Iron Making and Steel Making

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Module - 01
Lecture - 01
Introduction

Good morning, I am Professor G Roy, I am giving a course on Iron Making and Steel Making. And this is my first lecture and this is the model 1 lecture 1 on Introduction.

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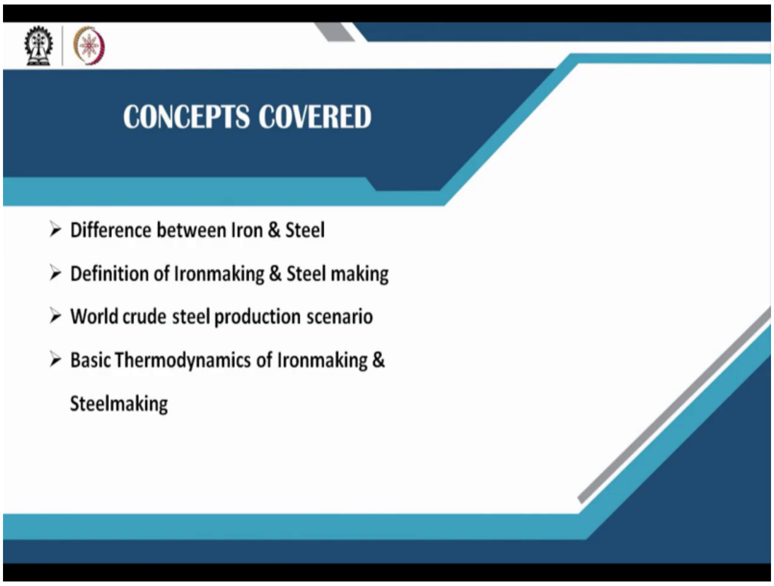

CONCEPTS COVERED

- Difference between Iron & Steel
- Definition of Ironmaking & Steel making
- World crude steel production scenario
- Basic Thermodynamics of Ironmaking & Steelmaking

The major concept covered in this lecture is given above. First I will talk about the difference between iron and steel. I will assume the class is very novice and so, you need to know what is called iron and what is called steel.

And then, I will talk about the definition of iron making and steel making; basically what do you mean by iron making and steel making, from a layman's perspectives. Then I will switch to world crude steel production scenario today; just today who is producing how much and what is the position of India. And then of course, I will talk about the basic of thermodynamics of iron making and steel making in brief, which will be discussed in details later.

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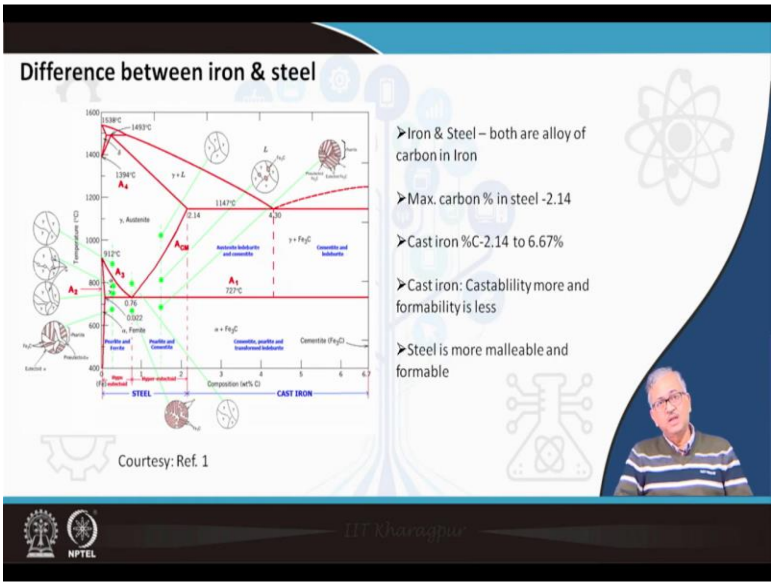
Difference between iron & steel

Courtesy: Ref. 1

- Iron & Steel – both are alloy of carbon in Iron
- Max. carbon % in steel -2.14
- Cast iron %C-2.14 to 6.67%
- Cast iron: Castablility more and formability is less
- Steel is more malleable and formable

So, first let us differentiate between iron and steel and what do you mean by iron and steel? Iron and steel both are the alloys of carbon in iron. The basic difference lies with the carbon percentage in these alloys. It is better to understand this in terms of iron carbon diagram and this is a very well known diagram in metallurgy. It is basically binary phase diagram between iron and carbon. The diagram shows the different stable phases as a function of carbon and temperature. Steel is defined with carbon percentage upto 2.14 and beyond that it is called the cast iron.

