnS,MgS,Ce_2S_3 ,
  - Nitirides: TiN,AlN,VN,BN etc.
  - Oxysulphides: $MnS.MnO$,$Al_2O_3.CaS$, etc
  - Carbonitrides: Titanium/ vanadium/Niobium carbonitirides, etc
  - Phosphides: Fe_3P,Fe_2P,Mn_5P_2

BY MINERALOGICAL CONTENT, OXYGEN INCLUSIONS ARE CLASSIFIED:

- Free oxides - FeO,MnO,Cr_2O_3,SiO_2(quartz)Al_2O_3 (corundum) and other;
- Spinels – Ferrites, chromites and aluminates.
- Silicates- SiO2 with a mixture of iron, manganese, chromium, aluminum and tungsten oxides and also crystalline silicates
- By stability, non –metallic inclusions are rather stable or unstable. Unstable inclusions are iron and manganese sulfides and also some free oxides.

MORPHOLOGY

- Globular shape is desirable. Certain inclusions like MnS, oxysulphides, iron aluminates and silicates are globular.
- Platelet shape: undesirable. Al deoxidized steels contain MnS in the form of thin films located along the grain boundaries.
- Polyhedral inclusions are not very harmful.

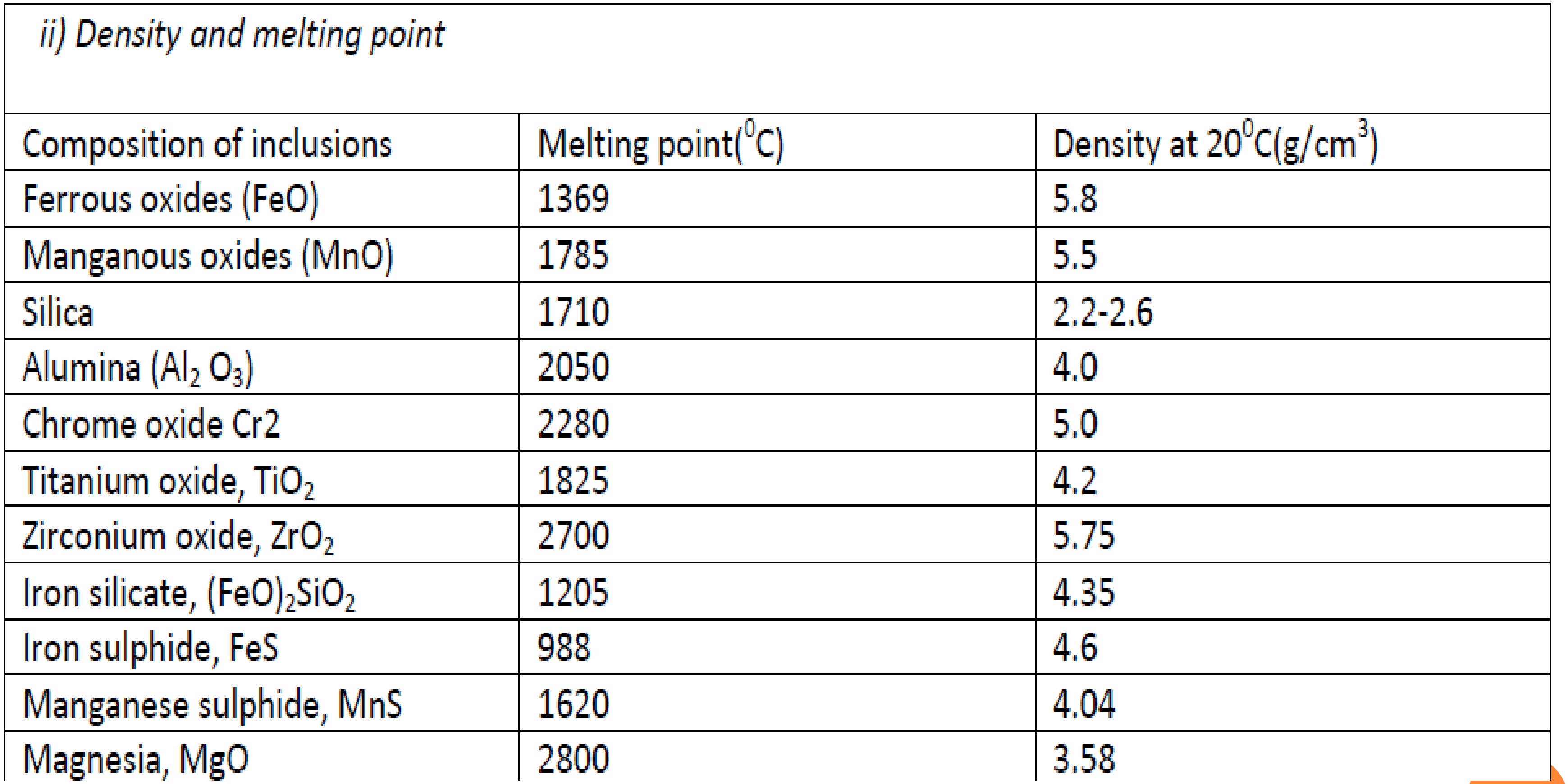
SIZE OF INCLUSIONS

- There are micro inclusions(size 1−100μm) and macro-inclusions (size greater than100μm) . Macro inclusions are harmful.
- Micro inclusions are beneficial as they restrict grain growth, increase yield strength and hardness.
- Micro- inclusions act as nuclei for precipitation of carbides and nitrides.
- Macro- inclusions must be removed. Micro inclusions can be used to enhance strengthening by dispersing them uniformly in the matrix.

