

Chapter 5 Exploration of the use of the DRI in steelmaking

This chapter explores the possible use of the DRI in steelmaking by melting. The DRI, made under the optimized conditions determined in the Chapter 4, was melted in a horizontal tube furnace as well as in an electric arc furnace. Compositional and microstructural characterization of the resulting green steel was carried out and compared to a mild steel.

5.1 Introduction

Direct reduced iron – electric arc furnace (DRI-EAF) route is growing steadily worldwide. In some of the countries like Mexico, where natural gas is abundant DRI-EAF is the dominant route [194]. Charcoal based direct reduction of iron ore (charcoal DRI) offers a number of benefits including significantly lower CO₂ emissions (0.5-0.7 t_{CO2}/t_{DRI}) compared to fossil traditional processes (2-2.5 t_{CO2}/t_{steel}) that use fossil fuels [195]. Direct reduction processes have significant flexibility in terms of reactor design and quality of raw materials [196-198]. Scrap or scrap with DRI are used as raw materials for melting in electric arc furnace commercially. DRI to scrap Charge ratio in EAF has increased due to favourable properties of DRI such as flexible composition, absence of trace elements, uniform shape and density along with convenience of charging [199-201]. Dishwar and Sinha studied impurities removal from the pig iron by addition of partially reduced highly fluxed DRI in an EAF [202]. They reported that the rate of removal of impurities such as C, Si, Mn, P and S increased in the first 5 minutes and decreased afterwards. They reported that less (30%) reduced DRI provided conditions suitable for effective dephosphorization and high (80%) reduced DRI provided conditions suitable for desulphurization. Less reduced DRI having high FeO content provided oxidizing slag which favors dephosphorization. They further reported that addition of 50% reduced fluxed DRI was able to remove P and S simultaneously. Dishwar et al., studied the effect of different modes of lime charging (lime pellets and fluxed DRI) and different plasma environment (air, nitrogen and hydrogen) on removal of the impurities from the pig iron during

melting in an EAF [203]. Nitrogen provides neutral whereas hydrogen provides reducing atmosphere to the melt. They reported that phosphorous removal was negligible possibly due to absence of oxidizing slag. However, sulphur removal took place up to approximately 91%.

The DRI in this study was prepared by using charcoal as a reductant. Use of carbon neutral biomass in the form of charcoal for the DRI production will eliminate the CO₂ emission from the process. The DRI produced from renewable charcoal along with pig iron or scrap can be melted in EAF. In this chapter, the parameters optimized for DRI preparation in chapter 4 were used to prepare the DRI, which was melted in an electric arc furnace. The composition and the microstructure of the melt were characterized to evaluate the promise of the process.

5.2 Experimental

5.2.1 Preparation of DRI in bulk

Iron ore collected from Tata Steel Jamshedpur was the same which was used earlier. *Leucaena* (W3) charcoal carbonized at 800 °C had resulted in maximum %Reduction in chapter 4 and hence, it was selected as the raw material. Lime was purchased from local supplier in Varanasi, India. Lime constituted of 95% of CaO and 5% of LOI. It is evident from the literature that adding lime facilitates removal of P and S by improved slag formation. Iron ore, lime and the *Leucaena* (W3) charcoal were used to make composite pellets with C/O ratio of 1.5 and basicity of 2. Basicity in this case is defined as the mass ratio of lime to silica. Lime was used to ease slag formation during melting of the product DRI. %Reduction and %Metallization of the DRI were 96.3±1.5% and 95.5±1.7% respectively.

5.2.2 Methods

Bulk reduction of iron ore was carried out in mild steel crucibles (Figure 5.1) at 1100 °C for 30 min in a muffle furnace. Approximately 3 kg of DRI was produced in multiple batches of ≈ 300gm each under identical experimental conditions. The DRI produced was stored in desiccators after cooling to avoid oxidation. 30 gm of DRI was kept in an alumina crucible and

