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Recent Advances And Emerging Trends In Steel Making Technology: A Detailed Overview

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Abstract

Steel is more than just a metal; it is the backbone of the modern world. As technology evolves, so does the way we make steel becomes cleaner, faster and smarter than ever before.

To meet these requirements, new emerging trends must be introduced. In steelmaking, oxidation of the impurity presents in the hot metal coming from the blast furnace to selectively eliminate them. The steelmaking industry is experiencing a major transformation driven by technological advances and emerging trends that focus on improving efficiency, sustainability and economic adaptability. With the rising global demand for steel, particularly in developing countries, the industry is exploring different routes for reducing greenhouse gas emission, while enhancing production by automation of process and cost-effectiveness by reducing the overall energy consumption in this process. One of the key advancements in recent years is the reduction of total energy consumption by 4 to 5 GJ per ton in steelmaking, bringing it to an average of 19 GJ per ton from 24 GJ per ton. Additionally, efforts are being made to develop green steel with significantly lower greenhouse gas emissions. Moreover, Artificial Intelligence in Industry 4.0 is being adopted for advanced data analytics and is increasingly applied to optimize production, improve quality control, and predict equipment maintenance. In Industry 5.0, human-AI collaboration is being used to automate processes in steel industry is also currently under development.

The aim of the present work is to gain an insight into the recent advancement in steel industry and to deeply probe into the emerging techniques to achieve the goal.

Chapter 1 – Introduction

Steelmaking is the process in which hot metal from the blast furnace is refined by adjusting its elemental composition, such as carbon, silicon, sulphur, phosphorus, and manganese through oxygen lancing. Given its extensive use across all modern industries, steel production must be precise, cleaner, and adaptable to achieve higher yields. As a result, India ranked second in global steel production as of December 2024, following China. In the financial year 2023-24, India's top steel producers were given below, **Tata Steel Limited** Produced highest approximately 34 million tonnes of crude steel, with 14 million tonnes exported.

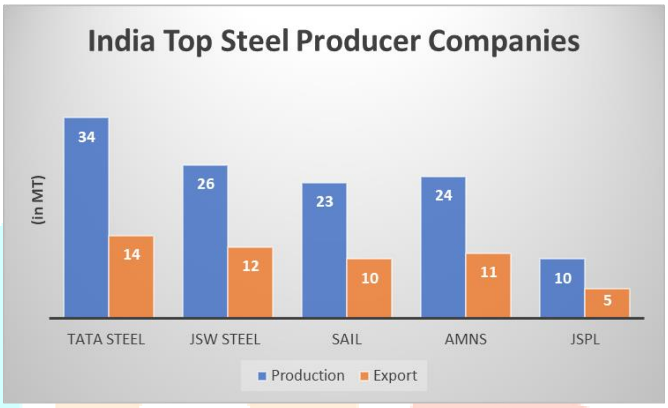

Fig. 1.1 – India Top Steel Producer and Exporter Companies

To meet the growing demand, these companies are investing significantly in capacity expansion. For instance, JSW Steel plans to increase its capacity to 38.5 million tonnes by 2024-25, while Tata Steel aims to add 5 million tonnes to its existing capacity. These expansions are expected to cost billions, with JSW Steel investing between $2-2.2 billion annually and Tata Steel between $1.21-1.51 billion in the financial year 2024-25.

This growth is driven by India's expanding infrastructure, construction, and automotive sectors, along with government initiatives like the National Steel Policy, which aims to increase steel production capacity to 300 million tonnes by 2030. To support sustainable growth, India is also investing in green steel technologies, including the use of hydrogen-based reduction and increased scrap recycling, to reduce carbon emissions in line with global climate goals. Moreover, Artificial Intelligence in Industry 4.0 is being adopted for advanced data analytics and is increasingly applied to optimize production, improve quality control and predict equipment maintenance.

Chapter 2 – Literature Review

Steel is not a pure metal but an alloy composed primarily of iron and one or more elements. The key alloying elements include carbon, sulphur, phosphorus, silicon, etc. Steel is classified based on composition; if carbon is the only main alloying element, it is called plain carbon steel. This is further divided into low carbon steel (up to 0.15% C), mild steel (0.15 - 0.35% C), medium carbon steel (0.35

- 0.65% C), and high carbon steel (above 0.65% C). When other alloying elements are also present, it is termed alloy steel, which is categorized into low alloy steel (up to 5% alloy), medium alloy steel (5 - 10% alloy), and high alloy steel (above 10% alloy). Historically, steels were also classified by the manufacturing method, such as Bessemer, acid open hearth, basic open hearth, electric, etc. Based on usage, steel is grouped as structural, deep-drawing, rail, forging, flats, etc.

There are four primary steel production routes:

- Blast furnace - oxygen converter route (hot metal is first made in a blast furnace, then refined into crude steel in a basic oxygen furnace, or BOF).
- Smelting reduction - oxygen converter route (hot metal is produced in a Melter-gasifier with minimal coke and no sintering, then refined in a converter).
- Direct reduction - arc furnace route (solid sponge iron is produced and then melted in an electric arc furnace to make steel).
- Scrap - electric arc furnace route (a recycling-based route that uses scrap metal, unlike the other three ore-based routes). [1, 2, 3]

2.1 Principle of Steel Making

Essentially, creating steel involves carefully removing unwanted substances from iron through oxidation, a process primarily different from iron production. While it shares a theoretical similarity with fire refining used for non-ferrous metals, steelmaking uniquely results in an alloy, not a pure metal. Starting with molten iron, sponge iron, or scrap metal, the journey to steel is complex, including steps like preparing the input materials, melting, refining, removing the molten metal, eliminating oxygen, reducing carbon content, adding alloying elements, pouring the molten steel, solidifying it in moulds, and removing it from the moulds. The term "steelmaking" suitably captures this complex and historically significant process. During this transformation, most impurities are converted into oxides (with sulphur being an exception, as it is reduced). These oxides are then eliminated either as gases, such as carbon dioxide, or as a liquid mixture of stable oxides called slag. This slag plays a crucial role by capturing and holding the removed impurities. Achieving the desired steel quality and composition focusses on having slag with the correct chemical properties, which are assessed by its basicity (the ratio of basic to acidic oxides) and oxidizing power. Effective steelmaking necessitates proper refining, which means creating suitable slag and ensuring a clean separation between the slag and the metal at the end. Early steelmaking relied on iron oxides from ore and mill scale, or even air, as oxidizing agents. However, modern methods predominantly use high-purity oxygen gas, leading to the widespread use of the term "oxygen steelmaking. The composition adjusted in steel making process was as follow: [1, 2, 3]

Table 2.1 - The initial and final composition during steel making

Elements	Initial Composition	Final Composition
Carbon	4.3 – 4.5%	0.002 – 1.8%
Silicon	0.5 – 1.5%	Up to 0.01%
Sulphur	0.05%	Up to 0.01%
Phosphorus	0.1 – 1.8%	Up to 0.02%
Manganese	0.3 – 1.0%	Up to 0.1%

2.2 Conventional and Basic Oxygen Steel Processes

In the 1850s, Bessemer introduced his steelmaking process, known as the Acid Bessemer Process. However, it did not gain widespread popularity because it could only be used with Swedish iron, which contains less than 0.05% of both sulphur and phosphorus. This type of iron is rare and can only be produced in a few exceptional locations. Later, the Basic Bessemer Process was developed, which used Thomas iron containing more than 1.5% phosphorus making the process more practical and widely applicable.

Subsequently, the Open-Hearth Process was introduced to reduce the heat loss experienced in the Bessemer process. It became quite popular for several decades. However, after the introduction of pure oxygen as a refining agent, the open-hearth method was eventually phased out.

In the 1950s, the LD (Linz-Donawitz) steelmaking process emerged. Its design is quite similar to that of the Bessemer process. Over time, several modifications were made to improve the efficiency of the LD process, such as the Kaldo process, LDAC/OLP process, OBM process, and the Hybrid Blowing process. However, none of these alternatives were able to match the performance and success of the original LD process: [4]

1. **Basic Bessemer/Thomas process:** This process is carried out in a converter with a perforated bottom. First, molten iron is charged into the vessel, and cold air is blown in from the bottom through the perforations to interact with the molten metal. The tap-to-tap time for the process is approximately 30 to 35 minutes. A diagram illustrating this process is shown below.

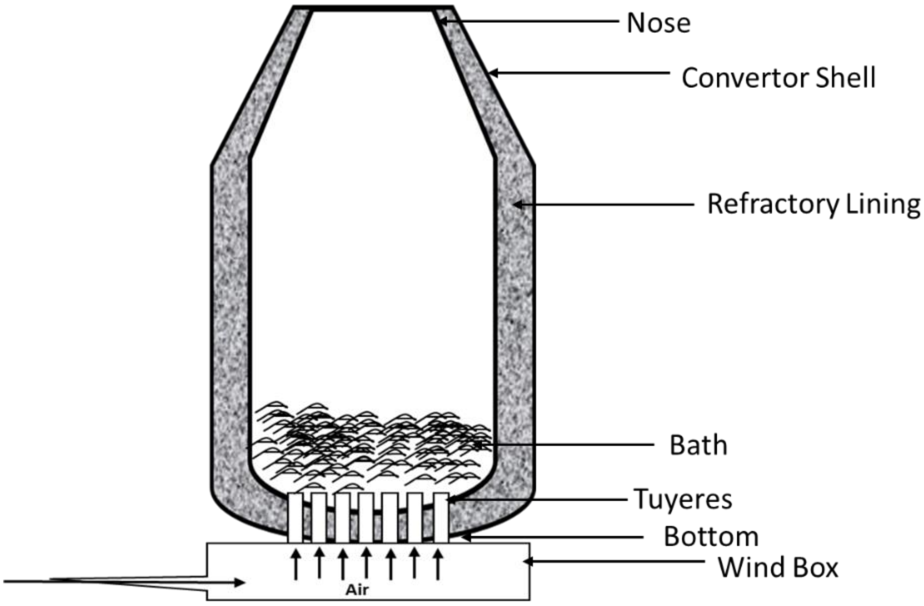

Fig. 2.1 – Basic Bessemer Process

2. **Open Hearth Process:** The vessel is relatively shallow and lined with basic refractory material. It is heated using liquid or gaseous fuel to reach a high temperature of approximately 1600-1700°C after the hot metal is charged. Scrap may also be charged before the hot metal by preheating it to near its softening point. The tap-to-tap time for this process is approximately 6 to 10 hours.