PROPERTIES OF INCLUSIONS:

- *i) Thermal expansion.*
- An inclusion is a mismatch with the steel matrix. There are inclusions like MnS,CaS, etc. which have thermal expansion greater than steel matrix. On heating steel with these types of inclusions voids or parting of the matrix can occur. The void can act as cracks.
- On the other hand Al_2O_3,SiO_2 and $CaO.Al_2O_3$, etc inclusions have thermal expansion smaller than steel matrix. On heating steels with these type of inclusions internal stresses of thermal origin can develop.

DENSITY AND MELTING POINT



ii) Density and melting point

Composition of inclusions	Melting point(^{0}C)	Density at 20^{0}C(g/cm^3)
Ferrous oxides (FeO)	1369	5.8
Manganous oxides (MnO)	1785	5.5
Silica	1710	2.2-2.6
Alumina (Al_2 O_3)	2050	4.0
Chrome oxide Cr2	2280	5.0
Titanium oxide, TiO_2	1825	4.2
Zirconium oxide, ZrO_2	2700	5.75
Iron silicate, $(FeO)_2SiO_2$	1205	4.35
Iron sulphide, FeS	988	4.6
Manganese sulphide, MnS	1620	4.04
Magnesia, MgO	2800	3.58

PLASTIC DEFORMABILITY

- The plastic deformability of an inclusion will govern any change in its shape under the action of external forces and will determine the amplitude of stress concentration.
- Brittle inclusions are dangerous as they may crack and cause fracture of the component under the application of external force.
- The majority of inclusions belong to pseudo-ternary system: CaO−SiO2−Al2O3,MgO−SiO2,−Al2O3 CaO−SiO2−Cr2O3 etc.
- Sulphide inclusions are mainly MnS. Other elements like Ti, Zr, rare earths, Nb, V etc. usually appear as solid solutions in existing inclusion phases.

ACCORDING TO KIESLLING

- (i) Calcium aluminates and Al2O3 inclusions in steel are undeformable at temperatures of interest in steelmaking.
- (ii) Spinel type double oxides AOB2O3 (where A is Ca, Fe(l), Mg and Mn,and B is Al,(Cr etc) are deformable at temperatures greater than1200℃ .
- (iii) Silicates are deformable at higher temperature range. The extent of deformation depends on their chemical compositions. Silicates are not deformable at room temperature.

- (iv) FeO,MnO and (Fe,Mn)O are plastic at room temperature but gradually lose plasticity above 400°C.
- (v) MnS which is highly deformable at 1000°C temperature but becomes slightly less deformable above 1000°C .
- (vi) Pure silica is not deformable up to 1300°C

INCLUSION ASSESSMENT

- Inclusion counts are performed to assess their shape, quantity and distribution to assess about the cleanliness of steel.
- The routine plant procedure employes the microscopic method. From the shape of the inclusion and knowledge of the steelmaking process in a plant, it is inferred to whether it is silica/ silicate, aluminate or sulphide inclusion
- Electron probe micro analyzer enables to determine the chemical composition of individual inclusions.

- The energy dispersive x-ray analysis (EDX) attachment for SEM allows quantitative chemical analysis of inclusion as well as quantitative mapping of distribution of various elements in and around the inclusions.
- Quantimet has an optical microscope fitted with video screen and associated microprocessor-based instrumentation. It can scan the specimen very quickly and provide a variety of information such as inclusion size, distribution, number, volume fraction, etc.

- Total oxide inclusion content of steel can be determined from the analysis of oxygen by sampling and the use of vacuum /inert gas fusion apparatus.
- Radioactive tracers can identify the origin of inclusion distributions, etc.

WHY INCLUSION CONTROL IS NECESSARY

- Impact properties are adversely affected with an increase in volume fraction of inclusion as well as inclusion length; spherical inclusions are better. Brittle inclusions or inclusions that have low bond strength with the matrix break up during early straining and create voids at the inclusion/ matrix interface.
- Hot fatigue strength of high strength steel is reduced by surface and subsurface inclusions those have lower expansion coefficient than steel

- The hot workability of steel is affected by the low deformability of inclusions
- Anisotropy of a property is caused by orientation of elongated inclusions along the direction of working. Macro inclusions of sulphides are desirable for better steel machining properties.

SOURCES OF INCLUSION FORMATION

- Inclusions can form either **(a) during transfer of molten steel from one reactor to other or (b) during solidification of steel or during solid state processing by any of the following mechanisms**

i. Reaction between rejected solute elements during solidification, for example, reaction between sulphur and manganese, and between oxygen and aluminium etc.

ii. Mechanical and chemical erosion of refractory and other materials.

iii. Oxygen pickup by teeming stream and consequent oxide formation.

iv. Chemical reactions.