melted in a tube furnace at 1500 °C for 30 min in ambient atmosphere. The air melted sample was subjected to optical and scanning electron microscopy to get the microstructures. Metallographic sample preparation was done following the procedure mentioned in ASTM E3-11(2017). 2% Nital was used as etchant. Leica DFC 295 optical microscope by Leica microsystems was used for optical imaging. DRI melting was also performed in an in-house fabricated electric arc furnace with 2 kg melting capacity shown in Figure 5.2 [204]. Firstly, 700 gm mild steel was melted to form a melt pool. Subsequently, a 500 gm of DRI was charged into melt pool and allowed to melt for 5 minutes. Slag was skimmed off and melt (named as EAF melt) was tapped in a graphite crucible with a height of 115 mm and inner dia of 30 mm. After cooling, the solidified EAF melt sample was analysed by optical emission spectroscopy (OES) for chemical composition on a WAS foundry master by Oxford instruments, UK. Average of the three measurements are reported. OES uses electrical energy to form a spark (under argon gas) between an electrode and a metal sample. This spark vaporises elements from the sample, which is brought to a high energy state by argon discharge plasma. These excited atoms and ions create characteristic emission spectral lines which can be identified and quantified by detectors such as photomultiplier tube or charge coupled device sensors. The EAF melt sample was characterized by scanning electron microscopy to get the microstructure by Zeiss EVO 18, Carl Zeiss, Germany. EDS was performed using 51N1000 – EDS System by Oxford Instruments Nanoanalysis.

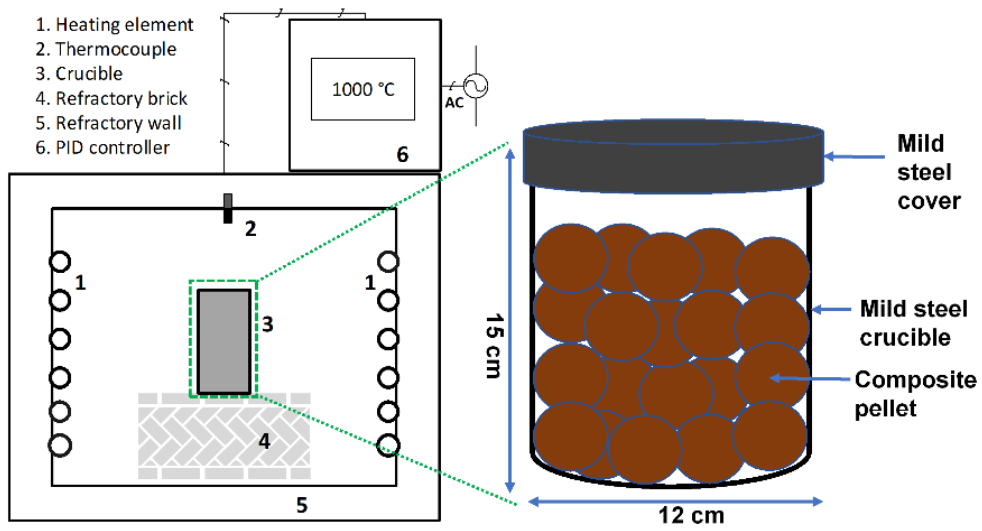


Figure 5.1 Schematic of crucible and furnace used for reduction experiments.



Figure 5.2 Tapping of the melt in a graphite crucible.

5.3 Results and Discussion

5.3.1 Electric resistance furnace melting

Optical and scanning electron microscope images were recorded to visualize the constituents of the air melt sample. Optical micrograph of air melted sample at a magnification of 500× is shown in Figure 5.3a. The figure shows two separate phases having dark and light contrast. Porosities and inclusions are also visible in the microstructure. It is noticeable that the two phases were intermixed. It was highly likely that the two phases corresponded to metal and slag. Scanning electron microscopy (SEM) was used for further clarifications about the nature of these phases. SEM micrograph of the air melt at 500× magnification is shown in Figure 5.3b. SEM micrograph (Figure 5.3b) confirms the two-phase microstructure seen in Figure 5.3a. EDS elemental mapping of phases is shown in Figure 5.4. The mapping shows that the light-coloured phase is rich in Fe and poor in O, Al, Ca, Si. The dark coloured phase has lower Fe content and higher O, Al, Ca, Si content. Small area EDS was performed at 3 spots on each of the phase to get the composition of the phases. Results (Figure 5.5) show that light coloured phase is predominantly Fe with minor amount of carbon. Dark coloured phase contains O, Al, Ca, Fe, Si and minor amount of C in the decreasing order. From the composition (Figure 5.4 and Figure 5.5), it was inferred that the dark coloured phase was slag phase and the light one was metal phase. The two phases remained separated after melting in absence of any movement or stirring. Lack of superheat in the melt could also be one of the reasons. Furthermore, the OES analysis on these samples gave erratic values. Poor conductivity of the melt sample due to the mixing of slag into metal phase led to the difficulty in the spark generation. This could be the most probable reason for getting erroneous and in some cases no values from the OES analyser. The DRI was then melted in an electric arc furnace with an aim to achieve a clear slag-metal separation.