3. **Basic Oxygen Process/ LD Process:** The LD converter is similar in design to the Bessemer converter, but it includes a tap hole near the nose of the vessel through which slag and steel are tapped. Unlike the Bessemer process, which uses air, the LD process uses pure oxygen for steel refining, introduced through a lance. This makes the process autogenous. The tap-to-tap time is typically between 40 and 60 minutes. [4]

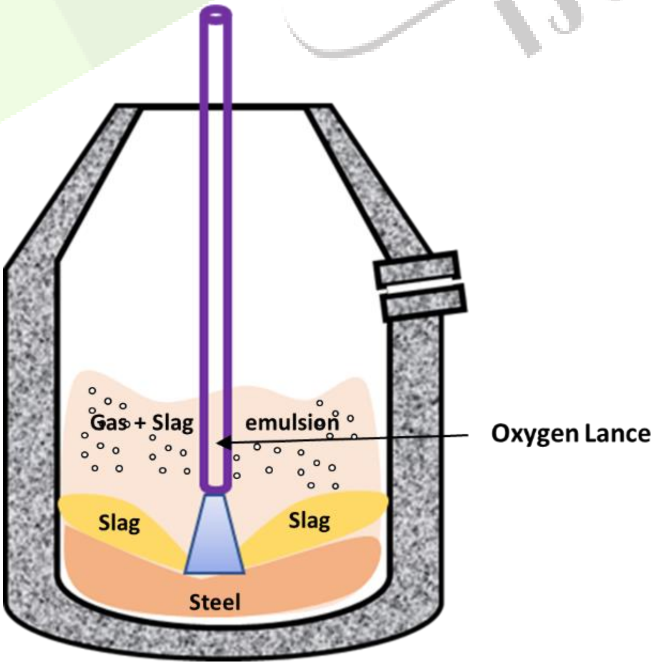

Fig. 2.2 – LD Process

2.3 Raw Materials for Steel Making

The most important raw materials used in steel making are:

1. Metallic Iron source.
2. Oxidising Agent.
3. Fluxes.
4. Source of heat.
5. Deoxidising and alloying agents.

- **Metallic material sources:** Molten iron from a blast furnace, termed hot metal, is the main metallic source for steelmaking, enhancing efficiency potentially through autogenous processing in integrated plants. Pig iron sees rarely use. Direct reduced iron/hot or briquetted iron offers an alternative, but required melting. Smelting-reduction also yields hot metal. Thus, blast furnaces or SR methods with oxygen steelmaking dominate, while DRI/HBI with electric furnaces constitute a significant steel production route.

- **Oxidizing Agent:** Steelmaking employs iron oxide (hematite/mill scale), air, and oxygen as oxidizers. Hematite ore and mill scale, by-products of hot steel fabrication, contain roughly 25% oxygen. Ores have low sulphur but high gangue; mill scale is purer but can have high sulphur. Their balanced use enhances yield but requires energy for oxide dissociation. Air, used in the Bessemer process, introduces embrittling nitrogen. High-purity oxygen (over 99.5%), produced affordably via the Linde-Frankle method, is now vital in BOF and hearth refining, with purity crucial for minimizing steel nitrogen content.

- **Fluxes:** Fluxes are added in smelting/refining to lower gangue softening points, reduce slag viscosity, and stabilize components within the slag. Steelmaking typically uses lime/limestone to create basic slag for phosphorus and sulphur retention. Fluorspar and bauxite are incorporated to thin refining slags.

- **Heat Source:** Bessemer and BOF pneumatic methods are self-heating due to exothermic impurity oxidation during refining. These require hot metal of appropriate composition as input. The heat produced exceeds requirements, necessitating scrap and/or iron ore additions for temperature control. Cold charges alone are insufficient for these processes. While for Electrical arc furnace it uses: Induction heating, Resistance heating, Arc heating.

- **Deoxidising and alloying agents:** In steelmaking, deoxidizers like aluminium, silicon, and manganese are commonly used to remove oxygen, with elements like zirconium, boron, and titanium serving this role in specific applications. Silicon, often added as ferro-silicon, is a primary deoxidizer that also improves strength, hardenability, and electrical properties, while manganese (as ferromanganese) adds toughness and strength, particularly in structural and Hadfield steels.

Aluminium, a potent deoxidizer (used in forms like ferro-aluminium), is also alloyed into heat-resistant steels. Less common deoxidizers such as vanadium, tungsten, titanium, zirconium, and boron also contribute to strengthening and hardenability. Alloying elements including chromium, nickel, molybdenum, niobium, vanadium, cobalt, and silicon enhance mechanical, corrosion-resistant, magnetic, or heat-resistant properties in various steel grades. Nickel and chromium are key in stainless steels, while molybdenum improves hardenability in components like gears and shafts. Carbon, added via coke, graphite, or anthracite, serves to recarburize steel and acts as a reducing agent in electric arc furnaces. Excess deoxidizers can remain as alloying agents, further influencing steel properties. [5, 54, 55, 56]

2.4 LD Process – Design and Operation

Oxygen lancing as a method for refining iron was first attempted by Professor R. Durer in Switzerland. However, it was in Austria specifically at Linz and Donawitz, where pilot experiments using vessels with capacities ranging from 2 to 5 tons were successfully completed, leading to the first casting of refined steel on June 25, 1949. Engineers found that vessels holding between 10 and 15 tons were economically feasible. Following extensive trials and quality checks at the commercial level, the first full-scale LD (Linz - Donawitz) plant was set up in Linz, where the first commercial steel casting took place on November 27, 1952. Donawitz later received a second plant. The technology was soon adopted internationally, with the first plant outside Austria established in Hamilton, Canada, in 1954. In India, Hindustan Steel Ltd. was the pioneer in implementing the LD process at its Rourkela facility in 1956, and production began there in 1960.

An LD plant consists of the following major constituents:

1. The vessel including foundations, rotating gears, etc.
2. The lance including its auxiliary gears.
3. The hood and the waste gas treatment plant.
4. The material handling and storage facilities.
5. Instrumentation and control pulpit.
6. The vessel lining and wrecking accessories.

In the LD (Linz-Donawitz) steelmaking process, the refining takes place in a specially engineered vessel that shares a general similarity to the classic Bessemer converter. This vessel is often referred to as the LD converter, LD vessel, or Basic Oxygen Furnace (BOF). It is structurally divided into three primary sections: a rounded base, a cylindrical middle portion, and a conical upper part. These sections are typically constructed using non-ageing steel plates, which are welded together.

Modern converters are designed as single piece units without mechanical joints. This joint free construction provides multiple benefits, it enhances safety, reduces the risk of warping, and lowers production costs. Where sections are joined, the welding is done with precision to maintain a smooth, continuous surface, which also helps preserve the internal shape of the vessel. The upper part of the vessel may be either concentric (aligned with the centre axis) or eccentric (offset to one side). The eccentric design is widely used because it provides several operational advantages. For example, it simplifies the removal of slag and molten metal, directs gas and material ejections to one side for easier cleaning, and makes it easier to install and manage the oxygen lance and overhead hood. It also offers improved protection and control of the lance due to the inclined positioning of the hood. Although these benefits, the eccentric design also brings certain drawbacks. Since the internal lining is not symmetrical, it becomes more difficult to install properly. Additionally, operations can become blocked, as both charging and tapping occur from the same side of the converter. On the other hand, the functional advantages of the eccentric layout have led to its widespread adoption.

The top of the vessel is shaped like a reduced cone and is tilted at an angle of roughly 8 to 10 degrees relative to the vertical axis of the converter. It is attached to the cylindrical body at an angle. At the point where the spherical bottom and cylindrical shell meet, a steel ring is welded inside the vessel to support the permanent refractory lining. In earlier models, the converter was tapped from the mouth, but in modern designs, a tap hole is placed at the junction of the conical top and cylindrical section specifically on the side where the cone is shortest. To protect this area, a removable wear plate is installed on the flange of the tap hole, helping maintain the integrity of the lining. The converter’s weight is supported by a steel ring at its centre of gravity, with trunnions mounted in foundation-anchored bearings. It can rotate 360°, though in practice it usually turns up to 220°. Rotation is powered by a motor and gear system, with two pinions for small vessels and four for larger ones.

For a given vessel capacity, bath depth is typically set between 110–180 cm to protect the bottom during oxygen lancing. A height-to-diameter ratio of about 1.5 is generally preferred. As capacity increases, bath area expands, though depth does not increase proportionally. Compared to open-hearth furnaces, bath area is about 50% smaller. Vessel volume has evolved from just over 1 m^3/t to 0.75 m^3/t, with modern designs trending back to 1 m^3/t. Lining thickness ranges from 600–1000 mm, with wear allowance based on 1–2 mm loss per heat. Vessel height ranges between 7–10 meters. The nose, typically one-third of the shell diameter and angled around 67°, is designed to minimize heat loss and wear while aiding charging and maintaining structural stability.

Oxygen gas, which serves as the main refining agent, is delivered into the furnace using a water-cooled lance, as shown in Figure 2.3. This lance is constructed from three concentric steel tubes, allowing water to circulate around the central section while oxygen flows through the innermost tube. Because the lance tip is exposed to extremely high temperatures, it is fitted with a copper tip, welded to the steel structure to enhance the cooling effect in that region.

Typically, the lance measures around 8 to 10 meters in length, with a diameter ranging from 20 to 25 centimetres depending on the furnace size. It requires about 50 to 70 cubic meters of cooling water per hour, supplied at a pressure of 5–7 kg/cm^2. The lance is suspended using a wire rope and is raised or lowered into the furnace using an electrically operated mechanism. It is held in a stable blowing position with jigs. Safety systems are in place to automatically retract the lance if the cooling water temperature exceeds a safe limit, generally around 40°C. Backup holding systems are also included to ensure control if the primary mechanism fails. In case of breakdown, a spare lance is kept ready and can be swapped within minutes to avoid interrupting the heat cycle.