- Inclusions produced by mechanism **(i) are called endogenous, whereas mechanisms ii and iii produce exogenous inclusions. Inclusions can form during**
- a) Tapping of molten stream from BOF/EAF to ladle. Erosion of launder refractory is the possible source. Pick up of oxygen from atmosphere and formation of FeO.
- b) Treatment of steel in ladle. Here molten steel is in contact with the refractory. Also during deoxidation and synthetic slag treatment oxide/sulphide inclusions may form

- c) Teeming of molten stream. Molten steel is in contact with stopper and nozzle refractory and elements like Ti, Mg etc., which can form oxides. Air entrainment into molten steel stream brings oxygen and FeO formation is initiated.
- d) Solidification in mould due to precipitation of excess solute elements.
- e) Final finishing operations like heat treatment and deformation processing. Here steel is heated to high temperature which may cause surface oxidation, surface sulphurization, inner oxidation,etc.
- f) Fusion welding. Oxidation of weld pool, electrode coatings are the possible source of inclusions in fusion welding processes.

CONTROL OF INCLUSIONS

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

- *Liquid state processing*
- During tapping of molten stream from BOF/EAF carry- over of slag must be minimized if not prevented. BOF slags are highly oxidizing in nature and contain oxides like FeO,MnO,SiO2, CaO, MgO etc. These oxides react with Al during ladle treatment and lead to inclusion formation.

- ii. Molten steel stream after treatment in the ladle is teemed into tundish and then from tundish to mould in the continuous casting.

- iii. Selection of tundish flux
  - Tundish flux should be selected such that it can easily absorb inclusions floating in the tundish .At the same time flux should also cover molten steel to prevent oxidation.

- iv. Tundish operation
  - Now a days sequence casting is commonly adopted in continuous casting. During ladle change- over tundish feeds the molten steel to different molds of the continuous casting machine. In this situation care must be exercised to ovoid slag entrainment into mold due to vortex formation. Tundish should not be emptied completely. Also tundish lining material should be inert with Al

- v. Inclusion can also form in the mold during solidification. As the steel solidifies the excess solute elements like oxygen, sulphur, manganese etc are rejected and lead to inclusions formation.

- Segregation during solidification must be avoided. Here stirring of molten steel is effective to minimize the segregation and inclusion formation
- *Solid state processing*
  - In the solid state processing steel is heated to a temperature ranging in between 800–1200°C to perform heat treatment and hot working. Here steel must be heated under inert atmosphere to avoid oxidation. During fusion welding, liquid pool is in contact with air and steel is prone to oxidation. Inert shielding may avoid the inclusion formation.

INGOT CASTING

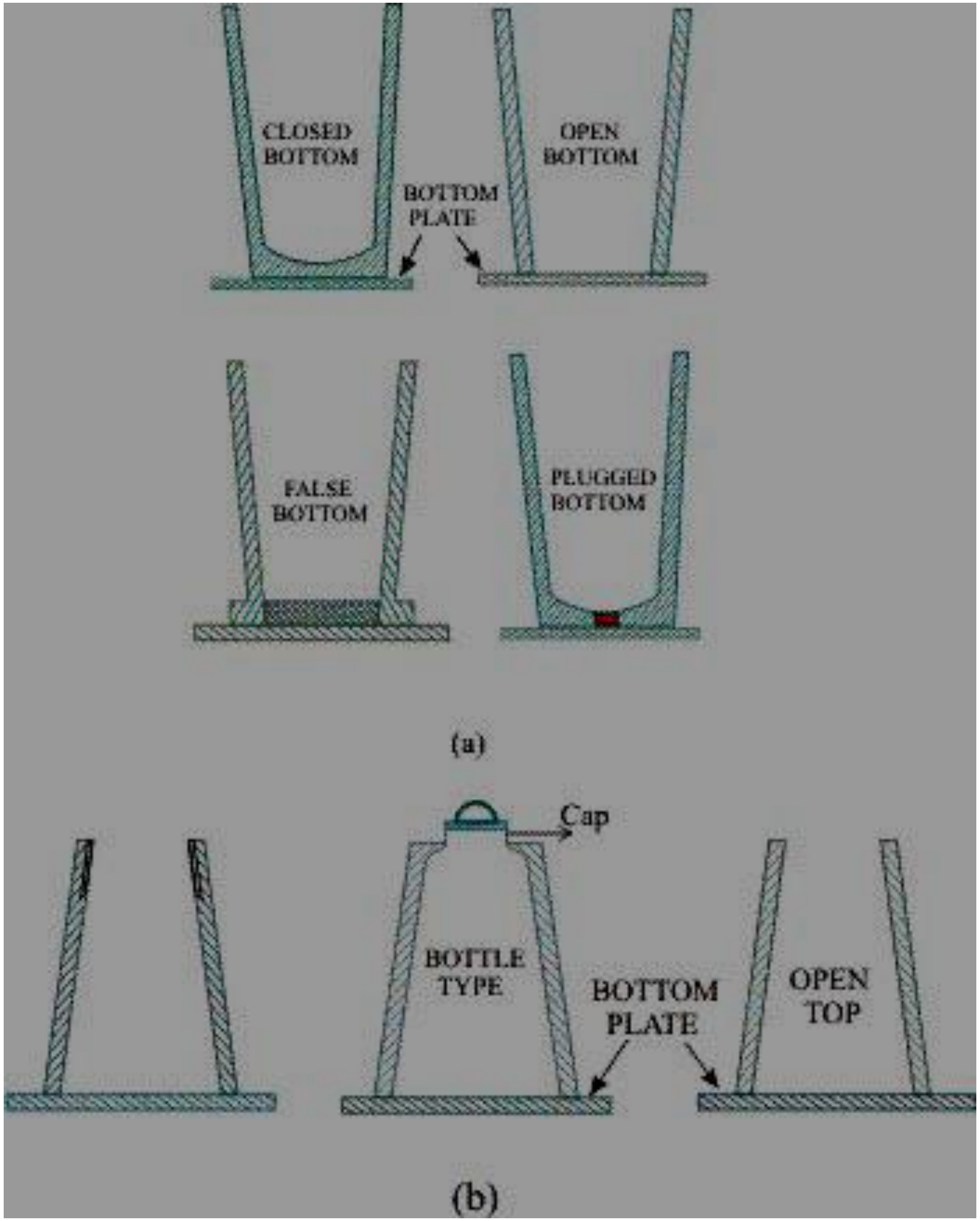
- **Introduction**
- Molten steel from BOF/EAF is tapped into a teeming ladle. Deoxidizers, decarburizes and alloying elements if required, are added for the final finishing with respect to oxygen content and other elements in steel.
- The steel may be degassed either before or during casting. In the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