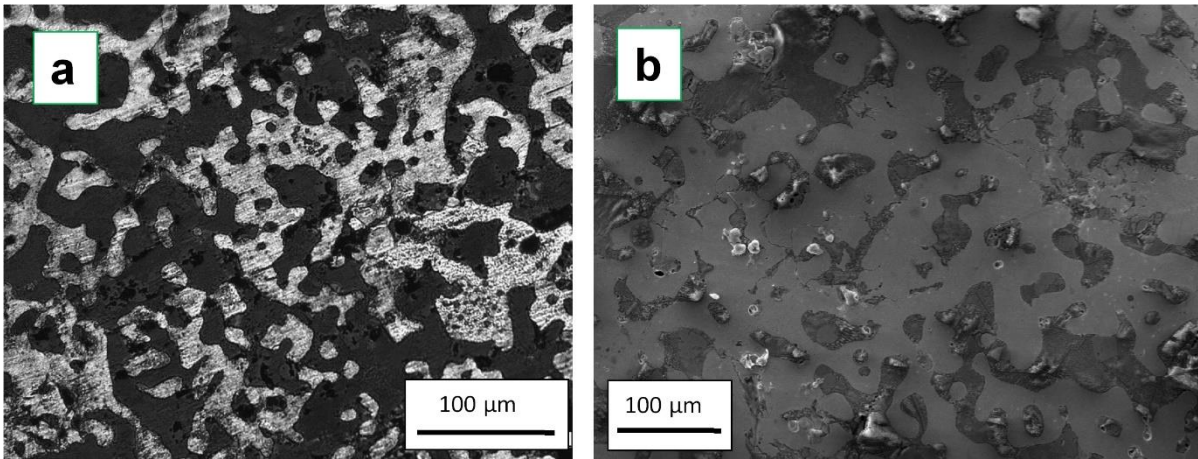


Figure 5.3 Microstructures showing constituents of the solidified melt (melted in a resistance furnace) under a) optical microscope and b) scanning electron microscope.

