Iron Making and Steel Making
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Module - 11
Lecture - 52
Alternative routes of Iron making:
Introduction to Direct Reduction (DR) and Smelting Reduction (SR) Processes (continued)

This lecture is in continuation of the previous lecture 51. In this lecture we will be discussing the introduction on direct reduction and smelting reduction processes.

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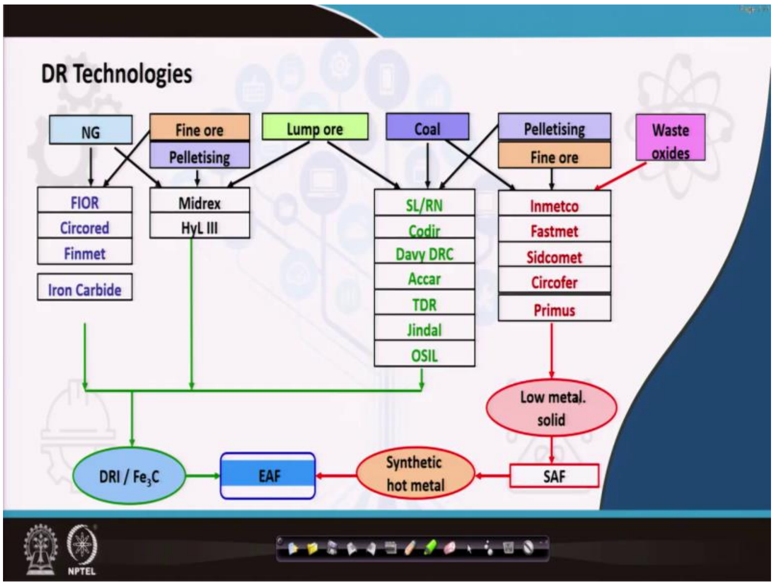

So, we have already talked about the basic definition of the DR processes and reactions involved there. Figure 52.1 shows the various DR technologies that are available.

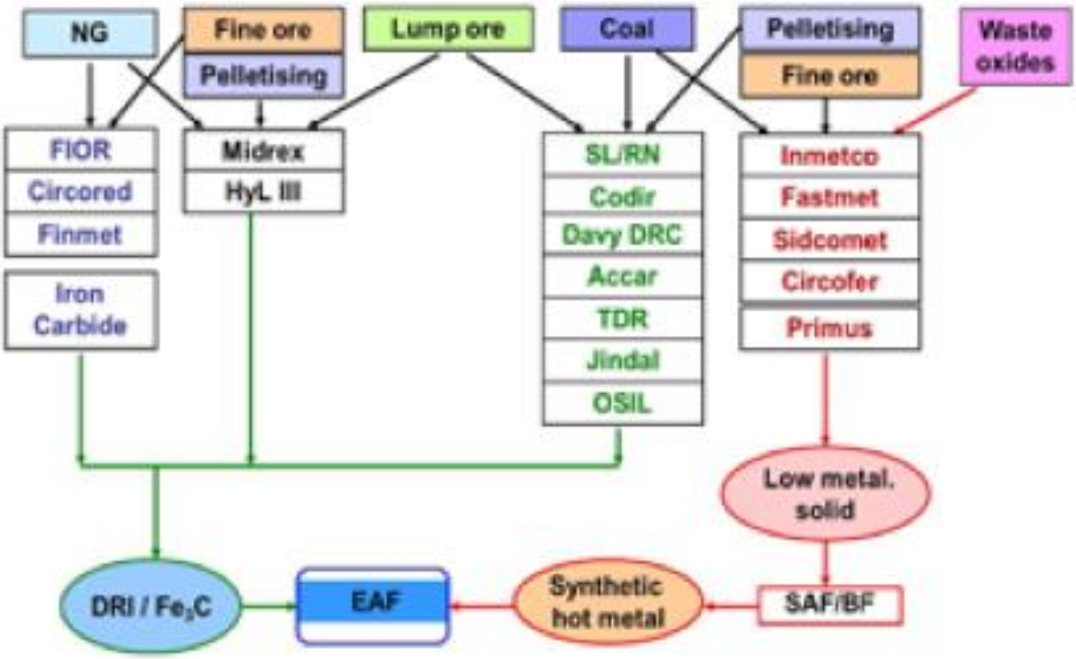

Figure 52.1: Various DR Technologies [1,2]