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

INGOT MOULD TYPES

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

- Molds are essentially of two types:
- i) Wide end up or narrow end down as shown in figure (a)
- ii) Narrow end up or big end down as shown in figure (b)


CLOSED BOTTOM
OPEN BOTTOM
BOTTOM PLATE
FALSE BOTTOM
PLUGGED BOTTOM
(a)
Cap
BOTTLE TYPE
BOTTOM PLATE
OPEN TOP
(b)

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

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

MECHANISM OF SOLIDIFICATION

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

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

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

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

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

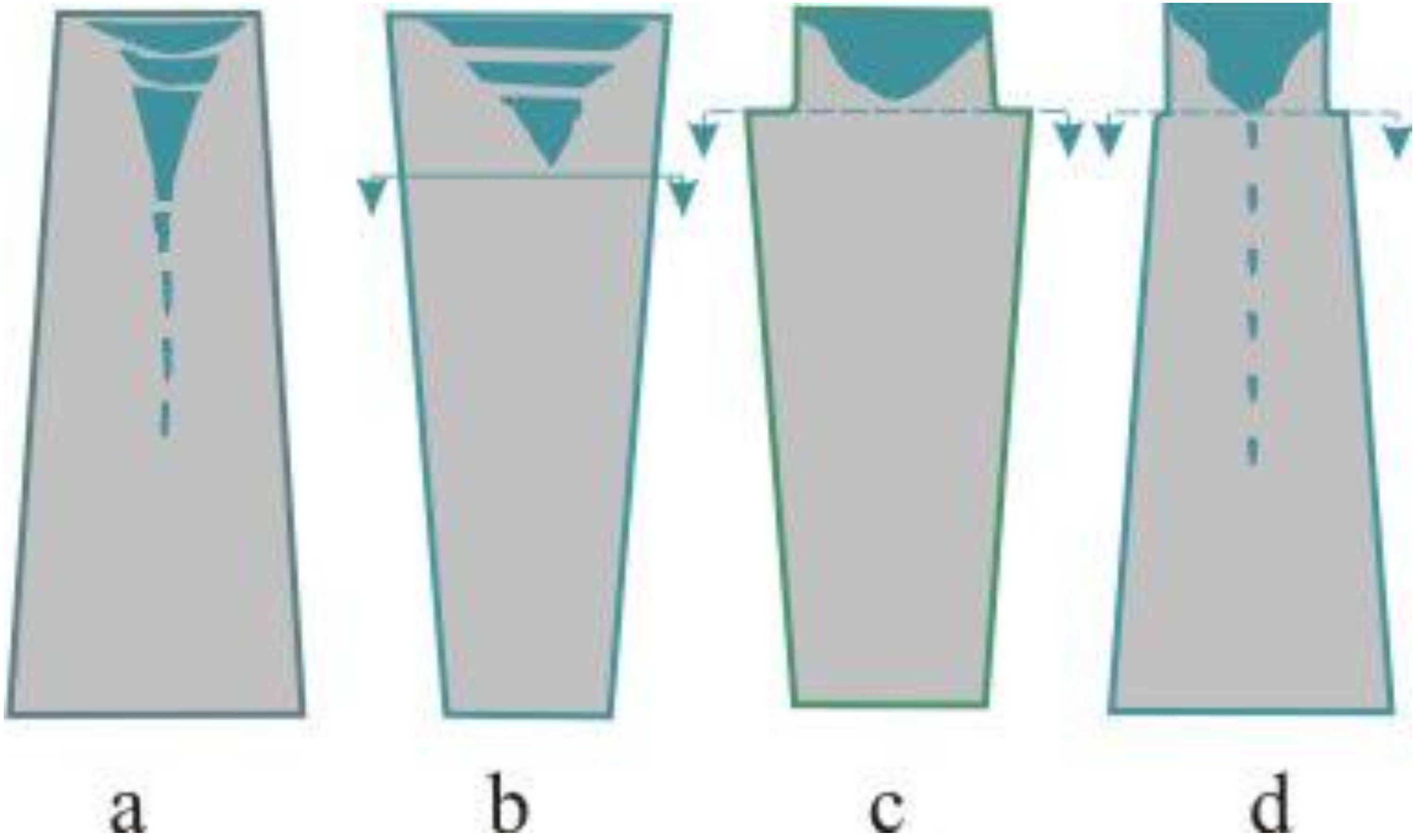
- The above zones of solidification depend on the evolution of CO gas due to carbon and oxygen reaction. In semi killed steels, not all oxygen removed from steel.
- Oxygen content of steel is very low. The necessary super saturation level of carbon and oxygen reaches towards the end of solidification.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