Pure iron is basically a very soft material and very malleable. When we introduce some impurity like carbon into pure iron, it becomes stronger yet malleable due to solid solution hardening, called mild steel. But if you go on increasing the carbon what happens? Then carbon cannot be accommodate into the iron structure, it precipitate in the form of iron carbide making the structure harder at the expense of ductility, called high carbon steel. With further increase in carbon, carbon comes out in the form of localized precipitation of carbides and even in the form of graphite flakes-leading to cast iron.

In case of the cast iron since it is carbon rich it becomes brittle and because of brittleness its formability decreases you cannot form by conventional deformation route like rolling/forging. So, they will break during the conventional forming process, but they have a very good castability especially when some impurities like silicon are present and that is why they are called the cast iron-that you can easily cast.

But steel is strong and at the same time it is formable, you can use any form of forming techniques like forging/rolling to deform steel and give different shapes and it is not required to be cast. So, after casting bloom or slab by continuous casting, you can give different shapes starting from thin sheet to wire to any other shapes later on.

The structure of steel consists of ferrite and cementite. Ferrite is a solid solution of carbon in iron, where the carbon percentage is only 0.02 weight percent and it a very soft material. Cementite is an intermetallic compound between iron and carbon and is quite hard. At 0.8% carbon, ferrite and cementite is converted to pearlite by eutectoid reaction. Pearlite is a structure formed by alternate layer of ferrite and cementite. At composition less than 0.8% carbon, the steel is called hypo-eutectoid which consists of ferrite and pearlite; and at composition greater than 0.8% carbon, called the hyper-eutectoid steel, which consists of cementite and pearlite. Anyway different categories of steel are there, namely low carbon steel, medium carbon steel and high carbon steel based on carbon composition.

So, we can see that cast iron is only castable, and it has no formability; while steel is more malleable and formable that is the important thing.

In the following slide we basically talk about the basic definition of iron making and steel making.

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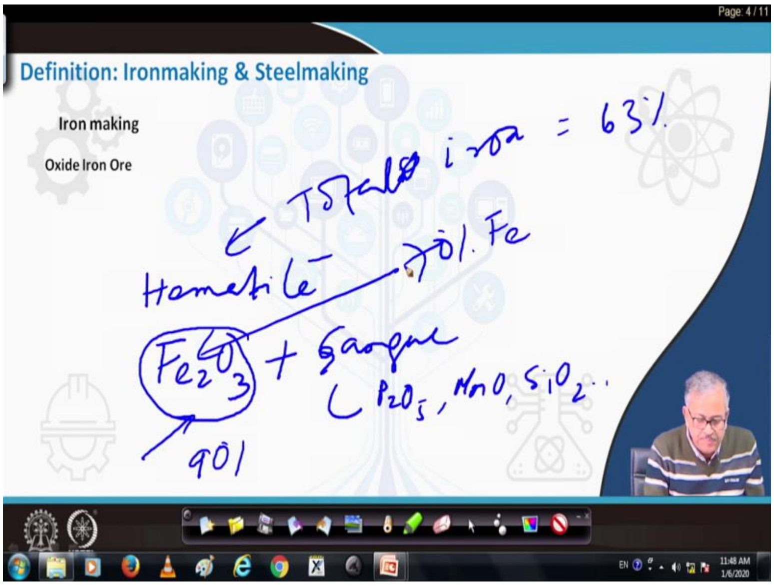

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Definition: Ironmaking & Steelmaking

Iron making

Oxide Iron Ore

Total iron = 63%

Hematite — 70% Fe

Fe_2O_3 + gangue

(P_2O_5, MnO, SiO_2..