On the extreme left, all fluidized bed technologies are presented. Both the FIOR and Finmet process are based upon the reduction of iron ore fines to metallic iron in series of fluidized bed reactors at high temperature and pressure using reducing gases produced by natural gas reforming. Finmet is an energy efficient variant of FIOR process where the off gas is recycled for ore preheating and subsequently the off gas is recycled back to the fluidized bed reactor after scrubbing CO_2. The product from both of the reactors are hot briquetted iron. The FIOR process was developed in the 1960s and the only commercial plant started up in Venezuela in 1976 and operated until 2000 and the plant is still in existence, but is currently idle. Finmet plants established in Australia and Venezuela by 2000. The Australian plant operated for several years, but shut down in 2005 due to operating issues. The Venezuelan plant is still in service with reduced output.

Circored process is based on hydrogen reduction in fluidized bed. It make reduction in two stages: first in a circulating fluid bed followed by fixed fluid bed. As the name suggest in CFB both the solid and gas stream are recirculated to make the process more efficient and less polluting. Hydrogen is produced by reforming natural gas and subsequently CO is converted to hydrogen by water gas shift reaction.

Iron ore fines could also be converted to iron carbide in fluidized bed using natural gas, which could also be feed to EAF. Iron carbide dissolves in liquid iron rather than being melted.

The fluidized bed could not see much success as it was difficult to run the fluidized bed continuously at high pressure and the DR process based on shaft furnace emerged successfully. The shaft furnaces are based on countercurrent gas solid reaction in a cylindrical reactor, where reformed natural gas is passed from the bottom and solid iron ore in the form of lump and pellets are charged from top. In this category two popular processes are HyL and Midrex. In Midrex the off gas from shaft furnace is used for gas reforming and in case of HyL steam reforming is used.

There are several coal based processes, where iron ore in the form of lump/pellets is reduced by coal in rotary kiln. SL/RN is a coal based oldest and most popular DR technology from Lurgi, Germany, that can use wide range of iron ore by optimizing temperature and gaseous atmosphere in the furnace using combination of gas/oil/air. Subsequently, various process variant of rotary kiln based DR technologies evolved like TDR, Jindal, OSIL in India and Allis-Chalmer in Canada.

Another category of coal based process is the Rotary Hearth Furnace (RHF) based process. Here lean iron ore fines, iron bearing solid waste fines from steel plant, and coal fines are cold bonded in the form of pellets or briquettes and reduced in RHF to get low metallized iron (70-80%) for subsequent melting in SAF (submerged arc furnace)/EIF (electric iron making furnace)/EAF (electric arc furnace), or, even in BF as metallised iron, depending on the grade of sponge that in turn depends on the total iron content of raw material. RHF is donut shaped furnace where rotating hearth carries the iron ore coal composite pellets through different temperature regimes like preheating, reduction and cooling through rotation of 360^{o} before delivering the sponge iron through discharge gate next to the entry gate. Such circular shape saves the floor space. Since the material does not move physically, the strength of the raw material could be compromised. Since reductant is inside the pellet only heat is required to be supplied. Since heat transfers from top furnace atmosphere to the solid bed, and subsequently heat penetrates through the solid bed mostly by heat conduction, thickness of the bed is limited by heat transfer and therefore productivity is less. RHF is evolving as a DR process for utilizing iron bearing solid waste from the plant. Fastmet, Inmetco are commercialized processes based on RHF technology.

Sidcomet is also a RHF based process but here unlike conventional RHF where composite pellets are charged, here iron ore and coal fines are directly fed on the hearth. Similarly, Circofer process is not based on RHF but utilize iron bearing solid waste fines in CFB using reducing gas obtained from carbon gassification. Primus process, on the other hand is basically based on coal based multiple hearth furnace process, which also convert iron bearing solid waste to metallized iron. Therefore, all methods in this category utilize iron based solid waste or lean ore to convert them to low metallized iron (70% metallization), compared to metallization of 90 and above in other conventional DR processes.