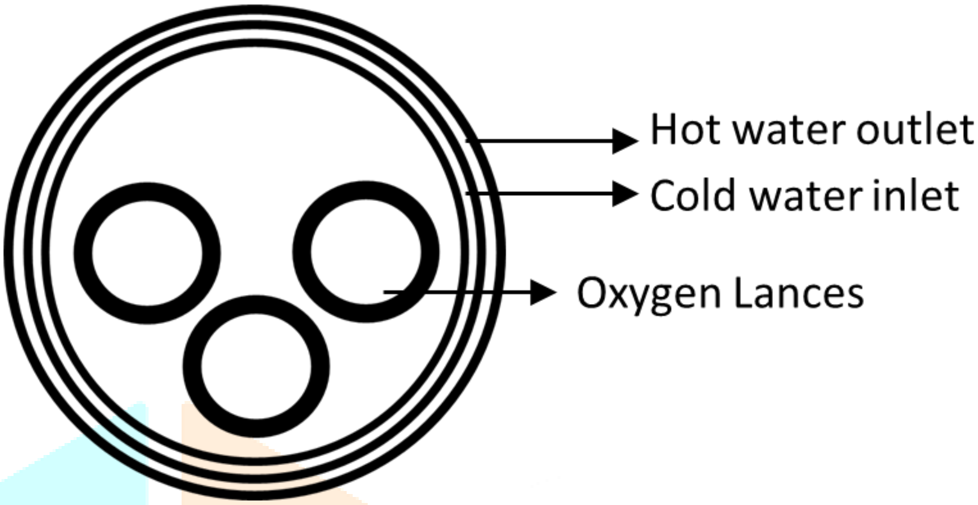

Fig. 2.3 – Oxygen Lance (bottom view)

Initially, the LD (Linz-Donawitz) process used lances equipped with cylindrical nozzles. However, it was later understood that for effective steel refining specifically for decarburization and dephosphorization, the oxygen jet must adequately penetrate the molten bath and cover the largest possible impact area. When oxygen exits a cylindrical nozzle, its static pressure remains higher than the surrounding atmospheric pressure, causing it to interact with the air and create shock waves. These interactions lead to fluctuations and a gradual drop in jet velocity, which negatively affects both the penetration depth and the surface area impacted by the jet.

To overcome these limitations, a Laval-shaped (convergent-cum-divergent) nozzle is now commonly used. Oxygen is blown through this type of nozzle at pressures of 8 to 10 atmospheres, producing a supersonic jet that typically reaches speeds between 1.5 to 2.5 times the speed of sound (Mach). [4]

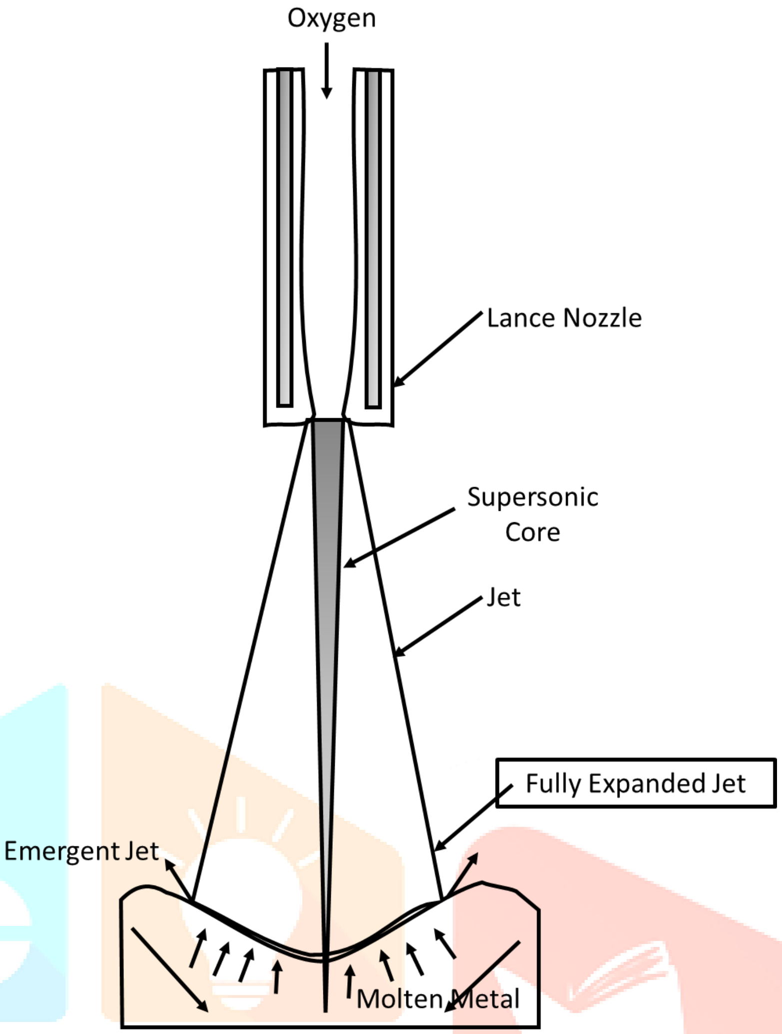

Fig. 2.4 - The effect of supersonic jet on bath circulation. The bath circulates outwards on the surface and upwards on the vessel axis. The characteristic supersonic core is also shown.

In the LD (Linz-Donawitz) process the steps involved are:

1. **Scrap Charging and Hot Metal Charging**: The process initiates with the charging of steel scrap into the converter. This scrap serves as a coolant, absorbing heat generated during the oxidation of the hot metal. Typically, 15 - 30% of the converter's volume is filled with scrap. Subsequently, molten pig iron, or hot metal, is introduced into the converter. This pig iron, derived from the blast furnace, contains approximately 4.3 - 4.5% carbon.

2. **Oxygen Blowing (Lancing)**: A water-cooled oxygen lance is lowered into the converter to inject high-purity oxygen (99.5%) at supersonic speeds onto the molten metal's surface. This injection initiates oxidation reactions, such as:

$$C + O_2 \rightarrow CO$$

$$Si + O_2 \rightarrow SiO_2$$

$$Mn + O \rightarrow MnO$$

$$P + O_2 \rightarrow P_2O_5$$

These exothermic reactions elevate the temperature to approximately 1600–1700°C, facilitating the removal of impurities and refining the steel.

During the oxygen blowing phase, fluxes like lime (CaO) and dolomite are added to the converter. These fluxes combine with oxidized impurities to form a liquid slag. The interaction between the molten metal and slag creates a distinct interface, essential for absorbing oxides such as SiO_2, MnO, and FeO. The vigorous turbulence from oxygen jets and gas evolution leads to the formation of a slag-metal emulsion, enhancing the contact between slag and metal and promoting efficient refining reactions.

The primary gas produced during the process is carbon monoxide (CO), resulting from the decarburization of the molten metal. This gas bubbles through the molten bath, expanding the slag and forming a foamy slag layer. This foamy slag provides thermal insulation, protects the refractory lining, and aids in further refining by maintaining a stable reaction environment

3. **Sampling and Temperature Measurement:** After the end of blowing, the converter is tilted to the side opposite the tap hole, and a sample is taken from the vessel using a long pole equipped with a thermocouple to measure the temperature. The sample is then sent for composition analysis to ensure that the refining process is progressing as desired and that the steel meets the required specifications.
4. **Steel and Slag Tapping:** Converters equipped with a tap hole can achieve nearly slag-free steel tapping by using a ceramic device known as a float. Designed in various shapes to suit different tap-hole configurations, the float has a density between that of slag (≈2.5 g/cc) and molten steel (≈7.5 g/cc), typically around 4.5 g/cc. During tapping, the float remains suspended in the steel without obstructing flow. As slag approaches, it positions itself at the interface, blocking steel from entering the tap hole. Once the slag is fully tapped, the float is removed from the hole and allow the steel to discharge.

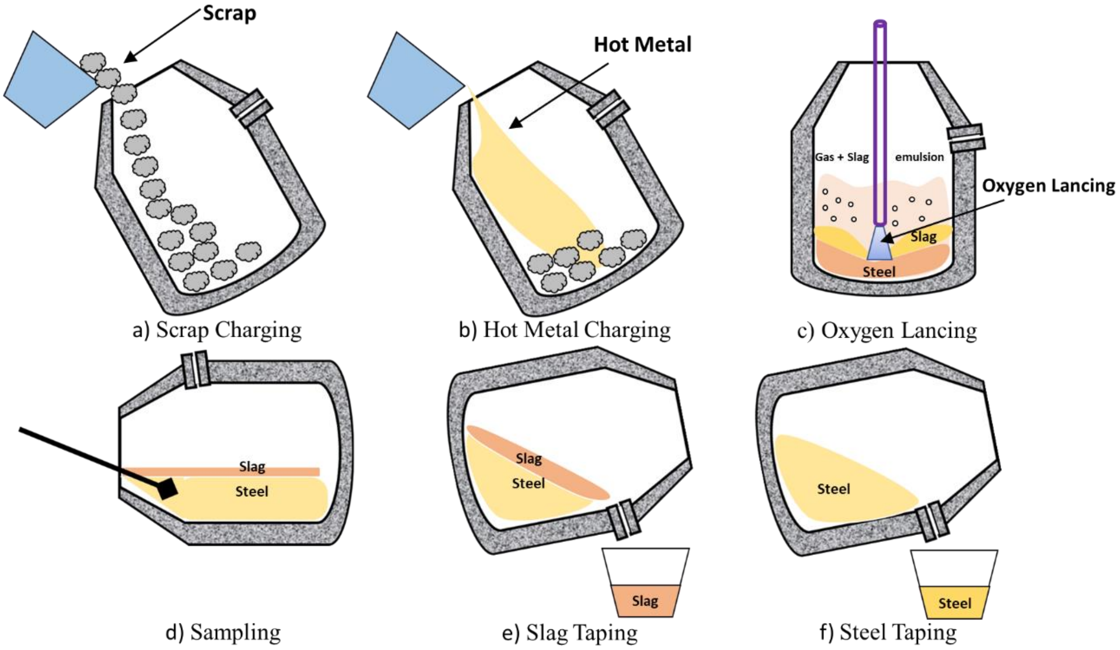

Fig. 2.5 – Steps involved in LD Process

2.5 Secondary Steel Making

In the past, traditional bulk steelmaking methods, such as the open hearth, LD, BOF, and OBM processes, were sufficient to meet the standard requirements for surface finish, internal soundness, micro-cleanliness, and mechanical performance of steel. These techniques fulfilled most industrial needs at the time. However, as demand for higher quality steel increased, expectations also became more demanding, focusing on factors like improved cleanliness, finer and more uniform grain structure, and a narrower range of hardenability. Initially, steel producers tried to meet these rising standards by altering or extending refining operations within the furnace itself.