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

INGOT DEFECTS: CAUSES AND REMEDIES

i) Pipe formation

- *Cause: Steel contracts on solidification.*
- *The volumetric shrinkage leads to formation of pipe. In killed steels pipe formation occurs toward the end of solidification.*
- *Figure a shows primary and secondary pipe in narrow end up mould and (b) in wide end up mould while casting killed steel. Only primary pipe can be seen in wide end up mould.*


a
b
c
d

- Rimming and semi-finished steel show very less tendency for pipe formation
- Wide end up moulds show smaller pipe as compared with narrow end up mould (in figure (a) longer pipe can be seen). The portion of ingot containing pipe has to be discarded which affects yields.
- *Remedy: use of hot top on the mold. The volume of the hot top is 10-15% higher than ingot volume. Pipe formation is restricted in the hot top which can be discarded. Use of exothermic materials in the hot top keeps the metal hot in the top portion and pipe formation can be avoided. Another method is to pour extra mass of metal.*

II) BLOW HOLES

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

- *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

$$K = \frac{\text{Concentration of solute in solid}}{\text{Concentration os the solute in liquid}}$$

- The value of $K \leq 1$. The solute elements whose $K = 1$ do not segregate. All elements whose <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 $Al_2O_3$are undesirable.
- 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.
- Smooth corners of the mould and gradual curvature minimize restriction cracks

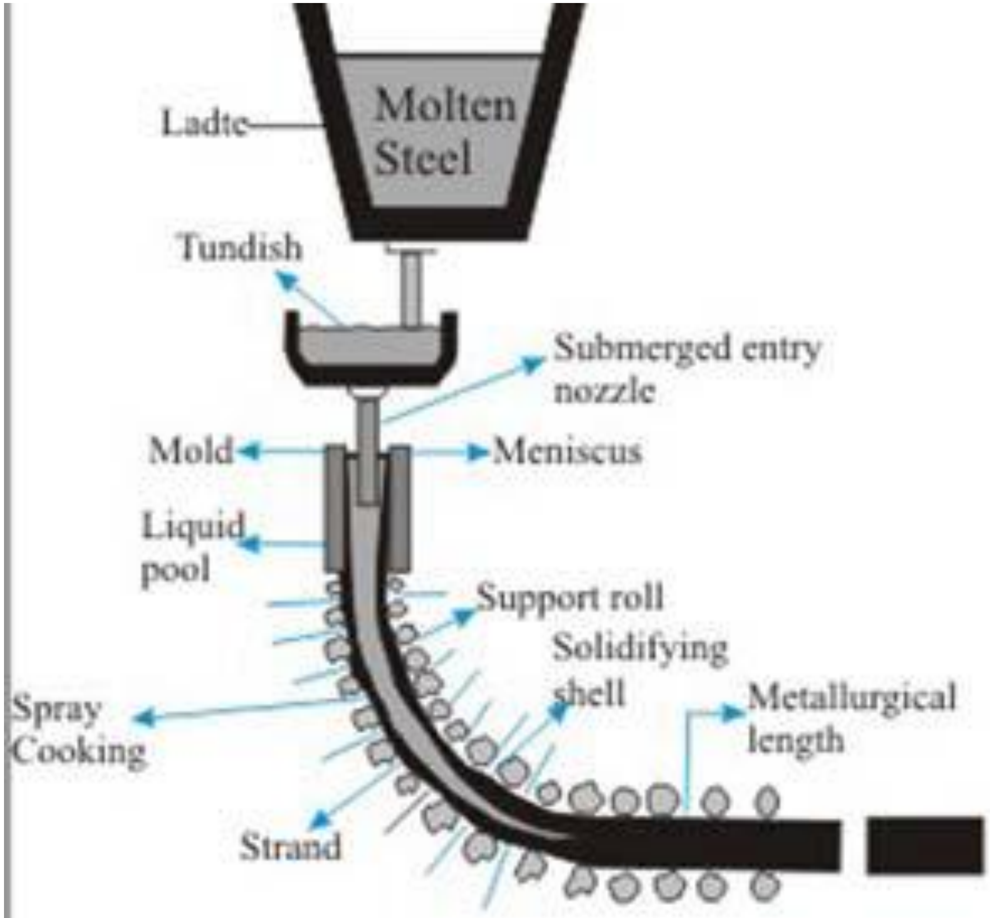
CONTINUOUS CASTING OF STEEL

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

- Quality of the cast product is better
- No need to have slabbing/blooming or billet mill as required when ingot casting is used.
- Higher extent of automation is possible
- Width of the slab can be adjusted with the downstream strip mill.
- Continuously cast products show less segregation.
- Hot direct charging of the cast product for rolling is possible which leads to energy saving.