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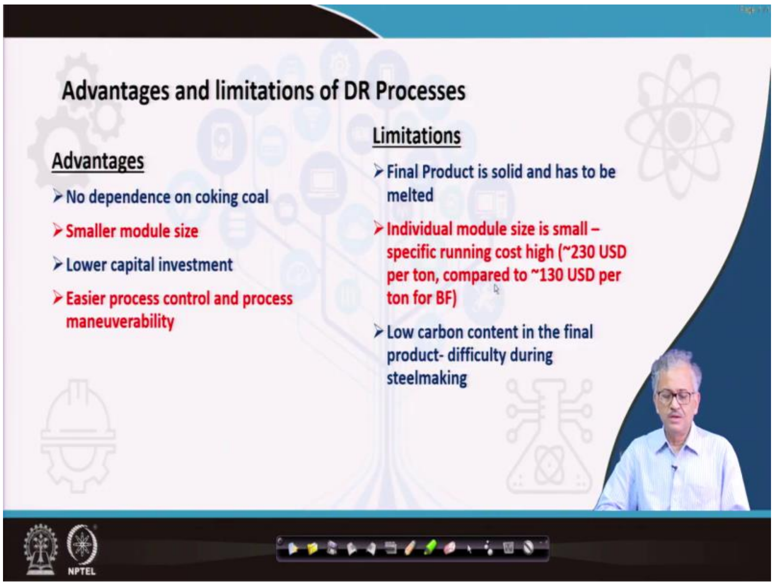

Now, let us discuss the advantages and limitations of the DR processes. Advantages: (i) No dependence on the coking coal and that is the major advantage. (ii) Smaller module size: so lower CAPEX and OPEX, water savings, lower space requirement. (iii) Easier process control and process maneuverability. Limitations: (i) the final product is solid and has to be melted that reduces efficiency, especially is DRI is cooled, stored and used later for melting. (ii) specific running cost is high. To produce large amount of iron comparable to one BF (say, 5000 tons/day), several DR units (say 10 rotary kilns) need to run to produce the same amount. Therefore, specific cost become high for DR process. For example, for DR process the specific operating cost is 230 USD per ton, compared to 130 USD per ton of BF hot metal.

(iii) Low carbon content in the final product, requires higher furnace temperature to melt it. Coal based DR contains around 0.1 wt% carbon only.

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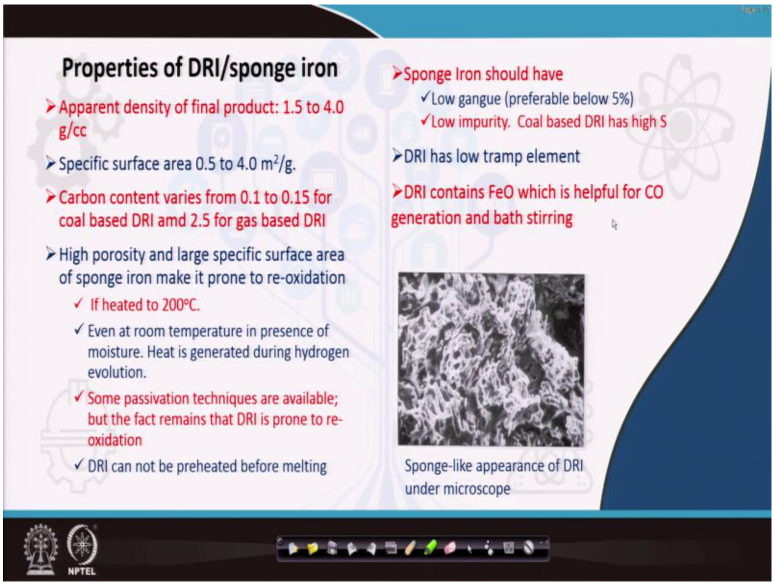

Now, let us discuss the properties of DRI, or the sponge iron.

(i) Apparent density of sponge iron is around 1.5 to 4 gram per cc. it may be compared to density of iron around 7 to 8 gram per cc. Large amount of gangue and unreduced iron oxide makes it apparent density lower.

(ii) Specific surface area is quite high 0.5 to 4-meter square per gram, which may be attributed to the presence of the numerous pores inside it. Figure 52.3 shows the appearance of sponge iron under microscope. It shows the texture of a sponge and that is why it is called sponge; although it is neither soft nor elastic like sponge.