As this evolved, a deeper examination of the steelmaking process emerged, driven by the goal of maintaining product quality while improving production efficiency. This critical revision eventually led to the introduction of secondary steelmaking techniques designed specifically for high-quality outputs. Consequently, traditional bulk processes were increasingly limited to producing basic, general-purpose structural steels. Higher-grade steels had to undergo additional treatment via secondary refining methods to meet the elevated standards. Often, efforts to refine steel only within the primary furnace setup were either inconsistent in achieving the required quality or proved impractical. In some cases, these approaches, though technically workable, came with drawbacks such as reduced productivity and inefficient use of expensive equipment. [6, 7, 8, 9]

At present, secondary steelmaking is primarily undertaken to fulfil one or more of the following objectives:

a) Enhancing the product's physical characteristics, such as superior surface finish and consistent internal structure.
b) Achieving close control and uniformity in the chemical composition of the steel.
c) Reducing the presence of impurities and unwanted trace elements.

d) Increasing the overall efficiency and speed of steel production.
e) Lowering energy consumption wherever possible.
f) Allowing the use of more economical or substitute raw materials.
g) Facilitating the use of alternative energy sources.
h) Improving the yield of added alloying elements.
i) Precisely managing and maintaining temperature during processing.
j) Achieving deeper levels of carbon removal (decarburization).
k) Reducing sulphur content to extremely low levels (desulfurization).
l) Minimizing phosphorus content to meet rigid specifications (dephosphorization).
m) Removing dissolved gases such as hydrogen and nitrogen (degassing).
n) Eliminating excess oxygen through controlled reactions (deoxidation).
o) Altering the shape and composition of non-metallic inclusions to improve material behaviour.
p) Enhancing the overall cleanliness and purity of the steel.
q) Controlling the solidification process to obtain the desired microstructure.
r) Introducing micro-alloying elements to refine grain structure and improve mechanical properties.

The commercially successful types of secondary steelmaking processes can generally be grouped into the following main categories:

1. **Stirring treatments:** Stirring the steel in the transfer ladle is a basic secondary steelmaking method used to promote uniform temperature and composition, support minor alloying, and help remove non-metallic inclusions for improved cleanliness. It is now widely used even during primary refining to enhance slag-metal interaction and refining efficiency.

2. **Synthetic slag refining with stirring:** In secondary steelmaking, synthetic slags are used to absorb impurities like sulphur and phosphorus. Stirring improves the slag-metal interaction, increasing refining efficiency. Desulfurization slags are low in FeO and MnO, while dephosphorization slags are highly basic and oxidizing in nature.

3. **Decarburization techniques**: Ultra low-carbon soft steel can be made through effective decarburization in primary furnaces, while low-alloy variants are produced via ladle additions of low-carbon ferro-alloys. Advanced decarburization methods like VOD, AOD, CLU, and MRP allow high-carbon materials such as HC Fe-Cr to be used without significant chromium loss. This duplex refining approach, arc furnace melting followed by secondary decarburization has greatly reduced stainless steel production costs.

4. **Vacuum treatments:** Gases dissolved in steel, when present beyond a certain level, can cause defects in the final product. Vacuum melting processes aim to produce steel with low gas content and minimal inclusions, either at a low cost or, in some cases, at a higher expense. The focus here is on vacuum degassing processes, developed for treating large volumes of steel (up to 300 tons) under reduced pressure in large-scale commercial steelmaking.

5. **Injection metallurgy:** Injection metallurgy involves injecting fine desulfurizing and deoxidizing powders into molten steel using inert gas, enabling rapid and efficient impurity removal and inclusion modification. This process enhances steel toughness by transforming harmful inclusions into harmless, globular forms, and is widely adopted using systems like the TN (Thyssen Niederrhein) method.

6. **Plunging techniques:** Plunging techniques involve immersing a crucible containing a small amount of reagent into the steel bath using a refractory-coated rod, allowing the reagent to react with the molten steel. This method is used for minor or non-routine additions, though injection techniques are now more commonly preferred for regular desulfurization.

7. **Post solidification treatments:** Steel quality can also be enhanced after primary refining and casting by re-melting and re-casting, as seen in zone refining for purer metals. Techniques like Vacuum Arc Re-melting (VAR) and Electro Slag Refining (ESR) are used to produce cleaner, low-sulphur alloy steels, though they are now mostly limited to specialized or research applications.

8. **Tundish metallurgy:** A tundish, once just a flow control device, now used in steel refining by enabling inclusion removal, deoxidation, and temperature control. With design features like slag covers, filters, and flow modifiers, it plays a key role in improving casting quality, an approach known as "tundish metallurgy." [6, 7, 8, 9]

Ladle Metallurgy: Many secondary steelmaking operations are performed directly in the steel transfer ladle or in a specialized vessel called a ladle furnace (LF). As a result, the term "ladle metallurgy" is commonly used to describe these processes and is widely recognized in industry literature.

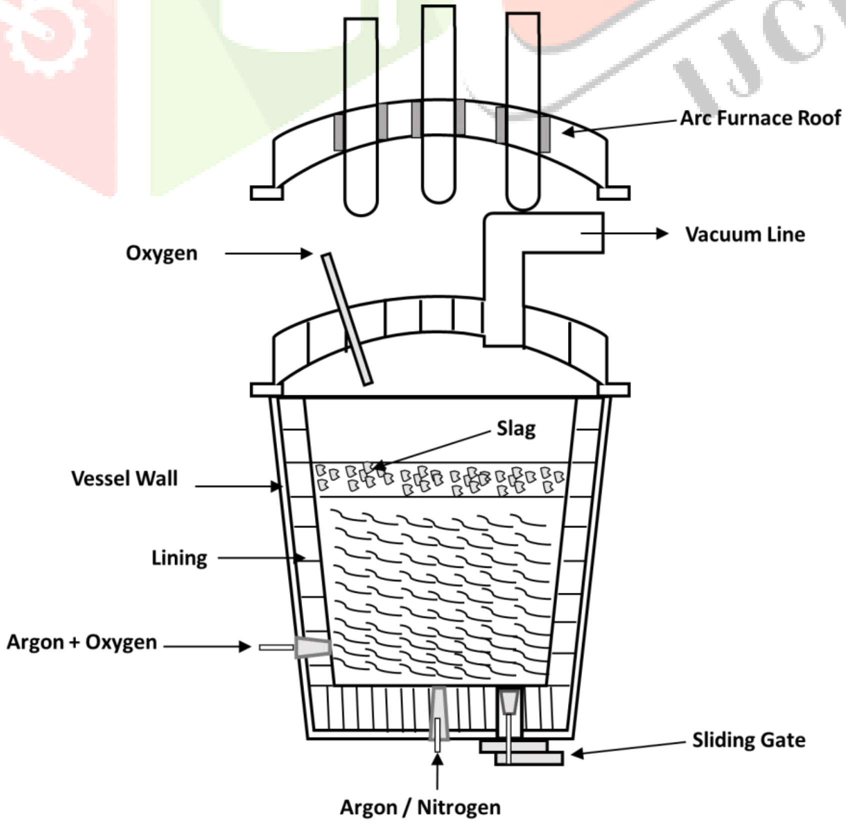

Fig. 2.6 – Ladle Furnace

A ladle furnace is a versatile refining unit equipped with a bottom plug for argon purging, electrodes for arc heating, and optional vacuum connections for gas treatment. It can perform various operations such as stirring, vacuum treatment, slag refining, plunging, and injection metallurgy, all while minimizing temperature loss. Depending on the refining needs, it can be customized with specific features, like ignoring vacuum attachments when gas control is not needed. This makes it adaptable for different steel refining processes.

Continuous casting Process: Continuous casting is a crucial and highly efficient process in modern steelmaking, designed to convert molten steel into solid semi-finished products like billets, blooms, and slabs, which are later processed into various forms such as sheets, bars, or structural profiles. The process starts once the steel has achieved the desired chemical composition and temperature in the ladle, a large refractory-lined vessel that stores and transports the molten metal. The ladle is then mounted onto a ladle turret, a rotating structure that positions it above the tundish, a shallow intermediate vessel. The tundish serves several vital functions: it controls the flow of molten steel into the mould, filters out non-metallic inclusions using flow control devices such as dams, weirs, or baffles, maintains a steady temperature, and allows continuous casting during ladle changes by acting as a buffer reservoir. From the tundish, the molten steel flows under gravity into the mould, typically made of water-cooled copper, which extracts heat rapidly and causes the outer shell of the steel to begin solidifying. To aid this initial solidification and prevent adhesion to the mould walls, the mould is oscillated vertically. The mould shape, open at the bottom, allows the forming strand to move downward continuously.