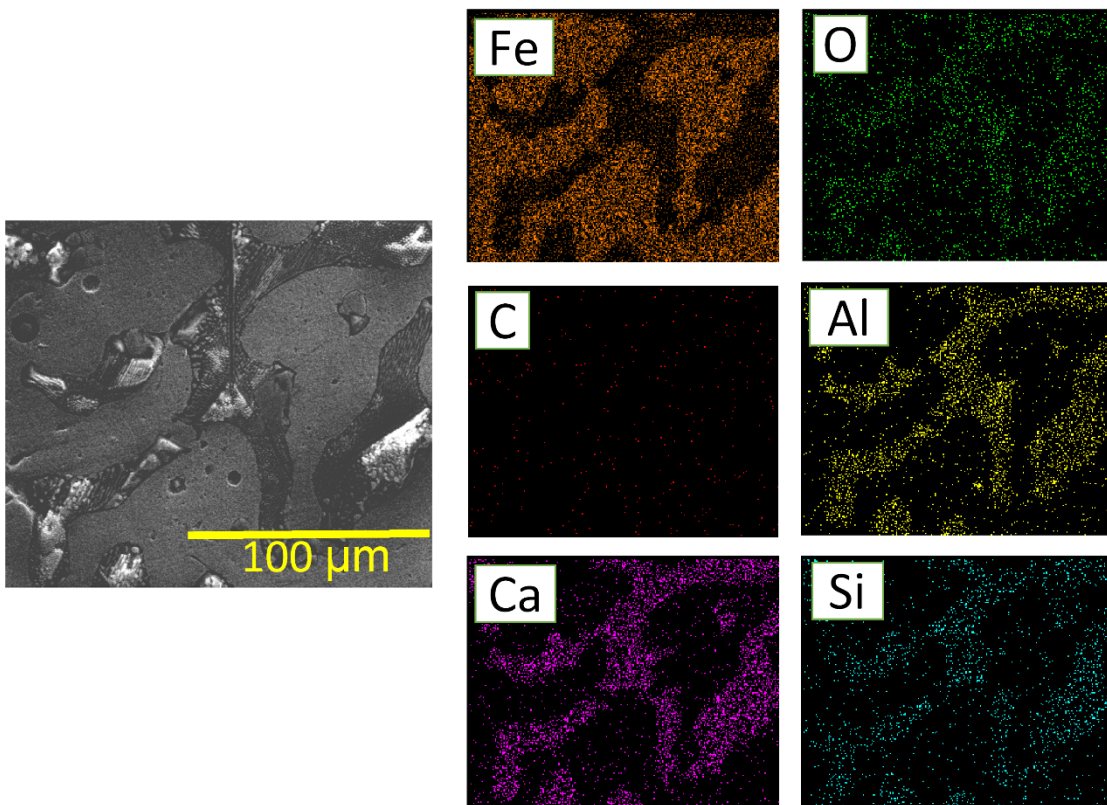


Figure 5.4 Elemental distribution in the slag and metal phase in air melt sample

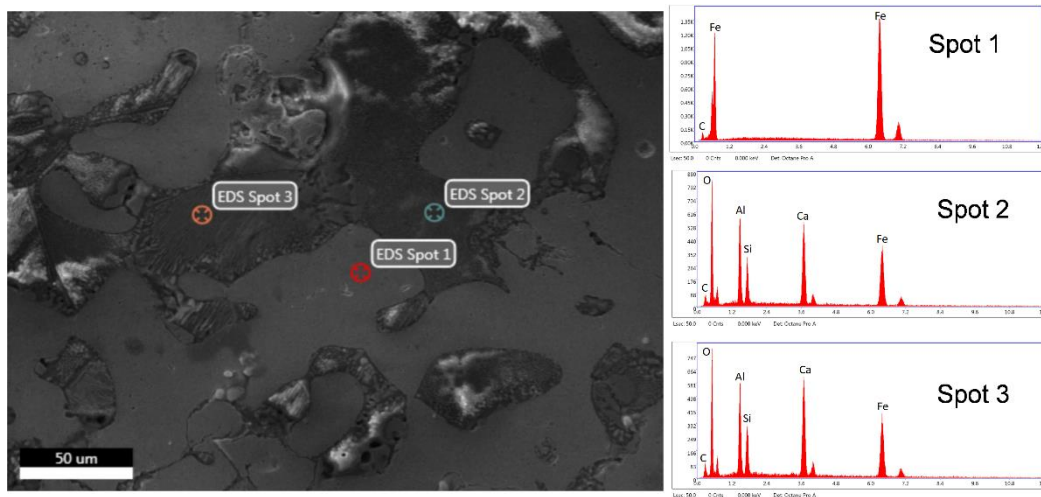
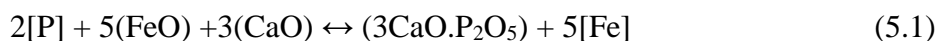


Figure 5.5 Composition corresponding to EDS spots in the SEM image of air melt.

5.3.2 Electric arc furnace melting

A mild steel pool was first created to enable melting of the DRI which otherwise would not melt in the arc furnace due to its poor electrical conductivity. The arc furnace is a direct arc type, where electric arc is struck between the electrode and the charge material. DRI seem to be breaking the electrical conductivity between the electrodes. Hence, it was decided to use a mild steel melt pool to melt the DRI. The composition of the mild steel and EAF melt was determined by the OES and is listed in the Table 5.1. Mild steel and EAF melt (DRI and mild steel, melted together) composition are similar. EAF melt exhibited 10% drop in phosphorous and 12% drop in sulphur content compared to mild steel. Decrease in the level of sulphur was majorly due to the use of charcoal for DRI making, as charcoal had less sulphur content than coal [205]. However, it is important to note that the decrease in level of phosphorous in the EAF melt cannot be associated with the use of charcoal. The partitioning reaction of P between metal and slag is shown in Equation 5.1. Equilibrium constant for the phosphorous partitioning can be represented by Equation 5.2.



$$k = \frac{a_{(3CaO.P_2O_5)} \cdot a_{[Fe]}^5}{a_{[P]}^2 \cdot a_{[FeO]}^5 \cdot a_{(CaO)}^3} \quad (5.2)$$

Formation of oxidizing and high basicity slag due to the presence of FeO and lime in the DRI facilitated the dephosphorization as per Equation 5.1. FeO is an effective oxidising agent which oxidises P from the metal to P₂O₅ enabling it to join the slag phase. External flux such as lime decreases the activity of P₂O₅ in the slag phase thus containing it in the slag. The DRI can have two possible applications: i) it can be melted with pig iron or scrap to decrease S and P content and ii) it can also be melted to form low S and P green steel.