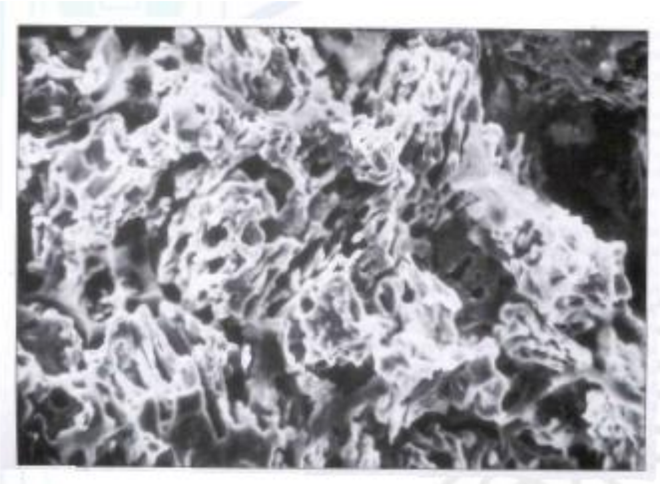

Figure 52.3: Microscopic morphology of sponge iron

(iii) Carbon content varies from 0.1 to 0.15 for coal based DRI, which may be attributed to lesser diffusion of carbon in iron during solid state reduction. However, carbon content in gas based DRI may be controlled and may achieve 2.5% or above. Higher carbon in DRI allows it to melt at lower temperature.

(iv) High porosity and large specific surface area makes sponge iron vulnerable to re-oxidation and burning in extreme case. It may re-oxidize even in room temperature in presence of moisture. Therefore, DRI cannot be preheated. There are some passivation technique like formation of surface iron-carbide on gas based DRI. Coal based DRI, is inherently protected by a slag coating.

(v) Sponge should have low gangue with high metallization for higher productivity. It should have low impurity. Coal based sponge has higher Sulphur.

(vi) Unlike in scrap, DRI does not contains trump elements like Cu, Ag, Ni, Cr, which are otherwise difficult to remove.

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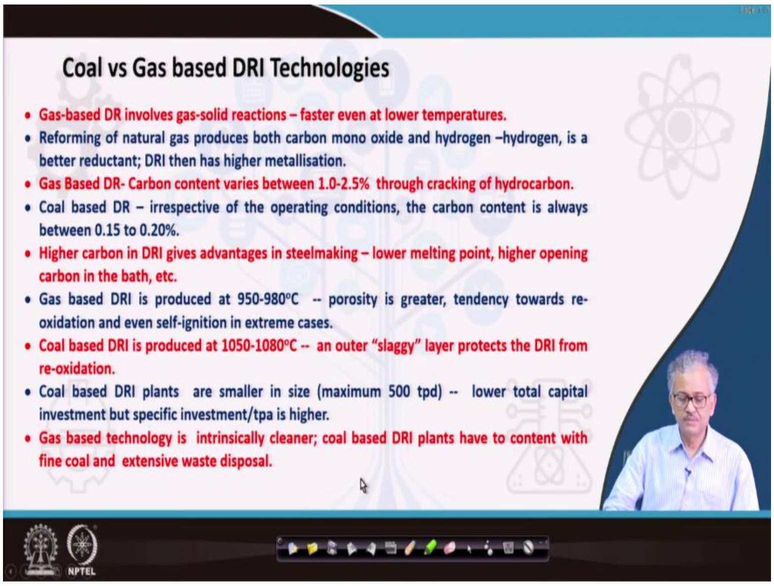

Now, let us discuss some differences between coal based versus gas based DRI technology.