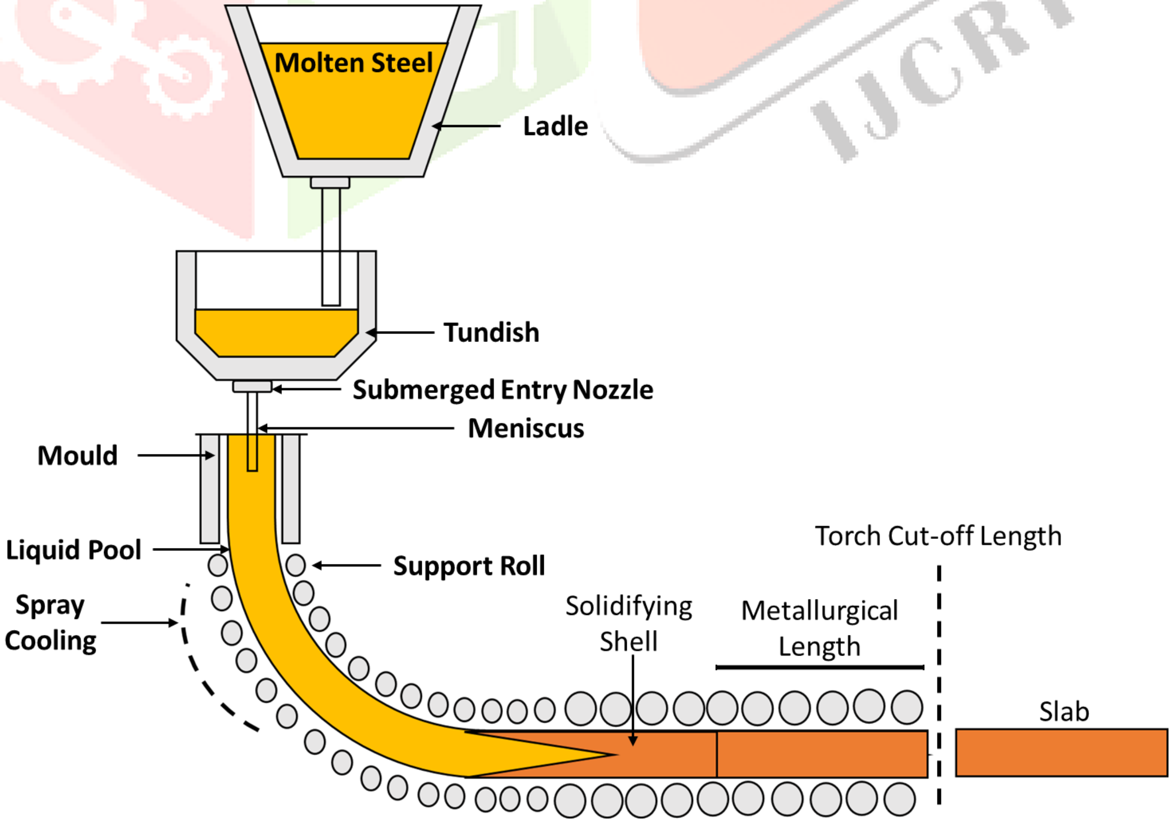

Fig. 2.7 – Continuous Caster

In many plants, a curved mould continuous caster is used to bend the vertical strand into a horizontal direction, reducing space requirements and allowing the steel to exit in a horizontal orientation suitable for further processing. As the strand exits the mould, it passes through the secondary cooling zone, where water sprays or misting systems are applied to accelerate solidification while preventing surface cracks and maintaining metallurgical integrity. At this stage, the strand still has a partially molten core, and the withdrawal system carefully extracts it at a controlled speed synchronized with the solidification rate to avoid deformation or internal defects. Roller's support and guide the strand through this zone, preventing bending or buckling. Once the steel is fully solid, it is straightened and directed to a set of flame cutters that slice it into predetermined lengths based on the specifications for further processing. These cut lengths are then transported to reheating furnaces, rolling mills, or forming units depending on the final product requirements. Continuous casting offers several advantages over traditional ingot casting, including reduced material wastage, improved surface quality, lower energy consumption, and the elimination of intermediate processes like stripping and remelting. The high level of automation and real-time monitoring in modern casting units ensures excellent process control, reduced manpower requirements, and enhanced consistency in product quality. Overall, the continuous casting process represents a major technological advancement in the steel industry, streamlining the transition from molten metal to usable solid forms while maintaining superior metallurgical properties and production efficiency. [6, 7, 8, 9]

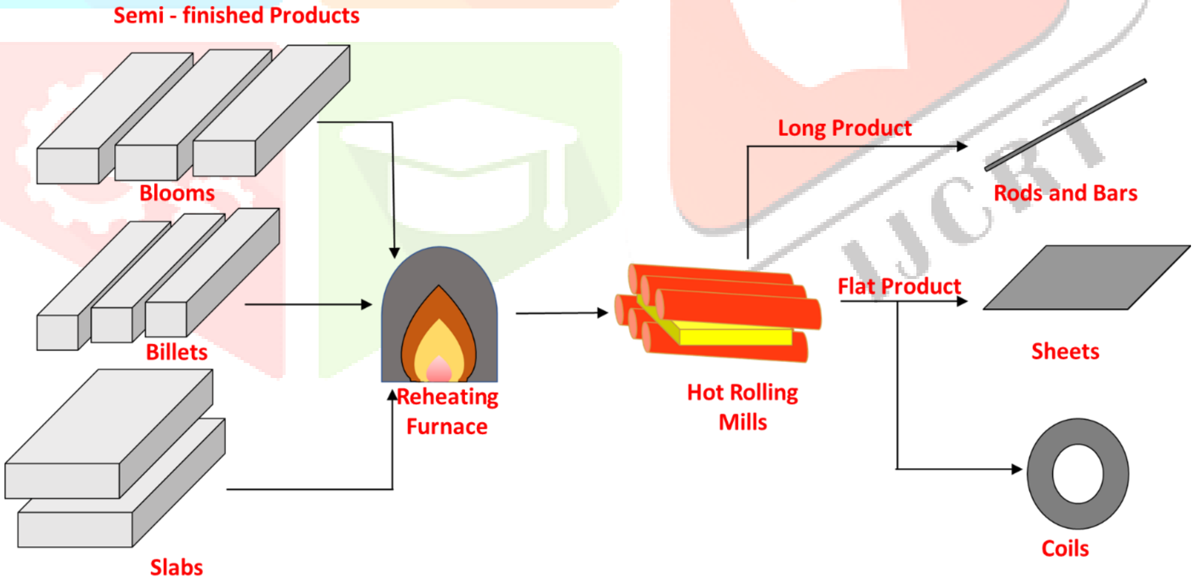

Fig. 2.8 – Semi – finished to Final Products

Chapter 3 – Challenges in Conventional Steel Making Process

3.1 Excessive Energy Consumption

The iron and steel industry are a base of modern infrastructure and industrial development, providing critical raw materials for construction, transportation, manufacturing, and energy sectors. However, it is also one of the most energy-intensive sectors globally, consuming large quantities of coal, natural gas, electricity, and other energy sources throughout its processes. this sector's excessive energy consumption is a fundamental challenge, not just from an operational cost standpoint, but also in terms of environmental impact, resource depletion, and long-term sustainability.

In particular, the traditional blast furnace-basic oxygen furnace (BF-BOF) route dominates global steel production but is extremely energy-intensive. Despite advances in efficiency, the BF-BOF route continues to consume 20-30 gigajoules (GJ) of primary energy per tonne of crude steel produced, making it one of the most energy demanding industrial processes in the world. In India, the energy consumption by the steel sector is particularly concerning due to the rapid growth in steel demand and relatively low adoption of efficient technologies. The sector consumes over 6% of the country's total primary energy, and many Indian steel plants still operate using outdated technologies with poor energy recovery systems. [1, 2, 3]

Table 3.1 - Different steelmaking processes consume energy at different rates

Process	Energy Intensity (GJ/tonne of steel)
Blast Furnace - Basic Oxygen Furnace (BF - BOF)	20–30 GJ/t
Direct Reduced Iron - Electric Arc Furnace (DRI - EAF)	12–18 GJ/t
Scrap - Based Electric Arc Furnace (EAF)	6–10 GJ/t

The BF-BOF route, while effective for producing high-quality steel from virgin iron ore is far more energy-intensive than scrap-based EAFs, which rely on melting recycled steel using electricity. The vast gap in energy use underscores the need for innovation in the BF-BOF process or a shift to less energy-intensive methods.

3.1.1 Root Causes of Excessive Energy Consumption

a) Inefficiencies in Traditional Processes:

- The blast furnace process is inherently energy-inefficient due to heat losses, incomplete combustion, and the use of coke as both fuel and reducing agent.
- Heat from flue gases and other off-streams is often not fully recovered or utilized.

b) Aging Infrastructure:

- Many steel plants, especially in developing economies, still operate with decades-old equipment that lacks modern energy-saving features.
- Upgrading these plants is capital-intensive and operationally disruptive.

c) Limited Process Integration:

- Lack of integration between different production stages leads to redundant energy usage.
- For example, waste heat from one stage may not be captured or redirected to another, resulting in thermal losses.

d) Inadequate Heat Recovery:

- Blast furnaces and coke ovens emit significant quantities of hot gases.
- Without proper recovery systems, a substantial portion of this thermal energy is lost.

e) Low Scrap Utilization:

- Scrap steel can be recycled at a much lower energy cost.
- However, in many regions (including India), the availability and quality of scrap is inadequate, resulting in higher reliance on energy-intensive virgin iron ore routes.

f) Overuse of Fossil Fuels:

- The energy mix in conventional steelmaking is heavily skewed toward coal and natural gas.
- Transitioning to renewables or hydrogen requires infrastructure and policy support, which are currently lacking. [10, 11, 12, 13]

3.2 Need for Digital Transformation and Reduction of Human Dependency

The steel industry is undergoing a significant shift toward intelligent manufacturing, driven by the global wave of digital transformation. Traditional steelmaking processes, while mature, are often labour-intensive and less adaptive to rapidly changing production demands. To enhance efficiency, quality, and flexibility, there is a growing need to integrate advanced digital technologies such as artificial intelligence (AI), big data analytics, and industrial internet of things (IIoT). Modern steelmaking processes are becoming more complex and require high levels of precision. However, relying only on human experience and manual intervention poses limitations, such as Operator fatigue, inconsistent judgments, and lack of adaptability under varying conditions can affect production quality. Skilled personnel shortages and increasing safety concerns make manual operations less sustainable.

a) Digital transformation enables:

- Real-time data acquisition and analysis from various production stages.
- Creation of digital twins that replicate physical processes, allowing for accurate simulation, prediction, and control.
- Improved traceability and intelligent decision-making, which are difficult to achieve with conventional control systems.

- This transformation supports the evolution from automation to increased intelligence, making it possible to self-optimize processes with minimal human intervention.

b) Introducing AI helps to:

- Automate knowledge-driven tasks such as quality prediction, fault diagnosis, and process control.
- Minimize human errors by providing consistent, data-driven decisions.
- Enable autonomous systems that learn and adapt over time, reducing the burden on human operators.
- Ultimately, reducing human dependency is not about removing people but about enhancing human capabilities and ensuring safer, more reliable production environments. [18]

3.3 Complex and Harsh Operating Environment

Converter steelmaking operates under extremely high temperatures, often 1600°C and involves fast, complex chemical interactions among molten metal, slag, and injected oxygen. These extreme operating conditions make direct human monitoring impractical and reduce the effectiveness of conventional sensors and instrumentation. The dynamic and irregular nature of the process, such as rapidly changing reaction rates and complex material behaviours, adds further difficulty to real time control and monitoring. These factors make it hard to optimize the process, ensure consistent quality, and maintain safety, all of which are essential in modern steel manufacturing. As a result, there's an increasing reliance on advanced digital technologies, such as digital twins, that can simulate, forecast, and virtually monitor converter operations without depending only on physical hardware. Under such harsh conditions, the converter environment becomes highly unstable and physically demanding, presenting numerous operational challenges:

- Limited Accessibility and Sensor Lifespan: The intense heat, dust, and corrosive fumes make it difficult to place or maintain physical sensors inside the converter for continuous monitoring. Even when high-temperature-resistant sensors are used, their operational lifespan is short, and frequent replacements disrupt production and increase maintenance costs.
- Rapid and Nonlinear Reactions: The reactions inside the converter occur in a matter of minutes and are highly exothermic and nonlinear. These conditions make it difficult to predict process behaviour using traditional static models or manual control systems, often resulting in variability in steel quality.
- Invisibility of Internal Processes: Since most chemical and thermal reactions occur beneath the surface of the molten bath, they are not directly observable. Traditional data collection methods cannot capture this internal behaviour in real time, limiting the operator’s ability to make informed adjustments during the process.

