1. INTRODUCTION

Of late, there is a growing demand for quality steel since in today’s world of technical modernization and economical globalization, customers are rather more conscious about the quality of steel than the quantity. The high quality steels essentially means lower levels of residuals such as sulphur, phosphorus, oxygen, hydrogen, nitrogen and tramp elements. The quality steels are most efficiently produced in electric furnaces (EAF / IF), because they have proved its worthiness in production of a wide variety of special alloy steels having controlled chemistry and better deoxidation procedures.

In India the earlies 1970s and 1980s saw a massive growth of electric arc furnace (EAF) and induction furnace (IF) based steelmaking units respectively. India is the only country in the world using induction furnaces on a large scale for production of steels. This had created a growing demand for steel scrap, as a result of which the scrap was in short supply. Moreover, significant improvements in steel plant yield, rolling technology and continuous casting processes have decreased the amount of in-plant generation of scrap. This ultimately has resulted into the shortage of scrap supply throughout the world and its fluctuating prices.\(^1\)

Although steel scrap is rather a tailor made input material, problems faced by steelmakers are its short supply, fluctuating prices, heterogeneous nature and above all higher content of tramp elements (0.1 to 0.8%). The non-availability of consistent quality scrap at a reasonable price necessitated the search for an alternative to scrap for use in secondary steel sectors. This problem has been tackled using direct reduced iron (DRI) or sponge iron which is not only a

STUDIES ON DIRECT REDUCED IRON MELTING IN INDUCTION FURNACE

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(Received 10 April 2004 ; in revised form 18 May 2004)

ABSTRACT

Of late, main problems faced by steelmakers are short supply, fluctuating prices together with extremely heterogeneous nature and presence of tramp elements of steel scrap. Use of direct reduced iron (DRI) as a partial replacement to scrap, to some extent does help in overcoming this hurdle. However, unlike scrap and even pig iron, DRI is characterized by high porosity, low thermal and electrical conductivities which, in turn, poses problems in its melting.

Attempts were made to study melting of DRI in a laboratory size induction furnace using molten steel bath as hot heel. The induction stirring accelerates the transfer of heat and promotes the melting of DRI. The effect of partial replacement of scrap by DRI on various melting parameters has been studied. Also kinetic studies were made to evaluate net melting rate. It was revealed that since melting and refining are taking place simultaneously, the increasing proportion of DRI in the input charge increases net melting rate and metallic yield. It was concluded that higher proportion of DRI, as a replacement to scrap, contributes to improve mechanical properties with no segregation of carbon content and the decrease in sulphur and tramp elements in the product that improves steel quality.
substitute for steel scrap as a feed material in EAF / IF but also a more suitable melting stock for the production of good quality steels.²

Unlike scrap and pig iron, the DRI is characterized by a high porosity, low density, low thermal conductivity, high specific surface area, relatively high oxygen content and intermediate carbon percentages.³ DRI has uniform chemical and physical characteristics; it hardly contains any tramp metallic elements (about 0.02%) and low sulphur content. This promotes the use of DRI in the charge as a partial replacement to scrap which ultimately improves the mechanical and metallurgical properties of the products.⁴ Advantages of using DRI as a feed material are reported elsewhere.⁵ Thus DRI is particularly suitable for the production of quality steels.

The DRI melting in EAF / IF is a well-established technology. Some workers³,⁶ measured the melting rate of DRI as a function of gas evolution. However, kinetic of melting DRI is very much under detail study. Keeping this in view an attempt was made in the present work, to study melting of DRI and its kinetics using molten steel bath as hot heel in the laboratory set up of induction furnace unit.

2. CHARACTERISTICS OF DRI

Direct reduced iron (DRI) is produced in three primary product forms namely lumps, pellets and hot briquettes. Other secondary product form is a cold moulded briquette made from DRI fines. Hot briquettes form is popularly known as hot briquetted iron (HBI), which is a combined solid form of lump and pellets, hot pressed at 700 to 800°C, immediately after the reduction. Proportion of lumps and pellets is judiciously selected to get appropriate quality of HBI. The important characteristic of HBI is its high density and lower specific surface area that improves the resistance to reoxidation and makes it easier to handle.⁷

Oxygen present in the DRI is in the form of FeO, which reacts vigorously with carbon in the molten bath and improves heat transfer, slag metal contact and homogeneity of the bath. Thus higher percentage of carbon is required in DRI and hence steelmakers prefer gas based DRI (which content 1.0 to 2.5% C) instead of coal based DRI (0.2% C). The degree of metallization varies from 85 to 95% depending on the process adopted for DRI production. Low degree of metallization leads to economic disruption such as higher energy consumption, higher slag volume, more heat time and lower yield during steelmaking.⁸ Being uniform in size, DRI is easy to transport, handle and permits continuous charging in electric furnace steelmaking.