(i) Gas-based DR involves gas-solid reactions – faster even at lower temperatures.
(ii) Reforming of natural gas produces both carbon mono oxide and hydrogen and hydrogen is a better reductant and it yields higher metallisation.
(iii) Gas Based DR- Carbon content varies between 1.0-2.5% by controlling cracking of hydrocarbon in the cooling zone of shaft reactor.
(iv) Coal based DR – irrespective of the operating conditions, the carbon content is always between 0.1 to 0.15%, due to limited diffusion of carbon in iron during solid state reduction.
(v) Higher carbon in gas based DRI gives advantages in steelmaking – lower melting point, higher opening carbon in the bath, etc.
(vi) Gas based DRI is produced at comparatively lower temperature 700-1000ºC. Porosity is greater, and tendency towards re-oxidation and even self-ignition in extreme cases.
(vii) Coal based DRI is produced at 1050-1080^{o}C. An outer "slaggy" layer protects the DRI from re-oxidation.
(viii) Coal based DRI plants are smaller in size (maximum 500 tpd). Lower total capital investment but specific investment/tpa is higher.
(ix) Gas based technology is intrinsically cleaner. While coal based DRI plants have to content with fine coal and extensive waste disposal.

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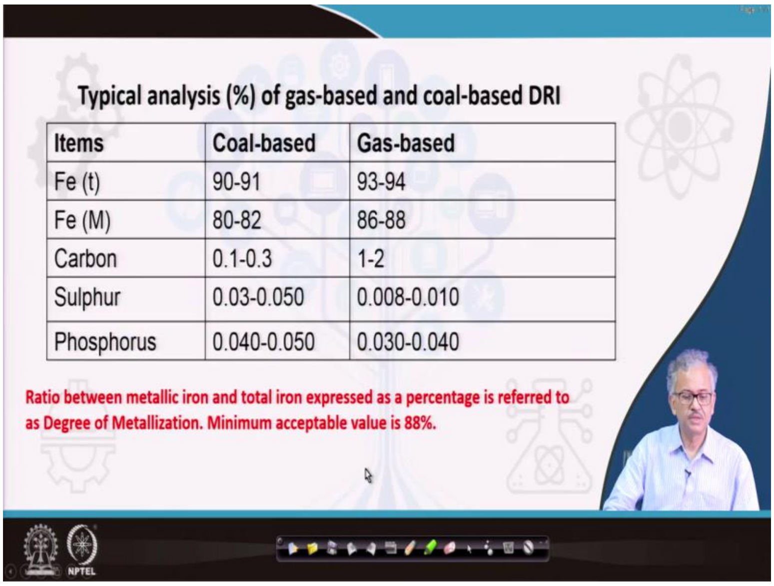

Table 52.1 shows the typical compositional analysis of coal and gas based DRI.

It is seen that both the total iron and metallic iron is higher in gas based DRI than coal based DRI. Total iron is higher because higher grade pellets are used partially in shaft furnace. Metallic iron is higher due to faster gas-solid kinetics and lesser gangue in raw material used in gas based process. Carbon is higher in gas based process, as explained before. Higher Sulphur in coal based DRI (0.03-0.05) is due to Sulphur partitioning from gangue of non-coking coal to DRI at comparatively higher temperature.

Table 52.1: Typical composition of gas based and coal based DRI

Items	Coal-based	Gas-based
Fe (t)	90-91	93-94
Fe (M)	80-82	86-88
Carbon	0.1-0.3	1-2
Sulphur	0.03-0.050	0.008-0.010
Phosphorus	0.040-0.050	0.030-0.040

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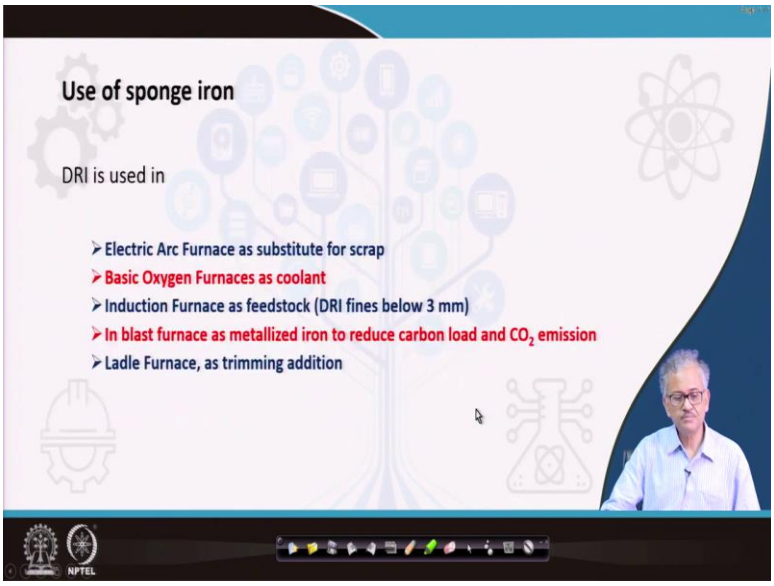