- Safety Risks: The converter's high energy and reactive materials pose significant safety hazards. Minimizing human exposure is crucial, but this also limits the ability to perform manual inspections or interventions.

- High Demand for Precision: Modern steelmaking requires tight control over the chemical composition and temperature of the final product. Slight deviations in process parameters can lead to defects, inefficiencies, or product rejection. However, achieving this level of precision is difficult without continuous, real-time insights into the converter's internal state. [19, 20, 21, 22]

3.4 Need of Increasing Scrap Consumption

The need to increase the scrap charge in the basic steelmaking process, particularly in the context of BOF (Basic Oxygen Furnace) and EAF (Electric Arc Furnace), is driven by several interrelated environmental, economic, and technical factors:

a) Reduction in CO_2 Emissions: Increasing scrap usage directly reduces carbon dioxide emissions because it lowers the reliance on primary iron sources like hot metal and DRI, both of which are carbon-intensive. This shift supports the global goal of decarbonizing steel production.

b) Energy Efficiency: Scrap melting requires significantly less energy compared to iron ore reduction. For instance, EAF-based steelmaking, which primarily uses scrap, consumes less energy and emits fewer greenhouse gases compared to BOF.

c) Circular Economy: Scrap steel is 100% recyclable. Increasing its use in steelmaking promotes a circular economy, where steel is continuously recycled and reused, reducing the need for virgin raw materials.

d) Resource Optimization: The limited availability and rising cost of iron ore and coking coal make scrap a more economically viable alternative. Using scrap helps in resource conservation and cost reduction over time. [23, 24, 25, 26]

3.4.1 Challenges in Increasing Scrap Charge in Basic Steelmaking (BOF & EAF)

a) Thermal Constraints in BOF

- BOFs depend on the heat from the oxidation of carbon in molten iron.

- Scrap is cold and absorbs heat, potentially lowering process efficiency or causing incomplete melting.

- High scrap loads may require external heat sources (e.g., burners or hot metal preheating), increasing complexity and cost.

b) Scrap Quality and Contaminants

- Scrap may contain undesirable elements (e.g., copper, tin) that are difficult to remove and degrade steel quality.

- Sorting, cleaning, and pre-processing are necessary but add operational cost and logistical burden.

c) Supply and Economic Limitations

- Inconsistent supply of clean, high-quality scrap, especially in countries with low recycling rates.
- Global competition for scrap raises prices, making it less economically viable in certain markets.
- Scrap markets are volatile, affecting production planning and cost predictability.

d) Technological and Infrastructure Barriers

- BOF plants are not naturally optimized for high scrap usage; retrofitting them can be expensive and technically challenging.
- EAFs are more adaptable to scrap, but transitioning from BOF to EAF requires significant capital and power infrastructure.
- Increased scrap use may require more advanced process controls and sensors to manage variability in scrap composition.

e) Policy and Regulatory Challenges

- In many regions, policies promoting scrap use, recycling infrastructure, or carbon pricing are either lacking or underdeveloped.
- Without regulatory drivers or incentives, many producers are slow to invest in scrap-intensive technologies. [23, 24, 25, 26]

3.5 Make the Steel Making Process Sustainable (Focuses on environmental aspect)

The study addresses the need to find effective and environmentally friendly solutions in the steelmaking process, specifically focusing on the utilization of Bayer red mud:

- Utilization of Industrial Waste: Bayer red mud, a by-product of alumina production, is generated in large quantities and classified as hazardous waste due to its high Na_2O content. The study aims to find ways to utilize this waste material, reducing its environmental impact.
- Improving Steelmaking Efficiency: Steelmaking requires fluxes to enhance slag fluidity and remove impurities like phosphorus. The research investigates Bayer red mud's potential to serve as an effective flux, improving the efficiency of hot metal dephosphorization and simulated steelmaking processes.
- Replacement of Harmful Materials: Traditional fluxes like CaF_2 can lead to environmental pollution. There is a need to identify alternative, environmentally friendly fluxes.

- Achieving High-Quality Steel: Effective dephosphorization is crucial for producing high-quality steel. The study explores the use of Bayer red mud to efficiently remove phosphorus from hot metal, achieving low final (P) concentrations in steel.

- Understanding Slag Chemistry: The research also seeks to enhance the understanding of the complex interactions between components like Al_2O_3, Na_2O, and TiO_2 in steelmaking slag. This knowledge is essential for optimizing steelmaking processes. [31, 32, 33]

3.6 Need for Green Technologies

The steel manufacturing sector stands as a foundation of global infrastructure and industrial development. However, this essential industry carries a significant environmental footprint, primarily through substantial carbon dioxide (CO_2) emissions. The critical need to revolutionize steel production methods to enhance quality, boost productivity, and drastically reduce its environmental impact is discussed here.

- Reduce greenhouse gas emission: Currently, the conventional production of one ton of steel releases approximately two tons of CO_2. This staggering statistic positions the steel sector as a major contributor to greenhouse gas emissions, exacerbating climate change and its associated detrimental effects. The energy-intensive nature of traditional steelmaking processes, heavily reliant on fossil fuels, is the primary driver of this environmental burden. Addressing this challenge is not merely an environmental imperative but also a crucial step towards a sustainable industrial future.

- Lowering carbon footprints: The necessity for green steelmaking technologies extends beyond mitigating climate change. The increasing global focus on environmental regulations and the growing demand for sustainably produced materials are creating significant market pressures. Industries that rely on steel are increasingly seeking suppliers with lower carbon footprints, making the adoption of green technologies a matter of economic competitiveness. Failure to innovate in this area could lead to market disadvantages and hinder the long-term viability of steel manufacturers.

- Resource efficiency and waste reduction: The pursuit of green steelmaking aligns with the broader goals of resource efficiency and waste reduction. Many emerging green technologies not only aim to lower emissions but also focus on optimizing resource utilization, minimizing energy consumption, and enhancing by-products like slag. This general approach contributes to a more circular economy, reducing the strain on natural resources and minimizing waste streams. Innovations in areas like alternative ironmaking processes, the use of hydrogen as a reducing agent, and advanced energy recovery systems hold immense potential in this regard.

- Adoption of advanced and cleaner technologies: Enhancing the quality and productivity of steel production is intrinsically linked to the adoption of advanced and cleaner technologies. Green steelmaking processes often involve advance control systems, optimized energy inputs, and innovative material handling techniques. These advancements can lead to improved product quality, reduced defects, and enhanced overall efficiency, thereby strengthening the economic performance of the sector alongside its environmental stewardship. [46, 47, 48, 49, 50, 51]

Chapter 4 – Recent Advancement and Trends in Steel Making

4.1 Advanced Electric Arc Furnace (EAF) Technology with Hot Metal Charging

Electric Arc Furnaces (EAFs) have traditionally relied on steel scrap as their primary input material. While this method is more environment friendly than BF – BOF based routes, but it also comes with some limitations such as inconsistent scrap quality, variable composition, and supply constraints. To address these challenges and improve operational efficiency, many steelmakers are now adopting hot metal charging, a technique that involves introducing molten iron (hot metal) into the EAF along with or instead of scrap.

Hot metal typically originates from blast furnaces, Corex units, or other ironmaking processes and is transferred in a molten state directly to the EAF. Because it enters the furnace at an elevated temperature (often around 1,300 - 1,500°C), it brings with it a significant amount of thermal energy. This helps to reduce the electrical energy required for melting the charge, thereby increasing the overall energy efficiency of the EAF process. [52, 53]

4.1.1 Key Features of Hot Metal Charging in EAFs

a) Partial or Full Replacement of Scrap:

- Instead of relying only on scrap, molten iron can be charged into the EAF.
- This allows steel producers to overcome fluctuations in scrap quality or availability.

b) High Thermal Energy Input:

- Since the hot metal is already in liquid form, less energy is required to bring the rest of the charge (e.g., scrap or direct reduced iron) to reach melting temperature.
- This significantly reduces the need for electric power during furnace operation.

c) Enhanced Process Stability:

- The composition of hot metal is more uniform and predictable than that of scrap, which may contain impurities, coatings, or foreign materials.
- As a result, process control improves, leading to more consistent steel quality.

d) Improved Productivity:

- The presence of hot metal shortens the melting cycle in the furnace.
- This enables quicker turnaround between batches and increases the number of heats per day, enhancing furnace output.