90%

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What do we mean by iron making? We know the richest ore of iron are basically oxide ores. And two major oxide ores are there, one is called the hematite; and the other is called the magnetite. The mineralogy of hematite is Fe_2O_3, plus the undesirable gangue. In the gangue you have P_2O_5, MnO, SiO_2.In case of the good grade of hematite ore, hematile is above 90 percent and total iron greater than 63%, as hematite contain 70% iron.

Similarly, we have another ore called the magnetite, and the mineralogy is Fe_3O_4 plus undesirable gangue. Usually magnetite ore are comparatively of poorer grade and requires beneficiation for its upgradation. India has large reserve of hematite ore and this is the major source of iron ore to the blast furnace.

So, if we want to produce iron from hematite ore, we have to extract oxygen and separate the gangue. So, if you take an iron oxide how you can reduce it? From your 12 knowledge you know iron oxide can be effectively reduced by carbon under high temperature that is called the carbothermic reduction.

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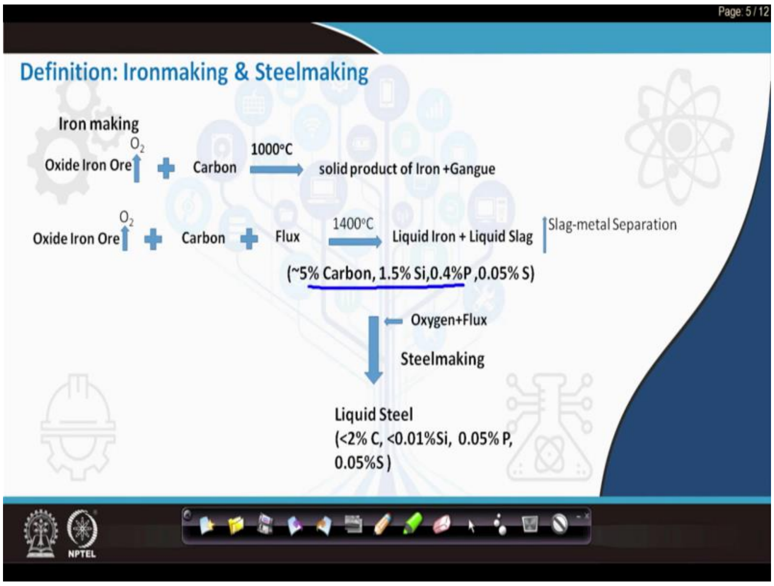


Definition: Ironmaking & Steelmaking

Iron making

Oxide Iron Ore $\uparrow O_2$ + Carbon $\xrightarrow{1000^{\circ}C}$ solid product of Iron +Gangue

Oxide Iron Ore $\uparrow O_2$ + Carbon + Flux $\xrightarrow{1400^{\circ}C}$ Liquid Iron + Liquid Slag | Slag-metal Separation

(~5% Carbon, 1.5% Si,0.4%P ,0.05% S)

$\downarrow$ $\leftarrow$ Oxygen+Flux

Steelmaking

Liquid Steel
(<2% C, <0.01%Si, 0.05% P,
0.05%S)

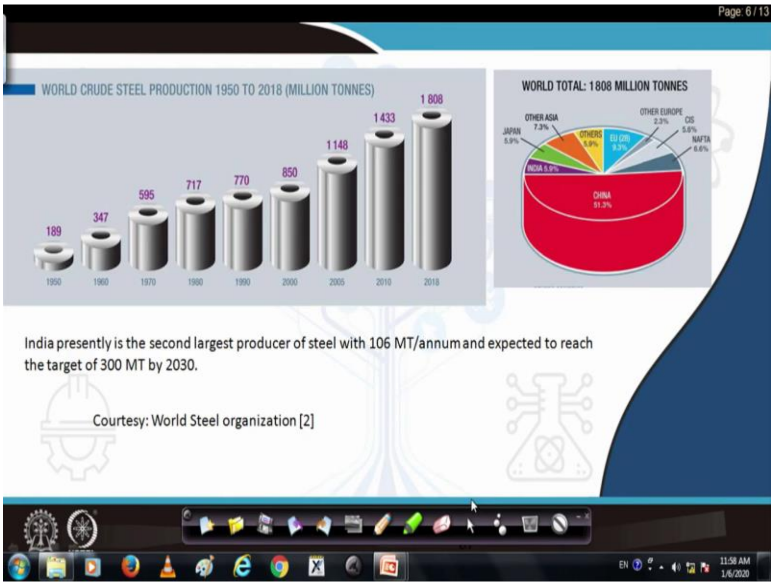
The slide above, shows two approaches of iron production. In the first method, oxygen is extracted from iron ore by carbon in solid state producing solid product of iron mixed with gangue-called the direct reduction. Since the reduction of iron ore in presence of carbon is highly endothermic, around 1000°C is required. Since the product is mixed with gangue, some high temperature post processing will be required to separate the gangue in the form of liquid slag over liquid iron.

