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Effect of FeO, Carbon Control and Boiling during Melting of DRI (Sponge Iron) in the Induction Furnace.

Girish Kumar G.K.
Vice President (Technical Services), Minera Steel and Power Pvt. Ltd.
girish@mineragroup.com
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Abstract
In sponge iron melting within an induction furnace - FeO content, carbon control, and boiling phenomena significantly impact the process. Low FeO content in sponge iron is crucial for efficient energy use and safety, as high FeO can lead to vigorous carbon boil when added to a high-carbon bath, which can be dangerous. Effective carbon control is essential for achieving desired steel composition and minimizing unwanted reactions. Boiling, while sometimes beneficial for refining and reducing impurities, can also disrupt the process if uncontrolled.

The availability of suitable raw material especially homogeneous scrap at a competitive price to a steel maker is a challenge. Use of DRI (Direct Reduced Iron or Sponge Iron) as a partial replacement to scrap, to some extent overcome the burden on costing and quality raw material. However, unlike scrap and even pig iron, DRI is characterized by high porosity, low thermal and electrical conductivities. DRI lumps and fines with high FeO, which in turn, poses problems in its melting.

Attempts were made to study based on chemical analysis of DRI lumps, fines and pellets w.r.t Fe(M) and FeO to understand the behaviour during melting of DRI in the induction furnace on its carbon control, boiling of the liquid metal, productivity and power consumption. With the limited data available, it is to conclude that, higher proportion of DRI as a replacement to scrap can be used based on market dynamics of scrap & DRI for cost optimization which also improves steel quality. However, due to low Fe(M) and high FeO in DRI fines may pose problems in carbon control and boiling of liquid metal, which can be resolved with process and operational controls while charging DRI fines along with DRI lumps/pellets to maintain FeO in the range 6-7% in the DRI lumps & fines.

Keywords: *Induction Furnace, Direct Reduced Iron or Sponge Iron (DRI), Metallic Iron ((Fe(M)), Iron Oxide (FeO).*

I. Introduction

In Induction Melting Furnace (IMF), heat energy for melting metallic charge is obtained from induced current produced by the principle of electro-magnetic induction. Furnace is comprised of a silica lined refractory crucible in a cylindrical steel shell. The coil lined with refractory material act as a primary coil. When electric current is passed through this coil, induced current is produced in metallic charge. The heat produced from the electric resistance, melts the solid charge. Due to electromagnetic action, induction heating produces circular eddy currents within the molten mass creating a stirring effect ensuring uniformly mixed homogeneous molten metal. In India, IMF is widely used for secondary steelmaking due to techno-economic and commercial reasons. The coreless medium frequency induction melting furnaces are available having 15 kW to 12 MW corresponding to the furnace capacity of 5 tons to 30 tons per charge respectively (IIM Metal News, 2020, Vol.23 No. 7).

In Induction Melting Furnace, the carbon reacts with unreduced iron oxide (i.e. $FeO + C = Fe + CO$) giving CO gas evolution from liquid bath i.e. carbon boil, which results into subsequent removal of hydrogen and nitrogen gases, as well as slag inclusion; and ultimately producing cleaned steel. The carbon boil also makes foamy slag which prevent radiation loss as well as absorption of nitrogen from atmosphere. Nitrogen picks up to the molten bath depend on dissolved oxygen content in the bath; less oxygen content in the bath, more nitrogen picks up to the molten bath. Therefore, higher carbon content in sponge iron/HBI is always desired by steelmakers.

In sponge iron melting within an induction furnace, FeO content, carbon control, and boiling reactions significantly impact the process. FeO in sponge iron, if high, can cause a vigorous carbon boil when introduced into a high-temperature, high-carbon bath, potentially leading to operational hazards and energy inefficiencies. Carbon control is crucial for achieving the desired steel composition, and the vigorous boil helps remove impurities and refine the steel. Boiling reactions are a result of the reaction between FeO and carbon, impacting heat transfer and gas purging.

Induction Furnace Industry:

Medium frequency induction furnaces have been used in India to produce crude steel for the last 25 years. It was only with de-regulation that the induction furnace industry in India emerged in big form. With a host of units producing mild steel ingots (apart from castings) in different pockets in the country, but more concentrated in the northern belt, the Induction Furnaces came up to cater to domestic demand, which could not be adequately met by the large-scale integrated steel plants. While furnace of bigger size and capacity were observed, there was also the large-scale acceptance and adoption of sponge iron in the charge mix. It may be seen that Induction Furnaces have started producing steel even in those states where crude steel is being supplied by integrated steel plants. The size of the Induction Furnaces used in making the crude steel is 5, 10,15, 20, 25 and 30 tonnes per charge. The old system of using 3 tonne per charge furnaces has now become obsolete. The induction furnace industry prospered in the immediate post de-regulation period, but fell victim to the slow down phase of the late 90's. This phase saw quite a bit of structural changes in the industry in the form of closure and consolidation. Over the time, induction furnace route has emerged as a key driver of crude steel production in the country with a rising share in total production. As it is expected that demand of steel in India will start rising very fast to narrow the gap of per capita steel consumption with developed countries, the demand of induction furnace steel may increase further.