3. DRI MELTING FOR STEELMAKING

India is the only country in the world using induction furnaces on a large scale for production of steels (15.5%). For smoothening of the melting operation, periodical removal of slag is required as it gets solidifies on top of the liquid bath and hinders further melting of DRI briquettes. DRI can be added directly into the liquid metal when the stirring action accelerates the transfer of heat to it and promotes the melting. Care must be taken to have enough molten pool before adding DRI. Merits of using DRI in induction furnace can be summarized as below.⁹

(i) No additional desulphurization is required and at the same time one can get product with sulphur content as low as 0.012 to 0.015%

(ii) Final product contains low amount of residual metals like chromium, copper, molybdenum, tin etc.

(iii) Charging time decreased which also reduces overall heat loss

(iv) It improves the product quality consistency.

Irrespective of charging mode, DRI is always charged after initial formation of molten pool (i.e. hot heel) by melting of steel scrap. Melting of DRI in EAF / IF is greatly influenced by factors like carbon content and degree of metallization of DRI. Carbon content of DRI reacts with unreduced iron oxide content of DRI giving CO evolution from liquid bath i.e. carbon boil takes place, which results into subsequent removal of hydrogen and nitrogen gases, ultimately producing clean steel. Carbon boil occurs at slag metal interface by the reaction:

\[ \text{(FeO)} + [\text{C}] = [\text{Fe}] + \{\text{CO}\} \]  (1)

For this very reason, steelmakers always prefer higher carbon content in DRI. With the appropriate slag conditions and massive gas evolution at the slag
metal interface results in foaming of slag and thus increase in the slag depth, while decreasing the slag density significantly. The combinations of a vigorous carbon boil and a deep foaming slag have different benefits.\textsuperscript{10}

Carbon content in the molten bath must be kept at a proper level in order to maintain appropriate carbon boil during melting period. The amount of carbon required (C, in Kg) to reduce the FeO content of the DRI is as follows:\textsuperscript{1}

\[
C = 1.67 \left[ 100 - \%M - \left( \%SI / 100 \right) \times \%Fe \right] \tag{2}
\]

Where, M is degree of metallization, SI is amount of slag; Fe is amount of iron in the slag.

To improve upon the product quality, input scrap quality should be controlled. The most troublesome residual elements (i.e. Cu, Co, Sn, As, Sb, Ni, Mo etc) from scrap are ultimately concentrated in steel. Their presence has been found to induce undesirable resistance to deformation, hot shortness and mechanical defects. Hence a charge mix with DRI has helped in lowering their concentration considerably. By using DRI, the highest quality flat products can be produced with excellent formability and aging characteristics\textsuperscript{4}. Also sulphur, nitrogen and other residual elements content have been remarkably lower down in steel, since DRI contain very low amount of these residual elements.

For induction furnace melting, the gangue content and unreduced iron oxide content of DRI should be as low as possible. Low iron oxide content is important for safety reasons as well as for energy consumption reasons. If a large quantity of unreduced iron oxide is introduced into a high carbon bath at high temperature, there is a vigorous carbon boil that could be extremely dangerous. An induction furnace for melting DRI should have a large ratio of cross sectional area to volume so heat transfer is high and it keep the slag hot and fluid.\textsuperscript{11}

\section{3.1 Basis of Calculation}

\subsection{3.1.1 Rate of Melting}

\textbf{a) On the basis of initial weight:}

DRI dissolve in molten bath,

\[
z = x - y \tag{3}
\]

where x and y are the initial weight and final weight of DRI before melting and after melting (gm) at time t (sec) respectively.

\textbf{Fraction of DRI dissolution, at time t ,}

\[
f = \frac{z}{x} \tag{4}
\]

Therefore, the rate of DRI dissolution (per sec),

\[
R = \frac{df}{dt} \tag{5}
\]

\textbf{b) On the basis of amount dissolved:}

Laboratory melting rate (\(R_1\), gm / sec) can be calculated by:

\[
R_1 = \frac{z}{t} \tag{6}
\]

Eq. (6) is not valid for industrial scale, so eq. (6) can be modified by \(R_2\), Kg / min:

\[
R_2 = 0.06 R_1 \tag{7}
\]

\textbf{c) On the basis of overall melting of DRI:}

If total weight of DRI (\(W_n\), Kg) melts in \(t_n\) minutes, then net melting rate (\(R_n\), Kg/min):

\[
R_n = \frac{W_n}{t_n} \tag{8}
\]

\subsection{3.1.2 Iron Yield}

Iron yield (%) can be calculated:

\[
\left\{ \frac{(F_2 W_2) \times 100}{(F_1 W_1 + F_T W_0)} \right\} \tag{9}
\]

Where, \(F_1\), \(F_T\) and \(F_2\) are percent of total iron present in steel scrap, DRI and steel product respectively. \(W_1\), \(W_0\) and \(W_2\) weight of steel scrap, DRI and steel product respectively.