The other approach is to produce the liquid iron directly, separated from slag. Here, you require further higher temperature and some fluxing agent to make liquid slag and separate it over liquid metal. So, basically the gangue you have separated in terms of slag now.

So, you get two liquid products- liquid iron with some impurities that are sourced from partial reduction of gangue oxides. The other product is liquid slag that are sourced from unreduced oxide in gangue and fluxing agent. The liquid iron has typical composition around 4 to 5 percent carbon (almost saturation level of carbon in iron). 0.8 to 1% Mn, 1 to 1.5 percent silicon, 0.2 to 0.4 percent phosphorus, and 0.05 Sulphur. Sulphur is quite low because iron production is reducing process and fluxing make the slag basic and both this conditions are favourable for sulphur removal. While other impurities are removed in their oxidized states, which requires a new process called the steel making.

So, hot metal with such high impurity content are not formable unless impurities are reduced significantly. The idea of the steel making is to remove the impurities by selective oxidation of these impurities in preference to iron. In steel making you need to add oxygen in some form (usually pure oxygen) as well as the flux. Oxygen are provided for oxidation of impurities and flux is used to retain and lock the impurity oxides in the slag and restricts reversion from slag to metal. Fortunately, most of the impurity oxides are more stable than FeO at steel making temperature that makes preferential removal of impurities. As we will discuss later that phosphorus removal requires a mandatory basic slag for its removal.

The structural crude steel contains less than 1000 ppm carbon much less than 2% carbon, by definition); silicon less than 00 ppm, phosphorous less than 0.05% (<500ppm) and sulphur to its original value at 0.05%, as Sulphur could not be removed during steelmaking. If Sulphur is required below 0.05%, then some external desulphurization may be carried out.



India presently is the second largest producer of steel with 106 MT/annum and expected to reach the target of 300 MT by 2030.

Courtesy: World Steel organization [2]

After understanding ironmaking and steelmaking, let us focus our attention to the world scenario of crude steel production. You can see here the chronological development of iron production over the world. In 1950 it was only 189 million ton, today we are producing 1808 million tons. And if you see the share of different countries you can find that China is producing around 50 percent of the world steel production. India today is the second largest producer of steel amounting 106 million ton, just over taking Japan producing 104 million ton. India is aiming to produce 300 million ton of steel by 2030. Next let us see the steel consumption pattern.

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APPARENT STEEL USE (CONSUMPTION) PER CAPITA 2018 (KILOGRAMS)

India's domestic steel consumption is growing and is expected to be the second largest (90MT) steel consumer surpassing USA

Courtesy: World Steel organization [2]

So, if you see the apparent steel use in terms of the per capita steel consumption (kg of steel consumption per person), how much steel we are consuming? You can see South Korea is consuming the maximum (1,000 kg per person) followed by China (590 kg), Japan (512 kg), with an world average of 250 kg. In contrast, India's per capita consumption is quite low, i.e, 70.9 kg. But you must take into account the population also; and from that point of view, you can see that China is consuming the largest amount of steel, but per capita consumption is less than that of South Korea, because China has a large population.

So, if you see total steel consumption wise, China is the major consumer of steel today. India's domestic steel consumption is also growing and very soon India is going to consume more than 90 million ton per annum and took up the second place surpassing the USA. USA now consuming maybe 90 million tons of steel per annum.