For induction furnace melting, high metallized sponge iron with low gangue content is required. Low iron oxide content is important for safety as well as for energy consumption reasons. If a large quantity of low metallized sponge iron is introduced into a high carbon bath at a high tempeature, there is vigorous carbon boil. Such violent boil hampers the process operation and can be extremely dangerous. Even when sponge iron has high metallization, its feeding must be properly regulated to control the magnitude of the reaction.

II. Methodology

Research Design, Selection Criteria and Analysis of Data

In sponge iron melting, FeO (Ferrous Oxide) significantly impacts carbon control and boiling behavior. FeO reacts with carbon in the sponge iron, creating carbon monoxide (CO) and leading to a "carbon boil." This reaction influences the melting process and can be managed to optimize steel quality and energy consumption.

Hence, the analysis of FeO and Fe(M) has been carried for sponge fines, sponge lumps and sponge pellets for a sample size of (29 samples were collected from a lot size of 9000 tons) to analyse the data in this research which are depicted in the below Table.

(Table Showing Analysis of Fe(M) and FeO in Sponge Fines, Lumps and Pellets)

Sample No.	**Sponge Fines**		**Sponge Lumps**		**Sponge Pellets**	
1	**Fe(M)**	**FeO**	**Fe(M)**	**FeO**	**Fe(M)**	**FeO**
2	77.00	15.74	79.03	9.66	78.37	6.37
3	79.25	12.96	78.98	10.09	78.45	6.30
4	77.75	14.76	78.67	10.13	77.70	5.60
5	79.00	13.10	78.03	10.53	79.15	4.85
6	79.07	13.55	77.83	11.13	79.37	5.01
7	79.01	13.53	78.03	9.12	79.15	4.96
8	79.02	14.31	79.42	8.88	79.27	5.10
9	77.77	14.53	78.18	10.11	79.15	4.85
10	75.02	16.85	77.47	10.24	79.10	4.76
11	77.20	14.55	77.90	11.18	79.13	5.03
12	77.55	14.37	77.73	11.15	78.56	5.12
13	77.50	14.63	77.40	11.23	78.67	4.96
14	78.03	14.96	77.27	11.20	77.37	5.48
15	79.10	14.63	78.44	10.31	79.70	4.65

16	77.50	16.02	78.46	10.21	78.40	5.14
17	78.33	15.31	77.02	11.20	78.05	5.31
18	74.35	16.53	77.55	11.02	78.45	5.15
19	68.20	18.20	77.00	11.44	78.10	4.91
20	71.75	18.12	76.16	11.65	78.07	5.18
21	79.35	12.34	77.90	10.56	80.02	4.56
22	80.10	11.10	78.53	10.02	79.18	4.78
23	79.10	11.35	79.20	9.61	79.15	4.33
24	80.40	12.30	78.45	9.85	79.48	4.12
25	79.15	12.63	79.20	9.02	79.15	3.96
26	77.76	13.50	79.13	8.64	78.93	4.18
27	78.20	12.68	79.20	8.53	79.13	3.89
28	76.70	13.12	78.81	8.41	79.10	3.95
29	79.00	10.89	79.11	8.15	79.15	3.90
Min	***68.20***	***10.89***	***76.16***	***8.15***	***77.37***	***3.89***
Max	***80.40***	***18.20***	***79.42***	***11.65***	***80.02***	***6.37***
Average	***77.58***	***14.16***	***78.22***	***10.12***	***78.84***	***4.87***
Note: Sample Size (29 samples - 9000 Tons Approx)						

III. Data Analysis and Findings

Based on data analysis as depicted in the above table, the findings are as below.

- **FeO Content, Carbon Control and Boiling:**

➢ Sponge iron with high FeO content can react vigorously with carbon in the bath, causing a violent "boil". This is particularly problematic when low metallization sponge iron is introduced. The FeO in the sponge iron reacts with carbon to produce carbon monoxide and iron, which can cause a violent reaction and increase the risk of explosions, especially if the sponge iron is not well controlled. This has been observed in DRI Fines and Lumps as per the above Table.

➢ The carbon content of the sponge iron, along with added carburizers, is crucial for achieving the desired steel composition. Carburizers like metallurgical coke or anthracite coal are used to control the carbon level and to ensure that the steel meets the required specifications. The vigorous boil also helps to remove impurities and refine the steel by reducing carbon and purging dissolved gases.