Use of sponge iron: (i) It can be used in the electric arc furnace as substitutes for the scrap. (ii) It can be used in basic oxygen furnace (BOF) as coolant. (iii) DRI fines (below 3 mm) can also be used in induction furnace as a feedstock. (iv) It can be used in the blast furnace as metallized iron to reduce the carbon load and the CO_2 emission, (v) It can also be added in lade furnace to adjust the final iron composition.

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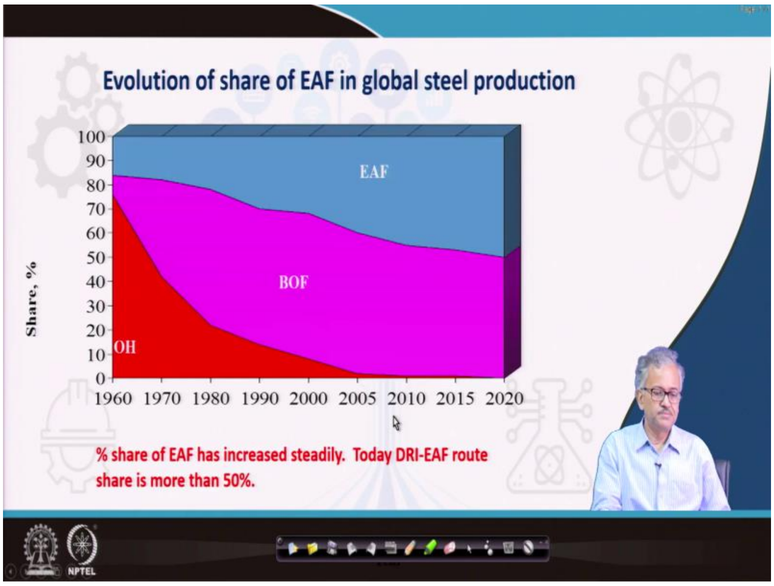

With increase in DRI production in the world, the share of EAF steel making is on the rise. Figure 52.4 shows the evolution of DRI-EAF share of crude steel production with time.

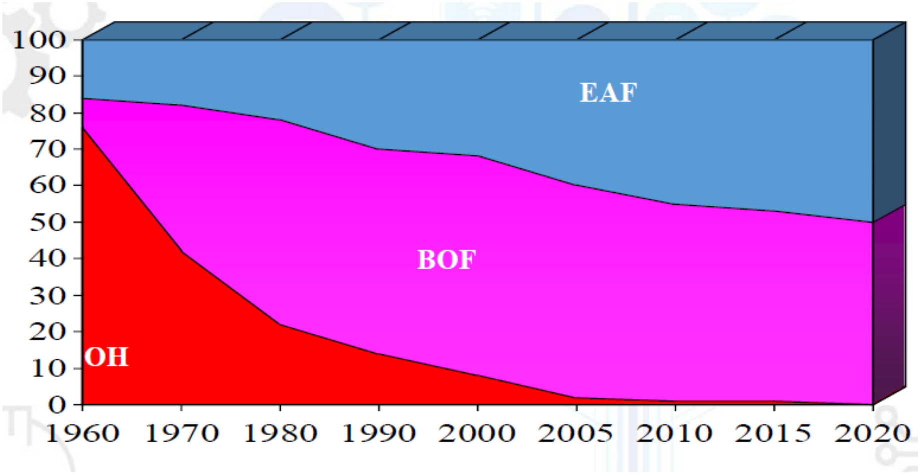

Figure 52.4: Evolution of EAF steel making over the years

Although the inhouse scrap generation has decrease with advent of continuous casting, but increase in steel production and consumption, the end of life scrap is generating rapidly. Enhanced DRI production along with end of life scrap, the supply of solid metallics are progressively increasing in the steel plant.