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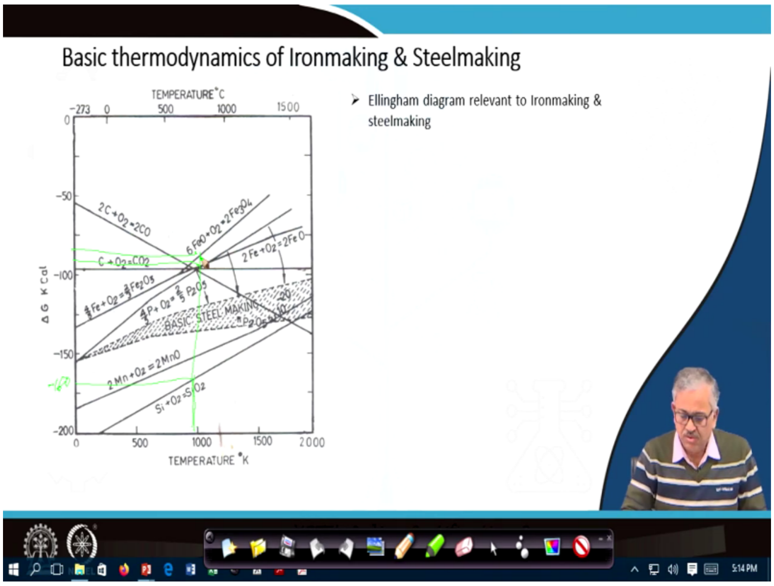

Basic thermodynamics of Ironmaking & Steelmaking

- Ellingham diagram relevant to Ironmaking & steelmaking

In this section, I will discuss briefly about the basic thermodynamics of iron making and steelmaking. And it will be a very brief outline and later on I will go into details. Now I will just show you Ellingham diagram that is very relevant to the iron making and steel making and possibly most of you know about this diagram. Ellingham diagram basically shows the standard free energy change for a metal-metal oxide system as a function of temperature.

As you can see different metal-metal oxide systems are represented by separate lines (almost parallel to each other) showing the variation of standard free energy change for the respective metal-metal-oxide system with temperature. The diagram compares the relative stability of an oxide with respect to the others. An oxide that is lying higher in position in the Ellingham diagram is less stable compared to an oxide that is positioned lower in the Ellingham diagram and therefore a metal in lower position will be able to reduce an metal oxide placed above in the diagram. For example, SiO_2, MnO are more stable (placed below) than FeO (placed above) at steelmaking temperature and therefore Si and Mn can be oxidized in preference to iron. In other words, iron being the bulk, if iron oxide forms initially due to oxidation, it will subsequently oxidize silicon and manganese and itself being reduced to iron.

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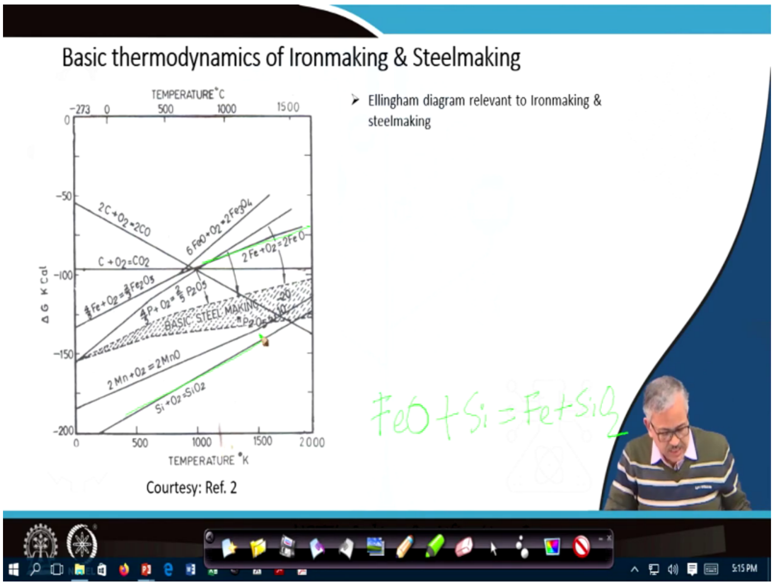