➢ The amount of FeO in the sponge iron, and therefore the extent of this reaction, directly affects the carbon content in the final molten steel. Higher FeO content leads to a greater reduction in carbon as CO is formed and expelled.

- **Boiling Reactions and Process Impact:**

The boiling reaction, primarily the reaction between FeO and carbon, has several effects:

➢ **Heat Transfer:** The reaction generates heat and helps transfer heat into the bath, accelerating the melting process.

➢ **Gas Purging:** The vigorous boil helps to remove dissolved gases (hydrogen and nitrogen) from the liquid steel.

➢ **Refractory Protection:** The reactions also protect the refractory lining of the furnace.

- **Energy Efficiency:**

High FeO content in sponge iron increases energy consumption, as more energy is required to reduce the FeO and maintain the desired bath temperature.

- **Process Control:**

Properly controlling the feeding rate of sponge iron, especially when it has low metallization, is crucial to manage the magnitude of the boiling reaction.

- **Refining Reactions:**

The boiling reactions also facilitate refining reactions by promoting homogeneity in the bath and improving the contact between slag and metal.

- **FeO and Carbon Reaction:**

When sponge iron, which contains FeO is melted, the FeO reacts with carbon present in the sponge iron to form CO. This reaction is an exothermic process, releasing heat and causing the "carbon boil".

- **Boiling Behavior:**
- The vigorous gas evolution (CO) during the reaction causes a foaming or "boiling" effect in the molten bath, which can be a significant factor in the melting process.

- **Energy Consumption:**

The exothermic nature of the FeO-C reaction can also affect energy consumption during melting. The heat released can partially compensate for the energy required to melt the iron, according to Corpus Publishers.

- **Slag Chemistry:**

The FeO content in the slag also influences the refining process. High FeO content in the slag can affect the oxidation potential of the melt, affecting the removal of impurities like phosphorus and sulfur.

- **Foaming and Viscosity:**

FeO content can affect the foaming and viscosity properties of the slag. Increased FeO content can lead to lower viscosity and potentially more stable foaming.

- **Impact on Steel Quality:**

Controlling the FeO content and the resulting carbon boil is crucial for achieving the desired steel composition and quality.

1. Effect of FeO:

- **Low FeO is preferred:**

Lower FeO in the sponge iron reduces energy consumption and enhances safety during melting.
Induction furnaces generally require high metallized sponge iron with low gangue content (including FeO).

- **High FeO:**

A higher amount of FeO in the DRI requires more energy to reduce and can lead to a more vigorous carbon boil.

- **Vigorous boil:**

High FeO content in sponge iron can lead to a violent carbon boil when introduced into a high-carbon bath, which can be dangerous and disrupt the process.

- **Redox reactions:**

FeO acts as an oxidizer, contributing to the overall redox reactions during melting. Controlling FeO levels helps manage the oxidation potential.

2. Carbon Control:

- **Carbon content:**

The carbon content of the sponge iron and the bath significantly impacts the final steel composition.

- **Carbon boil:**

Controlled addition of sponge iron fines can minimize the vigorous carbon boil associated with high FeO.

- **Carbon removal:**

Carbon can be removed from the molten steel by oxidation and by adjusting the bath composition.

3. Boiling:

- **Beneficial effects:**

Boiling can aid in refining the steel by removing impurities and promoting homogenization.

- **Potential hazards:**

Excessive boiling can be dangerous, disrupt the process, and lead to inconsistencies in steel composition.

- **Controlling boil:**

Proper feeding rate of sponge iron, bath temperature, and slag composition can help manage the boiling process.

4.Induction Furnace Considerations:

- **Electric heating:**

Induction furnaces use electric currents to generate heat, providing efficient and controllable heating.

- **Bath temperature:**

Maintaining proper bath temperature is crucial for controlling the melting process and the reactions within the bath.

- **Safety:**

Vigorous carbon boils can be hazardous, especially with low metallization and high temperatures

IV. Conclusion

- The experience of melting sponge iron in induction furnaces infers that the best usage and melting of the sponge iron can be achieved if the particle size of the sponge iron is in close range and its metallization is + 78%. The density of its particle should be as high as possible.
- The melting **rate increases with** the rise **in temperature**. This requires careful control particularly for the rate of charging of sponge **iron in** the metallic pool.
- Controlling FeO content, managing carbon levels, and understanding the effects of boiling are critical for successful sponge iron melting in an induction furnace. Proper process control is essential for achieving desired steel quality and safety.
- Metallurgists should regularly be monitored in the shifts for Fe(M) and FeO in the sponge Iron.
- Raw material blend to be optimized while charging in the melting furnace and also the sequence of charging to be strictly followed. Avoid direct charging of sponge fines, instead charge the sponge fines along with sponge lumps/sponge pellets
- The desired level of FeO in the lumps and fines shall be in the range of 6-7%.

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