HOW CASTING IS DONE CONTINUOUSLY?

- 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. In figure, the arrangement of tundish, mold and water spray is shown.


Ladte
Molten Steel
Tundish
Submerged entry nozzle
Mold
Meniscus
Liquid pool
Support roll
Solidifying shell
Metallurgical length
Spray Cooking
Strand

Curved

- *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:

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.

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.

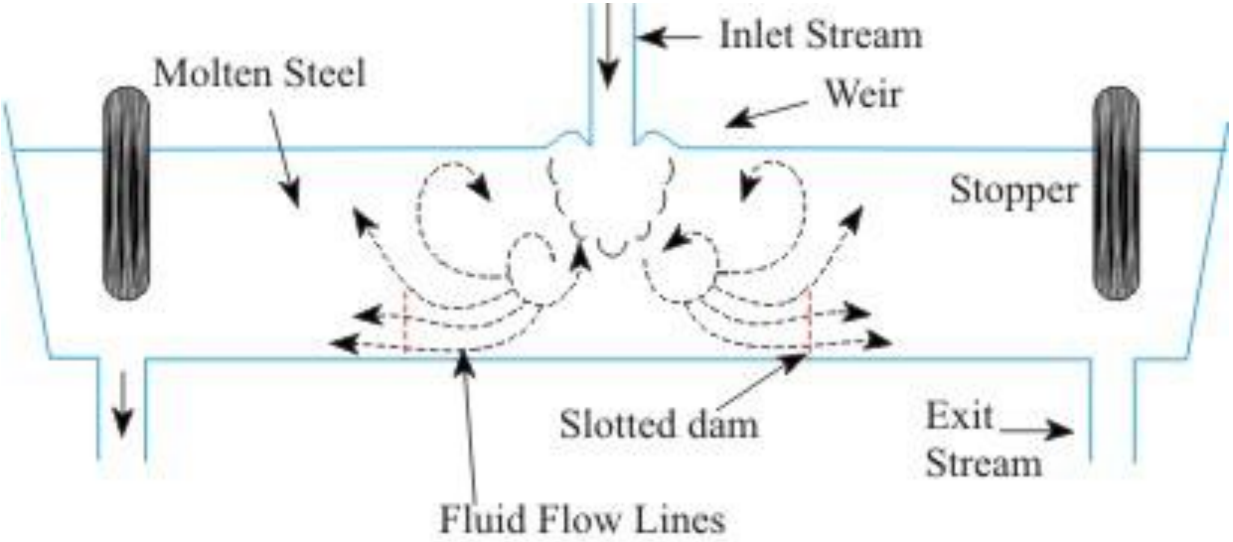
- Location of ladles stream in the tundish is important.
- It may be located symmetric or asymmetric to the centre of the tundish depending on the number of mold.
- For single strand machines, molten stream enters from one side and exits the other side of the tundish.
- In multi-strand tundishes, ladle stream is either at the centre of the tundish or displaced to the width side of the tundish.

INCLUSION REMOVAL

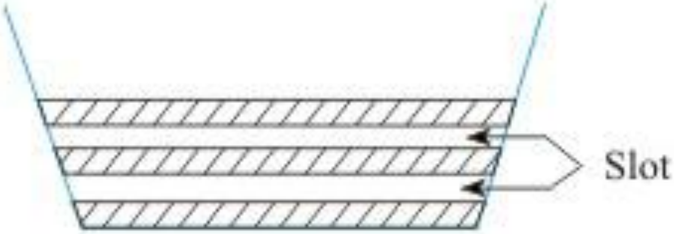
- Tundish helps to remove inclusions during the process of continuous casting.
- For this purpose liquid steel flow in the tundish is modified by inserting dams, weirs, slotted dams etc.
- The whole idea is to utilize the residence time available before steel leaves the tundish.

- 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 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.