Basic thermodynamics of Ironmaking & Steelmaking

- Ellingham diagram relevant to Ironmaking & steelmaking

Courtesy: Ref. 2

$FeO + Si = Fe + SiO_2$

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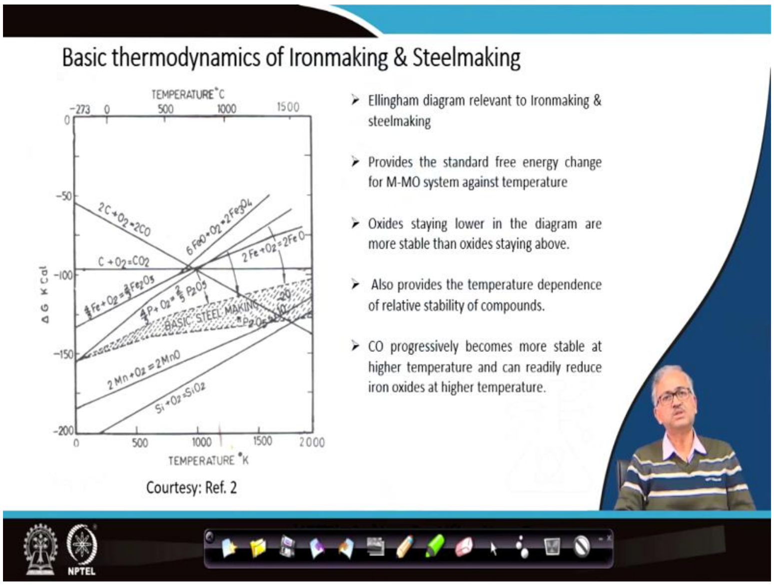

Basic thermodynamics of Ironmaking & Steelmaking

- Ellingham diagram relevant to Ironmaking & steelmaking
- Provides the standard free energy change for M-MO system against temperature
- Oxides staying lower in the diagram are more stable than oxides staying above.
- Also provides the temperature dependence of relative stability of compounds.
- CO progressively becomes more stable at higher temperature and can readily reduce iron oxides at higher temperature.

Courtesy: Ref. 2

In contrast to most of the solid oxides, which have positive slopes, C-CO line has the negative slop. The slope is basically given by the minus of entropy change for the reaction. When both metal and metal oxides are solid, entropy change is always are negative because on the left hand side of reaction you have gaseous oxygen. And this entropy change are almst equal unless metal or solid undergoes softening. Therefore, all metal-metal oxide lines are almost parallel. The C-CO line is with negative slope because two moles of CO is produced from one mole of oxygen. So, CO becomes progressively stable at higher temperature. Therefore, iron oxides are safely reduced by carbothermic reduction during ironmaking. During steelmaking also carbon is preferentially removed over iron.

But you can argue that during ironmaking you can also use the silicon to reduce the FeO. Yes, it is possible, but the problem is that the product of this reaction is solid silica. So, in this case SiO_2 has to be kept into the slag by adding flux and slag volume will be too large for smooth operation of the process. While in carbothermic reduction the product is gas, CO, which escapes to the atmosphere.

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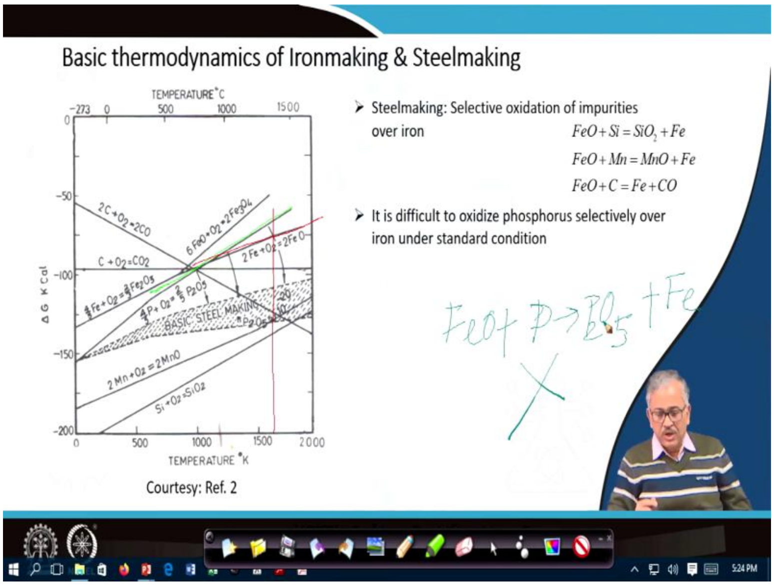