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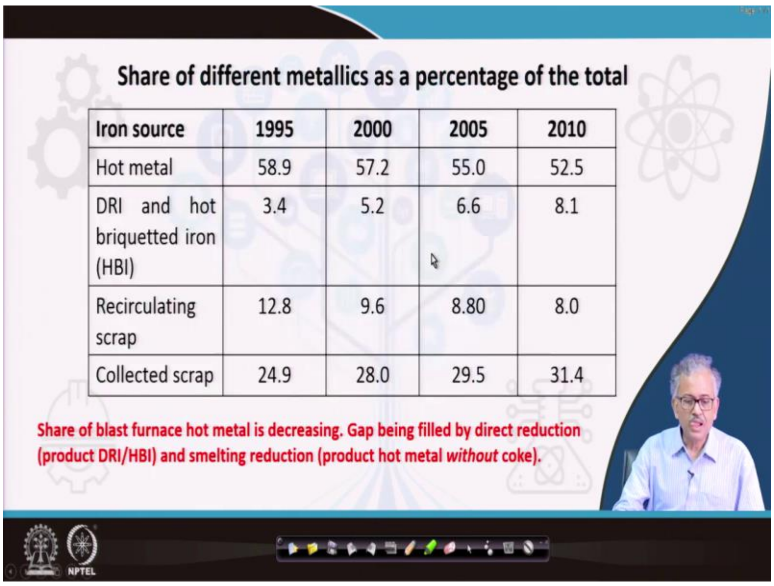

Table 52.2 shows the evolution of solid metallic as a percentage of total metallic including hot metal. Recirculating scrap indicates the in house generated scrap due to scaling, machining and rejection in the steel plant, which has subsequently decreased from 12.8 percentage to 8%, with the advent of continuous casting and its spread.

Table 52.2: Evolution of % solid metallic over the time.

Iron source	1995	2000	2005	2010
Hot metal	58.9	57.2	55.0	52.5
DRI and hot briquetted iron (HBI)	3.4	5.2	6.6	8.1
Recirculating scrap	12.8	9.6	8.80	8.0
Collected scrap	24.9	28.0	29.5	31.4

Collected scrap indicated the end-of-life scrap and segregated according to composition and it has increased from 24.9 to 31.4% with increase is usage of steel. DRI share in steelmaking has also increased significantly from 3.4 to 8.1%. Subsequently, the hot metal share in steelmaking has decreased from 58.9% to 52.5%. Since in BOF process addition of solid charge is limited to max 25% of the total charge, EAF is progressively getting importance, where solid charge at any proportion could be utilized. Today, only scrap based EAF steel production reached 30% of total production and overall crude steel production by EAF utilizing DRI, Scrap and hot metal, has reached around 50% of total steel production. Rest 50% is produced by conventional BF-BOF route.

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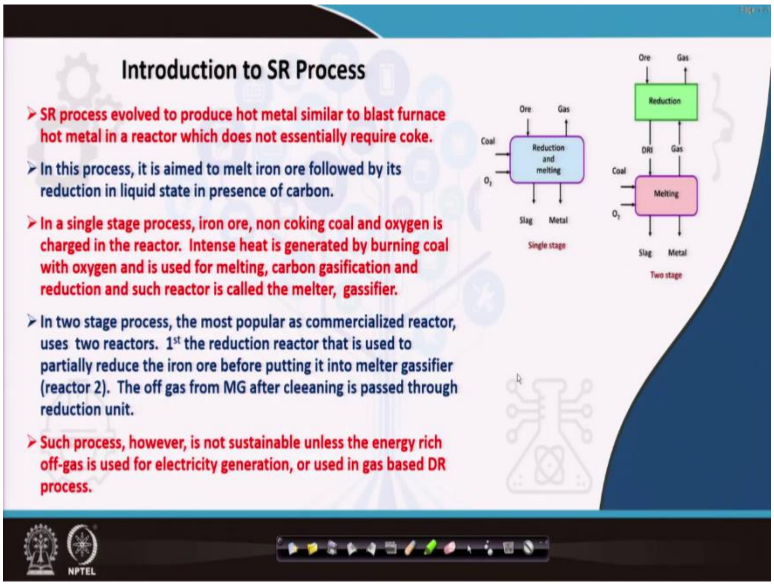

Finally, in this lecture I will give a general introduction to Smelting Reduction (SR).