\section{4. EXPERIMENTAL}

\subsection{4.1 Raw Materials}

DRI in the form of hot briquetted iron (HBI) from Essar Steel, Hazira; steel scrap and flux from local market, were used for experiments. Table 1 shows chemical analysis of HBI and scrap. Based on charge calculation, proportion of various charging materials taken for different heats are reported in Table 2.
Table 1
CHEMICAL ANALYSIS OF RAW MATERIALS.

<table>
<thead>
<tr>
<th>Material</th>
<th>Metallic Fe (%)</th>
<th>Total Fe (%)</th>
<th>Degree of Metallization (%)</th>
<th>C (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Gangue Material (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRI (HBI)</td>
<td>86.5</td>
<td>92.0</td>
<td>93.5</td>
<td>1.2</td>
<td>0.02</td>
<td>0.004</td>
<td>3.75</td>
</tr>
<tr>
<td>Mild steel scrap</td>
<td>0.42</td>
<td>0.068</td>
<td>0.18</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
RAW MATERIALS FOR CHARGING.

<table>
<thead>
<tr>
<th>Weight of scrap, Kg (%)</th>
<th>Weight of DRI, Kg (%)</th>
<th>Total weight Kg</th>
<th>Weight of flux Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 (80)</td>
<td>0.8 (20)</td>
<td>4.0</td>
<td>0.110</td>
</tr>
<tr>
<td>2.4 (60)</td>
<td>1.6 (40)</td>
<td>4.0</td>
<td>0.075</td>
</tr>
<tr>
<td>2.0 (50)</td>
<td>2.0 (50)</td>
<td>4.0</td>
<td>0.110</td>
</tr>
<tr>
<td>1.6 (40)</td>
<td>2.4 (60)</td>
<td>4.0</td>
<td>0.075</td>
</tr>
<tr>
<td>1.2 (30)</td>
<td>2.8 (70)</td>
<td>4.0</td>
<td>0.110</td>
</tr>
</tbody>
</table>

4.2 Melting

Laboratory scale high frequency (50 Hz) coreless induction furnace (M/s Inductotherm, Ahmedabad, 5 Kg capacity) having graphite crucible (10.8 cm length and 9.2 cm internal diameter) was used. Appropriate quantity of scrap was charged in induction furnace and it was started with the initial power input, after about 15 minutes of heating full power input was maintained. After complete melting of scrap, by using quartz tube (5 cm internal diameter) sample was collected, and then DRI was charged to the melt. During the course of DRI melting, intense splashing was observed, due to reduction reaction between iron oxide content of DRI and carbon content of the melt. Flux was added to take care of slag formed, which was then subsequently skimmed off. Pt – Pt/Rh thermocouple was used to measure bath temperature. Melt was cast, into rod forms, manually into sand mould. Sample, from each heat, was prepared for Rockwell hardness test. Hardness at various locations of the sample was measured to get some idea about segregation. Standard tensile specimens were prepared and tested on Monsanto – 20 Tensometer for tensile test.

For kinetic studies, samples of DRI were hanged with Kanthal wire on the top of the molten bath. After removal of slag from the molten bath, DRI samples were immersed into the molten bath with the help of Kanthal wire, one by one, for various times. Bath temperature was controlled at about 1550 ± 10 °C. Weight of the DRI samples before and after immersion were noted to calculate the rate of dissolution of DRI.

5. RESULTS AND DISCUSSION

Table 3 shows the chemical analysis of steel produced by melting of DRI, in different proportions. It is observed that with increase in the DRI proportion in the charge, carbon content of the product increases but tramp elements and sulphur are decreased. Table 4 shows the results of DRI melting. With increase in the DRI percentage in the charge, net melting rate and iron yield are increased.
Table 3
CHEMICAL ANALYSIS OF FINAL PRODUCTS.