Basic thermodynamics of Ironmaking & Steelmaking

- Steelmaking: Selective oxidation of impurities over iron

$FeO + Si = SiO_2 + Fe$

$FeO + Mn = MnO + Fe$

$FeO + C = Fe + CO$

- It is difficult to oxidize phosphorus selectively over iron under standard condition

$FeO + P \rightarrow P_2O_5 + Fe$

Courtesy: Ref. 2

As I have mentioned that iron being the bulk (95% in liquid iron), during steelmaking, oxidation of Fe is kinetically favoured and it get oxidized first. The oxidation of Si, Mn, C takes place subsequently by FeO as oxides of Si, Mn, and C are more stable than iron oxide.

But for phosphorus removal, situation is little different. Under standard state (pure state for both metal and metal oxide, as represented in Ellingham diagram) P_2O_5 is less stable than FeO. As a result, it is not possible to oxidize phosphorus by FeO under standard state. So the reaction as shown in the slide is not possible, when FeO and P_2O_5 are in their pure state. But if we can flux P_2O_5 by flux (say CaO), they form a strong compound, $P_2O_5.3CaO$, where the activity of P_2O_5 decreases significantly that allows the reaction as shown in the slide below possible.

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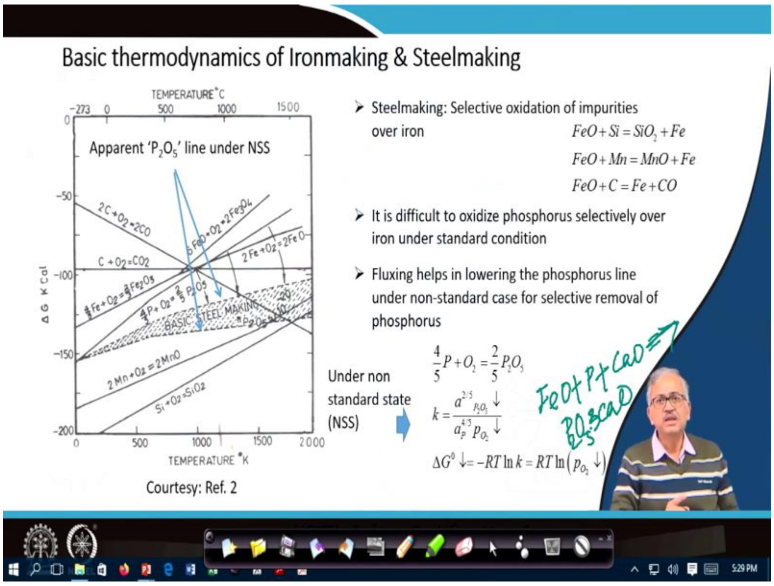

Basic thermodynamics of Ironmaking & Steelmaking

Courtesy: Ref. 2

- Steelmaking: Selective oxidation of impurities over iron $FeO+Si=SiO_2+Fe$ $FeO+Mn=MnO+Fe$ $FeO+C=Fe+CO$
- It is difficult to oxidize phosphorus selectively over iron under standard condition
- Fluxing helps in lowering the phosphorus line under non-standard case for selective removal of phosphorus