(a)



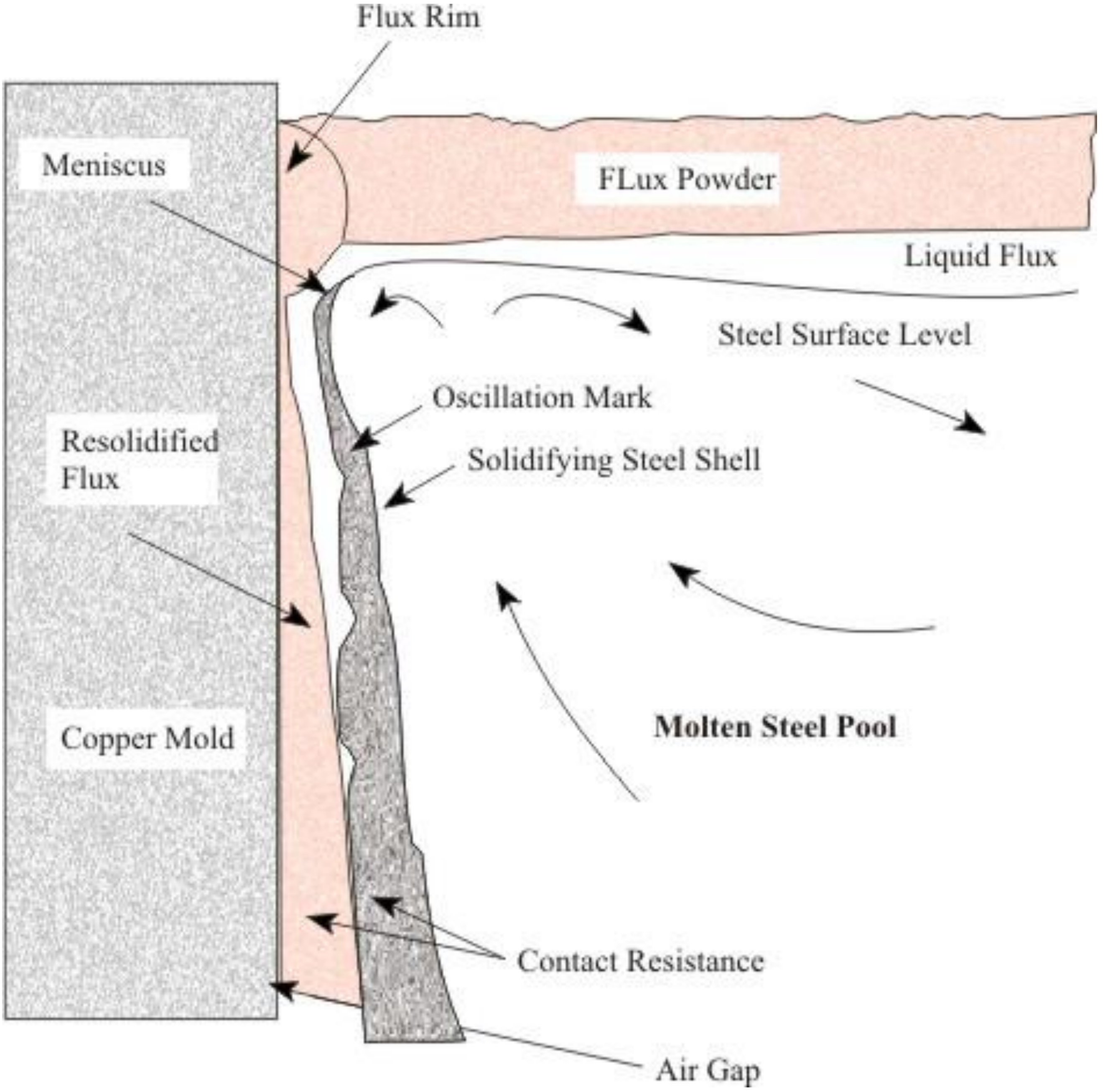
End view of tundish
showing Slotted dam

(b)

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. 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 as shown in figure

- 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.


Flux Rim
Meniscus
FLux Powder
Liquid Flux
Steel Surface Level
Oscillation Mark
Resolidified Flux
Solidifying Steel Shell
Molten Steel Pool
Copper Mold
Contact Resistance
Air Gap

- As seen in the figure, flux melts and enters into the gap between mold surface and solidified strand.
- Molds are made of copper alloys. Small amounts of alloying elements are added to increase the strength.
- Mold is tapered to reduce the air gap formation. Taper is typically 1% of the mold length.

- For 100mm X 100 mm cross section of mold the taper is about 1mm for 1m long mold. The cross section of the mold is the cross section of the slab/bloom/billet.
- Length of the mold is around 0.75-1.4m and is more for large cross sections. Mold cross section decreases gradually from top to bottom. Mould extracts around 10% of the total heat.
- The mold is oscillated up and down to withdraw the partially solidified strand (strand is either billet or bloom or slab).

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

THE FUNCTIONS OF MOLD FLUX ARE.

- Inclusion absorption capability.
- Prevention of oxidation.
- Minimization of heat losses.
- Flux on melting enters into the air gap and provides lubrication.

- For the above functions the flux should have the following properties.
  - Low viscosity
  - Low liquidus temperature
  - Melting rate of flux must match with the speed of the continuous casting.