<table>
<thead>
<tr>
<th>Charged (%)</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.063</td>
<td>0.173</td>
<td>0.038</td>
<td>0.018</td>
<td>0.020</td>
<td>0.034</td>
<td>0.025</td>
<td>0.233</td>
<td>0.091</td>
</tr>
<tr>
<td>40</td>
<td>0.075</td>
<td>0.210</td>
<td>0.163</td>
<td>0.018</td>
<td>0.024</td>
<td>0.039</td>
<td>0.039</td>
<td>0.403</td>
<td>0.071</td>
</tr>
<tr>
<td>50</td>
<td>0.231</td>
<td>0.082</td>
<td>0.140</td>
<td>0.015</td>
<td>0.015</td>
<td>0.016</td>
<td>0.022</td>
<td>0.400</td>
<td>0.019</td>
</tr>
<tr>
<td>60</td>
<td>0.725</td>
<td>0.205</td>
<td>0.075</td>
<td>0.027</td>
<td>0.037</td>
<td>0.045</td>
<td>0.003</td>
<td>0.214</td>
<td>0.082</td>
</tr>
<tr>
<td>70</td>
<td>0.789</td>
<td>0.309</td>
<td>0.140</td>
<td>0.017</td>
<td>0.040</td>
<td>0.017</td>
<td>0.033</td>
<td>0.028</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 4
RESULTS OF DRI MELTING

<table>
<thead>
<tr>
<th>Charged (%)</th>
<th>Total weight of metal produced (Kg)</th>
<th>Time for melting of DRI (Min)</th>
<th>Total time (Min)</th>
<th>Net melting rate ($R_n$) (Kg/min)</th>
<th>Iron yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.003</td>
<td>25</td>
<td>100</td>
<td>0.032</td>
<td>76.18</td>
</tr>
<tr>
<td>40</td>
<td>3.041</td>
<td>20</td>
<td>60</td>
<td>0.080</td>
<td>77.97</td>
</tr>
<tr>
<td>50</td>
<td>3.030</td>
<td>20</td>
<td>63</td>
<td>0.100</td>
<td>78.50</td>
</tr>
<tr>
<td>60</td>
<td>3.071</td>
<td>25</td>
<td>60</td>
<td>0.096</td>
<td>79.55</td>
</tr>
<tr>
<td>70</td>
<td>3.750</td>
<td>25</td>
<td>55</td>
<td>0.112</td>
<td>98.06</td>
</tr>
</tbody>
</table>

Figures 1 and 2 show that fraction of dissolution and rate of dissolution vs. time respectively. Initially, rate of dissolution increases with time, then subsequently decreases. This is due to after initial dissolution of DRI, molten metal layer stick to the surface of the portion of DRI sample, which is immersed in molten pool that ultimately reduces the further dissolution of the sample. Net melting rate was calculated on the basis of total DRI charged and time taken for melting. As shown in Table 4, net melting rate increases with increase of DRI in the charge. Ray and Prasad$^{12}$ have also reported similar trend. Since melting and refining are taking place simultaneously, higher melting rate can be achieved together with reduction in tap-to-tap time using DRI as the input material in induction furnace for melting.
of steel. With increase in proportion of DRI, iron yield of the furnace increase (as shown in Figure 3). Similar trend has also been reported elsewhere.\textsuperscript{5,11}

Tensile strength and hardness of the steel mainly depend on chemical composition in general and carbon content of steel in particular. Results show that tensile strength and hardness of the product steels are increased with increase in proportion of DRI (as shown in Figures 4 and 5 respectively).

With increase in the demand of special quality steel throughout the world, product should contain low amount of tramp elements as well as low sulphur and it should have less segregation in the products. Figure 6 shows the dilution effect of tramp elements content of the product steels by the addition of DRI to the melt, this is due to very low amount of tramp elements present in DRI. This is also reported in literature.\textsuperscript{13} As the DRI proportion increases in the melt sulphur content of product decreases (Figure 7). Meraikib\textsuperscript{14} also observed similar trend.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{iron_yield_vs_dri.png}
\caption{Iron yield vs DRI charged}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{ultimate_tensile_strength_vs_dri.png}
\caption{Ultimate tensile strength vs DRI charged}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{hardness_vs_dri.png}
\caption{Hardness vs DRI charged}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{tramp_elements_vs_dri.png}
\caption{Tramp elements vs DRI charged}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{sulphur_content_vs_dri.png}
\caption{Sulphur content vs DRI charged}
\end{figure}

\section{CONCLUSIONS}
1. Melting of DRI in induction furnace as a partial replacement to steel scrap as input charge materials can produce good quality steel.
2. Steel with low level of tramp elements and sulphur is produced by partial substitute of scrap by DRI in the melt.
3. Mechanical properties of steel produced are improved by using DRI in the charge material. Segregation of carbon in product steel is also decreased.
4. By using DRI in the charge, high iron yield is achieved and tap-to-tap time of the heats is subsequently decreased.
REFERENCE