Table 5.1 Composition of the mild steel and the EAF melt

Elements	Fe	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	Others
Mild steel	99.2	0.031	0.01	0.084	0.099	0.105	0.039	0.057	0.138	0.013	0.01	0.045	0.13
EAF melt	99.2	0.067	0.01	0.056	0.089	0.093	0.045	0.051	0.134	0.023	0.01	0.044	0.178
Change	0	0.036	0	-0.028	-0.010 (10%)	-0.012 (12%)	0.006	-0.006	- 0.004	0.011	0	-0.001	-

SEM micrographs (Figure 5.6a) show ferrite-pearlite microstructure typical of low carbon steel. On further resolving pearlite at 20000× magnification (Figure 5.6b), alternate lamellae of ferrite and cementite can be seen.

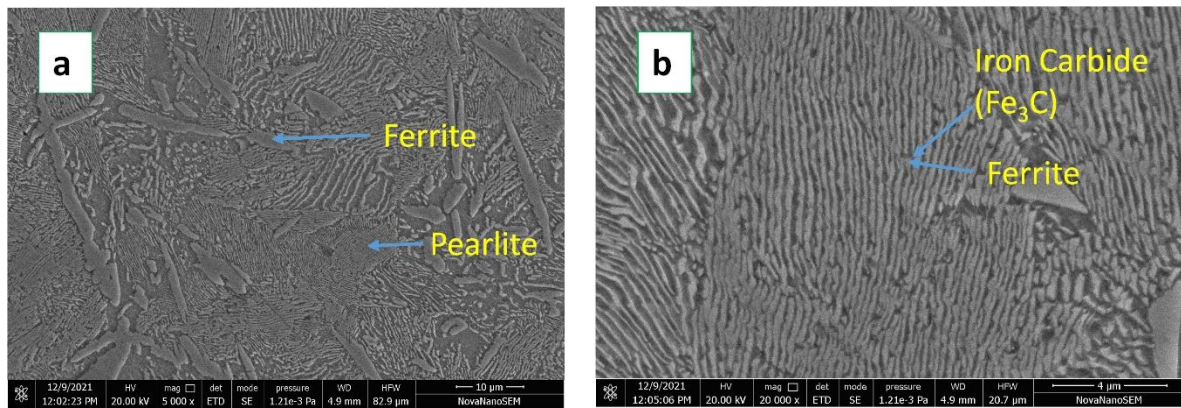


Figure 5.6 SEM micrograph showing a) ferrite and pearlite at 5000× magnification and b) ferrite and iron carbide lamellae at 20000× magnifications in EAF melt.

As per definition, green steel is a steel made without use of fossil fuels [206]. In this work, the mild steel pool will only be needed for the very first melt. In subsequent melting, the solidified melt itself can be used to form a melt pool for DRI melting. Therefore, the EAF melt can be treated as green steel, should the electricity come from a renewable source. Electricity from renewable sources or green electricity is available at competitive pricing in some parts of the world. Even in some countries like India, China and Australia renewable energy is 12 to 29% cheaper than lowest cost fossil fuel, according to a recent report by Wood Mackenzie [207]. Report also states that prices in other part of the world will go down and become competitive in due course. Another report from International Renewable Energy Agency (IRENA) states that the energy prices from two-third of the new renewable energy installations have lower costs than cheapest coal-based options in the G20 countries [208]. Thus, the promise of green steel in an environment of affordable green / renewable energy is on the horizon.

5.4 Conclusion

In the present chapter the DRI was prepared at larger scale (≈ 3 kg) to melt and make a steel. The following conclusions were drawn from the study:

1. The DRI melted in the electrical resistance heating tube furnace had slag and metal phases intermixed due to inadequate temperature and the absence of stirring. The DRI was then melted in an electric arc furnace with mild steel pool.
2. The steel made by melting the DRI in the mild steel pool had compositions and microstructure of low carbon steel with lower phosphorous and sulphur than the mild steel. Decrease in sulphur and phosphorous content was most probably due to the use of charcoal as reductant in DRI making and, the basic & oxidizing slag during melting respectively.

The steel made this way can be termed as a green steel as the process is devoid of fossil fuels. The future of charcoal based direct reduction of iron ore (charcoal DRI) and its melting in EAF looks promising as the technology continues to evolve and become more efficient. With increasing cost competitiveness of green electricity, the economic prospect of green steelmaking by charcoal DRI-EAF route also appears very promising.