(i)SR process evolved to produce hot metal similar to blast furnace hot metal in a reactor which does not essentially require coke.

(ii) In this process, it is aimed to melt iron ore first followed by its complete reduction in liquid state in presence of carbon.

(iii) SR process could be carried out in single reactor, or in two independent separate reactors.

(iii) In a single stage SR process, iron ore, non coking coal and oxygen is charged in the reactor. Intense heat is generated by burning coal with oxygen and is used for melting iron burden first. Subsequently, iron ore could be reduced by dissolved carbon, CO gas generated by in-situ carbon gasification reaction.

(iv) In two stage process, the most popular as commercialized reactor, uses two reactors. The first reactor is the reduction reactor (RR) that is used to partially reduce the iron ore before putting it into second reactor, called the melter gassifier (MG). The off gas from MG after cleaning is passed through RR unit. The two stage process follows the philosophy of iron production in blast furnace but in two independent reactors, which makes the process more versatile with reference to its raw material usage. In blast furnace two reactors (reduction in dry zone, and melting in wet zone) exists in the same furnace interfaced by a cohesive zone and therefore quality burden is essential to maintain such complex structure. In SR process the function of reduction and smelting are divided in two separate reactios with independent control that makes SR process more versatile with respect to its raw material.

(v) The carbon rate in SR process is much higher than BF and the off gas produced from SR process is large in volume and rich CO (as there in no nitrogen dilution), especially for single stage SR process. After scrubbing CO_2 this gas be utilized for power generation or could be used for DR process. In fact, the proper use of off gas is essential for energy efficiency and economics of the process. SR process is not sustainable unless the energy rich off-gas is used for electricity generation, or used in gas based DR process.

References:

1) Ghosh & Chatterjee: Ironmaking & Steelmaking-Theory & Practice, PHI, New Delhi, 2008
2) Amit Chatterjee: Sponge Iron Production by Direct reduction of Iron Oxide, PHI, New Delhi, 2012

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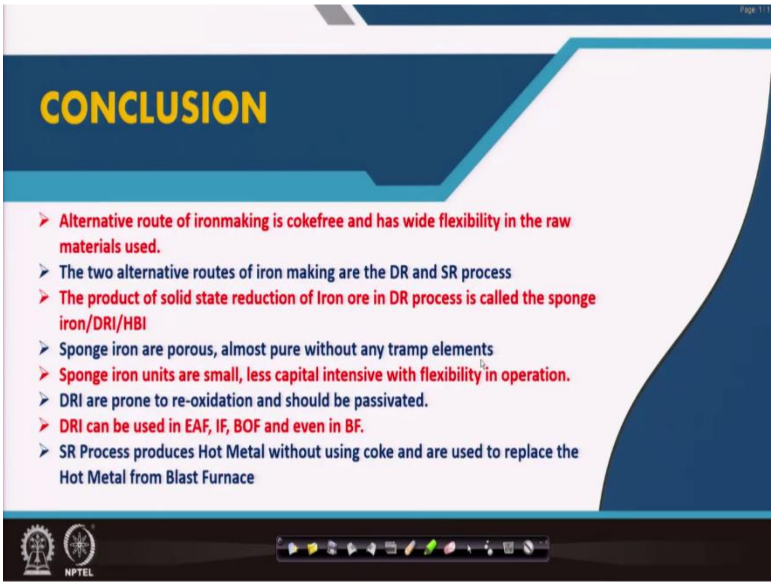

Conclusion:

(i) Alternative route of ironmaking is coke free and has wide flexibility in the raw materials used.

(ii) The two alternative routes of iron making are the DR and SR process

(iii) The product of solid state reduction of Iron ore in DR process is called the sponge iron/DRI/HBI

(iv) Sponge iron are porous, almost pure without any tramp elements

(v) Sponge iron units are small, less capital intensive with flexibility in operation. But specific operating cost is higher.

(vi) DRI, especially gas based DRI, are prone to re-oxidation and should be passivated.

(vii) DRI can be used in EAF, IF, BOF and even in BF.

(viii) SR Process produces hot metal of blast furnace quality without using coke.

(ix) Scrap-DRI-HM-EAF route has reached 50% mark of overall crude steel production today