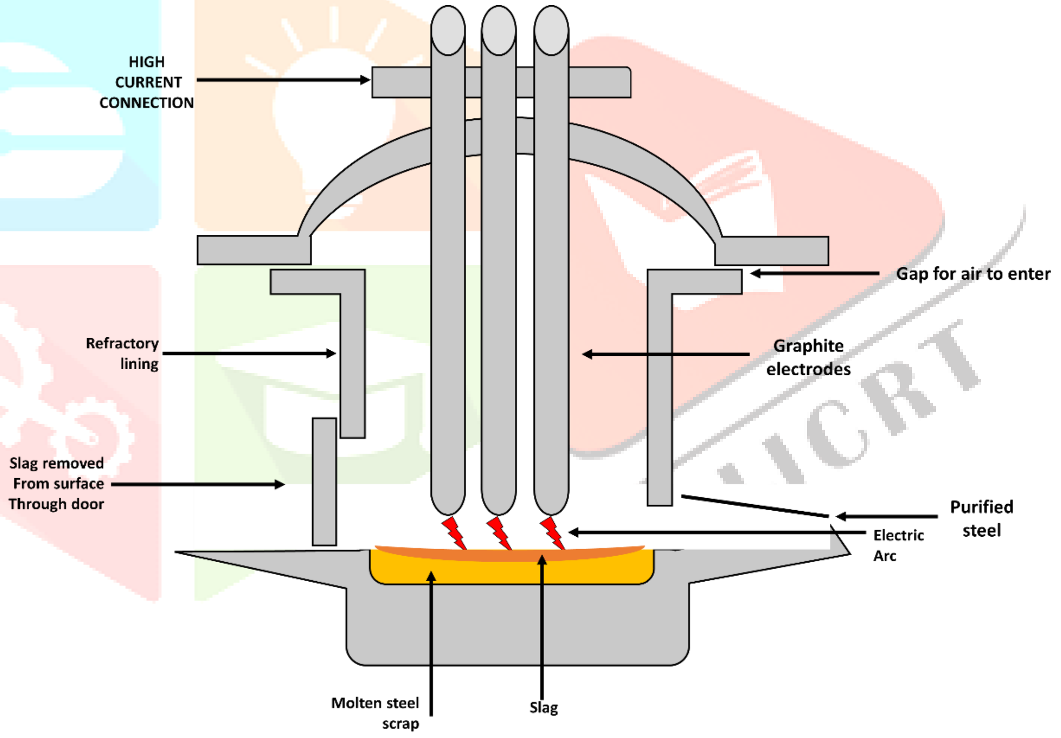

Fig. 4.1 – Advance Electric Arc Furnace (AEAF)

4.1.2 Benefits of Hot Metal Charging in EAFs

a) Energy Efficiency:

- One of the most significant advantages is the reduction in electric energy consumption.
- The thermal energy carried by the hot metal decreases the load on the electrodes and transformers, leading to lower electricity use per tonne of steel.

b) Operational Flexibility:

- During periods of scrap scarcity or high prices, hot metal charging allows producers to maintain stable production levels without compromising cost or quality.
- It also supports hybrid charging strategies, where scrap, direct reduced iron (DRI), and hot metal are blended based on availability and economics.

c) Improved Metallurgical Control:

- Due to the known chemical composition of hot metal, operators can better manage the steelmaking chemistry.
- This allows for more accurate additions of alloying elements, carbon, and fluxes, leading to improved steel grades and reduced rework.

d) Reduced Electrode Wear and Maintenance:

- Lower electricity input results in less intense arc activity, which reduces wear on the graphite electrodes.
- This, in turn, lowers operational costs and minimizes maintenance interruptions.

4.1.3 Technical Considerations and Challenges

While hot metal charging in EAFs offers clear advantages, it also introduces some technical challenges:

a) **Handling and Transport**: Molten iron must be safely transported from the blast furnace or ironmaking unit to the EAF without significant heat loss or delay.

b) **Refractory Life**: The higher thermal load from hot metal can accelerate wear on furnace linings, requiring robust refractory materials and regular monitoring.

c) **Slag Chemistry**: Because hot metal contains more silicon and carbon than scrap, careful slag conditioning is necessary to control basicity and impurity removal. [52, 53]

4.2 Introduction of AI in Steel Making

a) Application of Artificial Intelligence (AI) and Machine Learning (ML): AI and ML models are increasingly used to manage and optimize complex steelmaking processes. These systems can learn from large datasets to:

- Predict end-point temperatures in converters.
- Optimize slag composition and impurity removal.
- Control rolling force and temperature in real time.
- This reduces the need for manual calculations and decision-making.

b) Intelligent Sensors and Industrial Internet of Things (IIoT): Modern sensors integrated with IIoT platforms can continuously monitor parameters like temperature, gas composition, and element concentration. This allows:

- Real-time tracking.
- Immediate alerts for irregularities.
- Closed-loop control systems that act without human input.

c) Knowledge-Based Expert Systems: These systems encode domain knowledge (from experienced metallurgists) into rule-based engines. They provide:

- Automated recommendations.
- Fault identification.
- Support for process optimization.
- They help preserve expert knowledge and reduce reliance on highly skilled operators.

d) Process Modelling Using AI: ML-based process models are replacing complex first-principal models. These AI-driven models can:

- Predict system behaviour under varying conditions.
- Adjust inputs autonomously to maintain desired outcomes.
- This shift improves responsiveness and minimizes manual tuning.

e) Smart Human-Machine Collaboration: Emerging systems enable more intuitive interfaces where operators supervise AI-led decisions. This trend empowers humans to focus on high level strategies while machines handle repetitive tasks. [14, 15, 16, 17]

4.3 Digital Twin in Steel Making

A digital twin is a dynamic virtual replica of a physical system that integrates real-time data to simulate, monitor, and optimize performance. In converter steelmaking, it enables predictive control and intelligent decision-making by mirroring the smelting process. [19, 20, 21, 22]

4.3.1 Need for Digital Twin Technology

Given these challenges, digital twin technology offers a transformative solution. A digital twin is a real-time virtual replica of the physical converter, built using data from sensors, historical records, and physical models. It allows steelmakers to simulate, visualize, and predict converter behaviour without intrusive equipment. By integrating machine learning, real-time analytics, and physics-based modelling, digital twins can:

- Continuously monitor process conditions virtually, even in inaccessible areas.

- Predict outcomes of chemical reactions and temperature changes in real time.
- Improve control strategies by simulating different operating scenarios.
- Enhance safety by reducing the need for human intervention in dangerous environments.
- Optimize production efficiency and consistency by enabling proactive decision-making.

4.3.2 Digital Twins Address these Issues

Digital twin technology bridges this gap by integrating real-time sensor data, historical process records, and physics-based simulations into a single virtual model. This model can:

- Continuously estimate unmeasurable variables (e.g., internal chemical reactions, real time slag behaviour).
- Provide predictive analytics to forecast the outcome of the blow or identify potential failures before they happen.
- Support adaptive control by suggesting or automatically implementing optimized process adjustments.

This improved visibility and vision allow for greater process consistency, reduced material waste, and more stable operation, ultimately enhancing both product quality and operational safety. [19, 20, 21, 22]

4.4 Increasing Scrap in Conventional Steel Making Process

Technological Advancements Enabling Higher Scrap Use in BOF are:

a) Hot Metal Desiliconization: Removes silicon from hot metal before it enters the BOF using oxygen, lime, etc. Reduces heat losses during the oxygen blow, preserving thermal energy and enabling more scrap to be charged without compromising temperature.

b) Increased Post-Combustion: Burns CO and H_2 inside the BOF with controlled oxygen to recover additional heat. The extra heat supports scrap melting, reducing reliance on hot metal as a heat source.

c) Bottom Stirring with Inert Gases: Injects gases like argon or nitrogen from the bottom of the converter to promote better mixing. Ensures uniform temperature distribution, enhancing thermal efficiency and allowing more scrap to be processed without creating cold spots.

d) Scrap Preheating Technologies: Preheats scrap before charging into the BOF. Preheated scrap requires less energy to melt, increasing the feasible scrap ratio in the charge mix.

e) Oxy-Fuel Burners: Supplies additional heat through oxygen-fuel combustion inside the BOF. Compensates for the energy deficit caused by higher scrap content, supporting full melting and efficient refining.

f) Advanced Sensors and AI-Driven Control: Uses real-time sensors (e.g., temperature, chemical composition) and AI models to optimize process parameters. Enhances control over thermal and chemical balances, reducing risks when operating with higher scrap ratios.

g) Use of Dense Metallic Feed (Briquettes or HBI): Introduces compact, high-density metallics like Hot Briquetted Iron (HBI) or steel scrap briquettes. Melts uniformly and efficiently, improving heat transfer and making it easier to handle higher scrap charges.

h) Hybrid Steelmaking Integration: Combines BOF with electric steelmaking techniques, such as increased scrap charge and supplemental oxygen. Offers flexibility to shift away from hot metal dependency and adapt to changing feedstock availability. [23, 24, 25, 26, 27, 28, 29, 30]

4.5 Bayer's Red Mud as a Flux in Steel Making

The use of Bayer red mud as a flux in steelmaking, focusing on its role in dephosphorization—the removal of phosphorus, a detrimental impurity, from molten iron and steel. Here's a breakdown of the process findings:

a) The Challenge: Phosphorus in Steel and Red Mud Waste

- Phosphorus Problem: Phosphorus in steel causes embrittlement, particularly at low temperatures, making the steel brittle and prone to fracture. This significantly reduces the quality and applicability of steel products. Therefore, removing phosphorus is a critical step in steelmaking.
- Red Mud Burden: Alumina production generates a large amount of Bayer red mud, a waste product with high alkalinity (due to residual sodium hydroxide) and potential environmental hazards. Disposing of this red mud is a significant environmental and economic challenge.

b) The Proposed Solution: Red Mud as a Flux

- Flux Function: Fluxes are essential additives in steelmaking that aid in removing impurities. They work by:
    - Lowering the melting point of the slag (the molten mixture of impurities).
    - Increasing slag fluidity, making it easier to separate from the molten steel.
    - Chemically reacting with impurities to facilitate their removal.
- Red Mud Composition: Bayer red mud contains components that could potentially make it a useful flux:
    - Iron Oxide (Fe_2O_3): Can help oxidize impurities
    - Sodium Oxide (Na_2O): Provides alkalinity, which is crucial for phosphorus removal.
    - Aluminium Oxide (Al_2O_3) and Silica (SiO_2): Influence slag melting point and viscosity.