SECONDARY COOLING

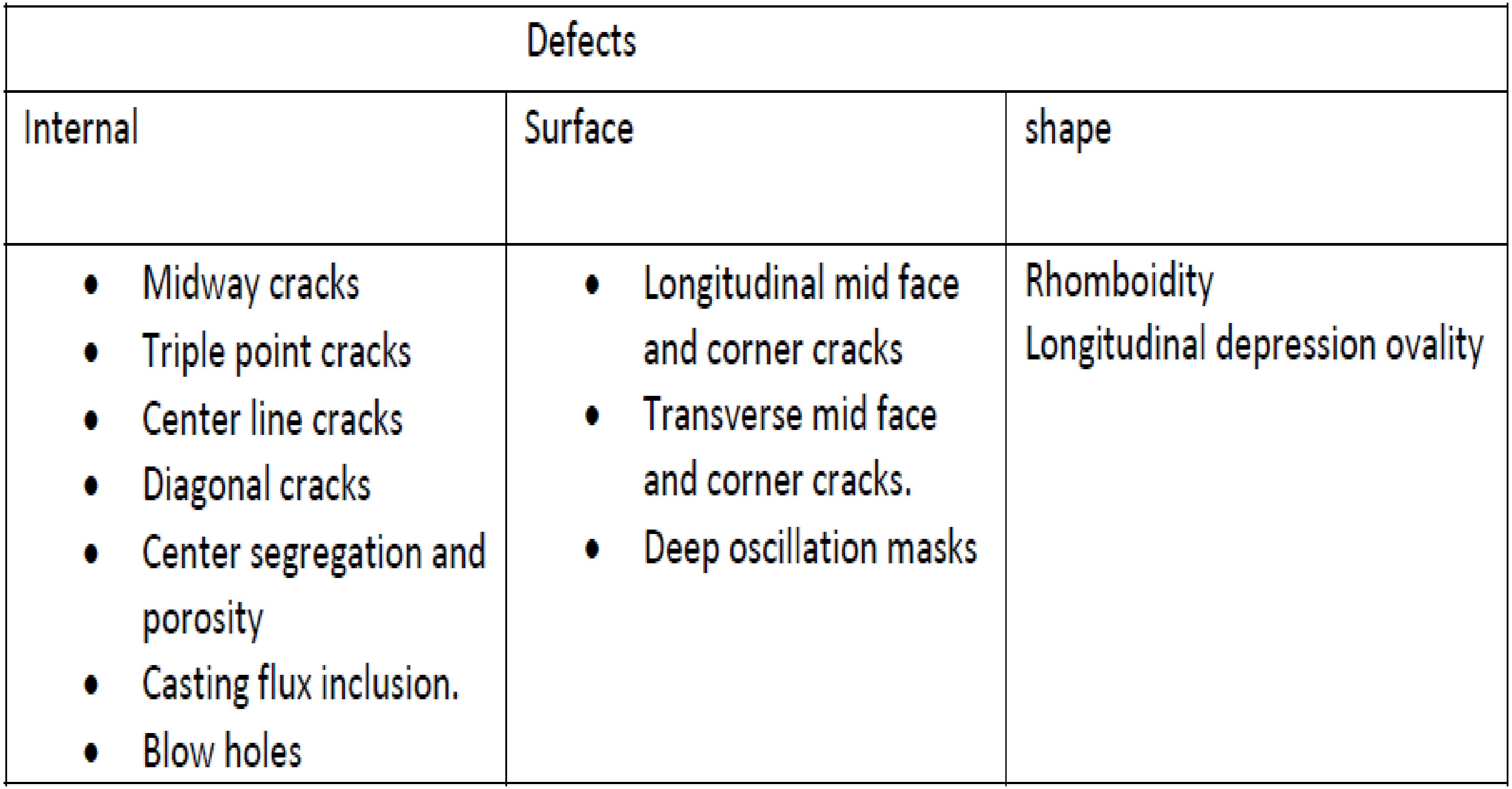
- Below the mold partially solidification strand is water sprayed to complete the solidification. Parameters affecting the heat extraction are:
  - Water drop flux
  - Mean drop size
  - Droplet velocity hitting the strands
  - Wetting effects

- Spray cooling essentially involves boiling heat transfer. A water vapour blanket forms on the strand surface which prevents direct contact of water droplets with strand surface
- Velocity of droplets should be such that droplet can penetrate the vapour layer so that droplets can wet the surface and cools the surface.
- In secondary cooling, number of nozzles is distributed over the surface of the moving strand. Overlapping of spray may occur, distance between the nozzle is important.

Products and casting defects

Presently killed steels are cast continuously into slab for flat products and bloom and billet for structural products.

Defects in continuous casting originate from several factors like mould oscillation, mould flux, segregation coefficient of solute elements; phase transformation etc. In the following, a brief presentation is given on defect formation.



Defects		
Internal	Surface	shape
• Midway cracks • Triple point cracks • Center line cracks • Diagonal cracks • Center segregation and porosity • Casting flux inclusion. • Blow holes	• Longitudinal mid face and corner cracks • Transverse mid face and corner cracks. • Deep oscillation masks	Rhomboidity Longitudinal depression ovality

- Cracks are originated in the cast product due to mechanical and thermal stresses. Material factors are also responsible
- Mechanical stresses are created due to
  - Friction
  - Ferro static Pressure
  - Bending and Straightening operation
  - Roll Pressure

- Mechanical stresses can be reduced by improving mold practices like:
    - Controlling powder feed rate
    - Resonance in mold
    - More accurate strand guidance
    - Casting powder