Under non standard state (NSS)

$$\frac{4}{5}P+O_2=\frac{2}{5}P_2O_5$$

$$k=\frac{a^{2/5}_{P_2O_5}\downarrow}{a_P^{4/5}\,p_{O_2}\downarrow}$$

$$\Delta G^0\downarrow=-RT\ln k=RT\ln\left(p_{O_2}\downarrow\right)$$

$FeO+P+CaO \Rightarrow P_2O_5.3CaO$

Therefore, fluxing helps in lowering the phosphorus line (under non-standard state of P_2O_5) for selective removal of phosphorus over iron. Since equilibrium constant is fixed at a particular temperature, is the activity of P_2O_5 is decreased, the partial pressure of oxygen is also decreased. Therefore, the apparent P-P_2O_5 line goes below (as shown by dotted line) the Fe-FeO line under non-standard condition of P_2O_5 and make the preferential removal of phosphorus possible. Depending on the amount of flux addition, or basicity of the slag, the position of the dotted line may fall in a range as shown.

Therefore, silicon, manganese and carbon can be removed under acid slag, and basic slag is not a must. But, for removal of phosphorous selectively over iron, the fluxing is essential. Obviously, the basic slag also help in removing the silicon as the activity of silica in basic slag become low that promotes further silicon removal.

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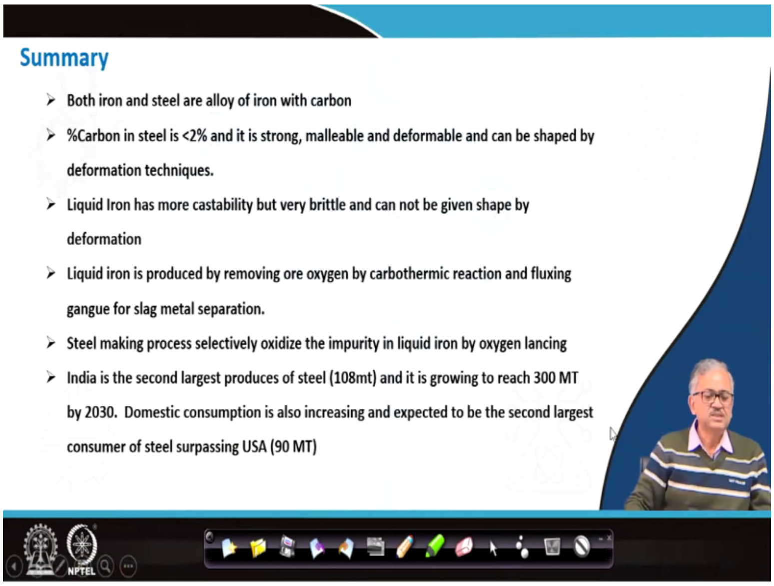

Summary

- Both iron and steel are alloy of iron with carbon
- %Carbon in steel is <2% and it is strong, malleable and deformable and can be shaped by deformation techniques.
- Liquid Iron has more castability but very brittle and can not be given shape by deformation
- Liquid iron is produced by removing ore oxygen by carbothermic reaction and fluxing gangue for slag metal separation.
- Steel making process selectively oxidize the impurity in liquid iron by oxygen lancing
- India is the second largest produces of steel (108mt) and it is growing to reach 300 MT by 2030. Domestic consumption is also increasing and expected to be the second largest consumer of steel surpassing USA (90 MT)

In conclusion: we have first differentiated between iron and steel and we have said that both iron and steel are the alloy of carbon in iron. Carbon in the steel is less than 2 percent, and it is strong malleable and deformable and can be shaped by any deformation technique like rolling, forging. Liquid iron on the other hand has more castability, but very brittle, and cannot be given shape by the rolling forging. That is why the liquid iron is usually converted to the steel by eliminating level of impurities to very low level.

Liquid iron is produced by removing ore oxygen by carbothermic reduction and fluxing of gangue for slag metal separation This is done in a major reactor called the blast furnace where basically you get the liquid iron product by separating the gangue in the form of a slag.

Steelmaking process selectively oxidize the impurity over iron by oxygen using flux. As I have mentioned that for phosphorous removal a basic slag is a must.

China is the leading producer of steel today. India is the second largest producer of steel and it is targeting 300 million by 2030. China is the leading consumer of steel followed by India. But India has a meagre per capita steel consumption of 70 kg/person compared to world average of 250 kg.