- Dual Benefit: Using red mud as a flux offers a dual benefit: solving a waste disposal problem and potentially improving the steelmaking process.

c) Experimental Methodology

- Hot Metal Dephosphorization Experiments: The researchers conducted laboratory-scale experiments to simulate the dephosphorization of hot metal (molten iron). They mixed synthetic hot metal with varying compositions of Bayer red mud and calcium oxide (CaO) at high temperatures.
- Simulated Steelmaking Experiments: Further experiments simulated the entire steelmaking process, again using red mud-based fluxes.
- Analysis: The researchers analysed the composition of the slag and the final phosphorus content in the metal to evaluate the effectiveness of the red mud flux.

d) Key Findings

- Improved Slag Fluidity: The use of Bayer red mud-based flux resulted in good slag fluidity in both hot metal dephosphorization and simulated steelmaking. This is attributed to the presence of Al_2O_3 and Na_2O in red mud, which effectively lowers the melting point of the $CaO\text{-}FeO\text{-}SiO_2$-based slag.
- Enhanced Dephosphorization:
    - In hot metal dephosphorization, a Bayer red mud: CaO ratio between 1:1 and 2:1 achieved high dephosphorization ratios (over 80%) and low final phosphorus content (below 0.018%).
    - Simulated steelmaking experiments also showed high dephosphorization ratios (over 85%) and very low final phosphorus content (below 0.005%).
- Effective Separation: The experiments demonstrated better separation between the slag and the molten metal phases when using red mud flux, which is crucial for efficient impurity removal.
- No Rephosphorization: The study observed no rephosphorization (phosphorus returning to the metal) during the steelmaking process, indicating the stability of the dephosphorization achieved.

e) Implications and Significance

- Sustainable Steelmaking: This research suggests that Bayer red mud can be a viable alternative flux in steelmaking, promoting a more sustainable approach by utilizing industrial waste.
- Improved Efficiency: The use of red mud flux can enhance slag fluidity and dephosphorization efficiency, potentially leading to cost savings and energy reduction in steel production.
- High-Quality Steel: The study demonstrates the potential to produce high-quality steel with low phosphorus content using red mud-based fluxes.

- Environmental Benefits: Reducing the environmental burden of red mud disposal and minimizing the use of harmful traditional fluxes like calcium fluoride (CaF_2). [37, 38, 39, 40, 41, 42]

4.6 Green Steel Making

Green steelmaking aims to produce steel with significantly lower greenhouse gas emissions compared to traditional methods. This involves using technologies like hydrogen-based reduction, electric arc furnaces with renewable energy, and carbon capture. It also emphasizes energy efficiency, resource optimization, and increased recycling. Ultimately, it's about minimizing the environmental impact of steel production, the most dynamic changes are happening now are:

a) Hydrogen in Steelmaking: Hydrogen steelmaking uses hydrogen gas as a reducing agent to extract iron from iron ore, replacing traditional carbon-based fuels like coal. In this process, iron ore reacts with hydrogen at high temperatures to produce direct reduced iron (DRI) and water vapor instead of carbon dioxide. This method significantly lowers CO_2 emissions and can be nearly carbon-neutral when powered by green hydrogen from renewable sources. Hydrogen steelmaking primarily refers to Direct Reduced Iron (DRI) production, where hydrogen gas (H_2) is used instead of carbon (usually in the form of coke or natural gas) to reduce iron ore (Fe_2O_3 or Fe_3O_4) into metallic iron (Fe)**.**

- A major shift is the exploration of hydrogen as a reducing agent to replace coal in the blast furnace or in direct reduced iron (DRI) production.
- Instead of CO_2, the main by-product is water, sharply reducing carbon emissions.
- Hydrogen-based DRI processes can be integrated with renewable energy sources, enabling near-zero-emissions steel production.
- Reduction of iron ore with hydrogen:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

(Or, for magnetite)

$$Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O$$

- This occurs in a shaft furnace at temperatures around 700–1000°C. The iron is not melted but comes out as solid sponge iron (DRI).
- The by-product is steam (H_2O vapor), instead of carbon dioxide, which is released in traditional blast furnaces using coke:

$$2Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

- Adoption of hydrogen can reduce dependency on fossil fuels, contributing to energy security and climate goals.

- The transition may require significant investment in new infrastructure, including green hydrogen production, storage, and transportation.
- Technical challenges remain, such as optimizing the reduction kinetics and modifying existing plants to accommodate hydrogen.

b) Carbon Capture, Utilization, and Storage (CCUS) Technologies: It refers to a set of technologies designed to capture carbon dioxide (CO_2) emissions from industrial processes, including iron and steel making, and either store it underground or use it for various purposes. In ironmaking, the blast furnace emits a large amount of CO_2 due to the use of coke as a reducing agent. CCUS can capture this CO_2 from the exhaust gases before it's released into the atmosphere, mitigating the environmental impact. CCUS technology in iron and steel making captures CO_2 from the flue gases of blast furnaces and other steel production facilities. The captured CO_2 can either be stored in deep geological formations or utilized in industries such as enhanced oil recovery (EOR), chemical production (e.g., converting CO_2 into synthetic fuels), or in the production of carbonated beverages.

Advantages:

- Reduces direct CO_2 emissions from steelmaking.
- Allows continued use of traditional steel making technology while transitioning to more sustainable practices.
- Potential for CO_2 to be used in various industries, adding economic value to the captured carbon.

Challenges:

- High cost of implementation, including retrofitting existing plants with CCUS technology.
- Energy consumption for capturing and compressing CO_2.

c) Coke Dry Quenching (CDQ): CDQ is an energy-efficient and environmentally friendly process used in steel plants to cool down hot coke (about 1000°C) that comes out of the coke oven. Instead of using water (as in traditional wet quenching), CDQ uses an inert gas (typically nitrogen) to quench the hot coke in a closed, dry environment.

Working:

- Hot coke from the coke oven is fed into a sealed CDQ chamber.
- Inside, inert gas circulates and absorbs the heat from the hot coke without causing combustion.
- This recovered heat is used to generate high-pressure steam, which can drive turbines for electric power generation.
- The cooled coke is then discharged with improved mechanical strength, better size uniformity, and lower moisture content.

Table 4.1 – Features of CDQ compare to Wet Quenching

Features	CDQ	Wet Quenching
Cooling Medium	Inert gas	Water
Energy Recovery	Yes (via steam generation)	No
Environmental Impact	Lower (No effluent, less dust)	Higher (Steam, dust, water)
Coke Quality	Higher	Lower

Benefits of CDQ:

- Energy Recovery: Converts waste heat into usable energy, reducing external power needs.
- Environmental Impact: Minimizes CO_2 and particulate emissions compared to wet quenching, which releases steam and dust.
- Improved Coke Quality: Dry quenching results in stronger, cleaner coke that performs better in the blast furnace.
- Reduced Water Use: Unlike wet quenching, CDQ requires no water, preserving water resources and preventing wastewater generation.

In short, CDQ enhances both energy efficiency and environmental sustainability in steel production by turning waste heat into power and improving coke quality without water. [43, 44, 45]

Chapter 5 – Result And Conclusion

This review of recent advancements and emerging trends in steelmaking shows a clear shift toward more sustainable, efficient, and intelligent processes. The combination of advanced electric arc furnace (EAF) operations with hot metal charging represents a significant rise in optimizing energy consumption and process efficiency. Hot metal charging in EAFs not only reduces electricity demand but also minimizes the use of costly carbon additives and promotes faster melting. The key features such as lower tap-to-tap time, decreased electrode consumption, and reduced CO_2 emissions make this hybrid method highly viable for modern steel plants seeking decarbonization without compromising output. [52, 53]

However, this integration brings technical challenges such as controlling slag foaming, managing refractory wear, and ensuring stable process parameters. These need a higher level of process control and metallurgical understanding. Here, the adoption of Artificial Intelligence (AI) plays an innovative role. AI-driven systems are increasingly used for real-time process monitoring, prediction of melting parameters. Through machine learning models, steelmakers can enhance product consistency, and reduce interruption. [14, 15, 16, 17]

The application of Digital Twin technology further strengthens the digital transformation in steelmaking. By creating virtual replicas of real-time operations, digital twins provide deep understanding into process dynamics. They help simulate various operating conditions, enabling preventive step to potential interruption. Digital twins address the need for greater operational transparency, problem prediction, and data-driven decision-making, thereby significantly improving process reliability and lifecycle management. [19, 20, 21, 22]

Moreover, the trend of increasing scrap usage in traditional steelmaking serves the dual purpose of reducing raw material dependency and promoting circular economy principles. To manage the variability in scrap composition and enhance its suitability, technologies like direct reduced iron (DRI) blending and improved sorting mechanisms are increasingly employed. This not only reduces CO_2 emissions but also lowers production costs.

Another innovative development is the exploration of Bayer’s red mud, an industrial by-product, as a fluxing agent in steelmaking. Utilizing Bayer’s red mud in basic oxygen furnaces (BOFs) or EAFs provides a sustainable alternative to conventional fluxes like limestone and dolomite. It contributes to slag formation, aids in refining, and helps manage waste from aluminium industries, aligning with the goals of waste recovery and circular resource use.

Lastly, the concept of green steelmaking is gaining momentum as the industry strives to meet global decarbonization targets. Strategies such as hydrogen-based direct reduction, renewable energy integration, carbon capture and utilization (CCU), and biomass based reducing agents are being actively explored. These initiatives aim to reduce the carbon footprint of steel production and meet environment standards.

In conclusion, the future of steelmaking is changing with the help of cleaner methods, smart technology, and new materials. These changes bring many benefits such as infrastructural investment, and skilled workforce development, better equipment and facilities, and training for workers. Using things like hot metal charging, artificial intelligence, digital twins, green raw materials, and eco-friendly technology is helping the steel industry become cleaner, smarter, and stronger for the future.

Future Scope

Steelmaking is undergoing significant transformation due to the increasing demand for high performance steel, energy efficiency, and environmental sustainability. Emerging technologies and innovative processes are shaping the future of the industry, addressing challenges such as carbon emissions, raw material efficiency, and production costs.

Among the significant innovations,

1. **Laser alloying and cladding** are gaining attention for their ability to significantly improve surface properties of steels. By precisely adding alloying elements or coating materials, these techniques enhance resistance to wear, corrosion, and fatigue. They are versatile and can be adapted to a wide range of steel types, making them suitable for critical applications in automotive, aerospace, and heavy machinery sectors. [57, 58, 59]

2. **Increased use of steel scrap** in primary production. With a growing importance on circular economy and carbon footprint reduction, modern steel plants are optimizing scrap usage through advanced sorting, melting, and refining technologies. This shift supports energy savings and contributes to eco-friendly production processes. [23, 24, 25, 26]

3. Digital technologies such as **augmented reality (AR) and virtual reality (VR)** are transforming training and operational practices in the steel industry. These tools create surrounding, interactive simulations of plant environments, enabling workers to learn procedures, figure out equipment, and improve safety awareness without direct exposure to industrial hazards. This not only shortens training times but also improves workforce readiness. [60, 61, 62]

Overall, the integration of surface engineering methods like laser processing, sustainable raw material strategies, and engaging digital tools marks a significant climb toward smarter and more efficient steelmaking. As these innovations continue to evolve, they promise to redefine the performance and sustainability standards of steel production.

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