Effect of manganese ore blends on performance of submerged arc furnace for ferromanganese production

V. Tathavadkar¹, V. Singh*¹, P. K. Mishra¹, P. Mallick² and B. D. Nanda²

Manganese ore blends are used in ferromanganese production. The blend composition controls the operational performance of submerged arc furnace. A case study has been carried out at FAP, Joda, Tata Steel to better understand the process. The results of experiments revealed that the phase decomposition and decrepitation of Mn ore at low temperatures (500–900°C) in the upper part of the furnace increased the furnace top temperature and thereby promoted agglomeration of the charge, which caused the violent eruptions in the furnace. The root cause of the problems in reaction zone (bottom part) of the furnace was changes in the composition of slag, i.e. low silica and high alumina, which was also due to selection of Mn ores in the blends. Various options for silica addition were examined and compared. The pretreatment of the Mn ores and use of synthetic slag for silica adjustment options were identified to overcome the operating problems and to utilise the captive Mn ores.

Keywords: Mineralogy, Manganese ores, Smelting reduction, Submerged arc furnace

Introduction

High carbon ferromanganese is produced by a carbothermic smelting reduction process in a submerged arc furnace. In this process, lumpy Mn ores, reductant (LAM Coke) and flux (dolomite and/or limestone) are charged in the SAF. Mn ores with Mn/Fe above 5 : 1 are preferred and therefore low grade Mn ores are blended with high grade Mn ores to maintain the required Mn/Fe ratio.¹ As the charge descends inside the furnace, it is heated by hot gases coming from the furnace bottom. During smelting reduction, oxides of Mn, Fe, P and Si reduce and form molten ferromanganese. Oxides of gangue minerals (Al₂O₃, SiO₂, MgO, etc.) combine with fluxes to form the slag. Part of the Mn oxide also combines with slag. The operational performance of the SAF depends on the complex gas–slag–metal reactions and equilibrium in the various zones of the furnace. The process yield, power consumption, and coke rate of the process depend on the complex reactions taking place inside different zones in the SAF.²,³ The mineralogical properties of the ores also play a vital role in the furnace performance. For example, Mn ore with high moisture and alkali content increases the coke rate.⁴

Problem definition

In the ferromanganese making process, different manganese/iron or ferruginous manganese ores are blended along with the reducing agent and any fluxes are mixed outside of the furnace (often called charge mix) and then charged as shown in Fig. 1. In the SAF, the electrodes are usually buried deep in the furnace burden and the reduction reaction takes place near the tip of the electrodes. The current flow between electrodes creates the intense heat needed for the high temperature and energy required for the reduction reactions. Charge mix is added periodically and the metals are collected during tapping at appropriate intervals. The process faces various technoeconomic problems:

(i) specific smelting power consumption
(ii) specific carbon consumption
(iii) exhaust gas temperature
(iv) furnace top temperature
(v) charge eruption in the furnace
(vi) crust formation.

In the current scenario ferroalloy producers are facing intense pressure to reduce the cost of production. Therefore, studies were carried at FAP, Tata Steel for systematic root cause analysis of the process issues. The plant produces 50 000 t per annum (tpa) of high carbon ferromanganese using a 15 MVA furnace. The plant was using the feed blend as given in Table 1 to maintain the best operating conditions at power consumption around 2600 kWh during consistent/stable operation. Studies were carried out to determine the effect of the ore blend on the operational performance. The thermodynamic computation and laboratory studies were carried out to study the smelting reduction reactions. The results of the research work were used to modify the furnace operating practice and same are discussed in this paper.
Experimental

Physical and chemical characterisation of Mn ores, coke, quartz, dolomite, slag and Fe–Mn alloy, was performed. Samples were first ground to $2^{10} \text{mm}$ size and the representative samples were prepared by the standard coning and quartering technique to eliminate variations in the results of analysis.

Chemical analysis

The chemical analysis of the samples was carried out using ICP-OES (see Table 1). All captive Mn ores except mine ‘C’ reported more than 10% loss on ignition, which is significant, and also influences the burden calculations.

Decrepitation test

One hundred grams of Mn ore sample (lumps) was weighed and transferred to an alumina crucible. The crucible was placed in a muffle furnace and heated to 500°C (heating rate 8°C min$^{-1}$) for 20 min in air. The sample crucible was removed and cooled in air. The sample was then screened through 10 mm sieve and the fines ($<10 \text{mm}$) generated and lumps were weighed. The results are given in Table 2.

Microscopic studies

Polished samples were first examined under the optical microscope and then in scanning electron microscope (SEM, JEOL JXA-6400). The analysis of various phases present in the ores was carried out using energy dispersive X-ray spectroscopic (EDX) technique attached to the SEM (see Fig. 1a–c). The optical micrograph of the Mn ore shows Mn mineral is present in either needles and a well developed crystal form or in the form of concentric curved layers. These curved surfaces are considered to be manifestations of surface tension effects in viscous material and are therefore indicative of colloidal origin.$^5$ Zoning is also apparent in the ores from colour banding and also from zonal distribution of inclusion. The EDX analysis of the mineral phases also confirms the distribution of inclusions.

Results and discussion

The experimental studies were carried out to determine the causes of the different operational performances due to charge variation. The furnace operation was studied with the known charge composition. The problems were identified with possible causes and solutions were computed using FACT-Sage software.

Identification of operational problems

The problems were broadly divided in two categories:

(i) top zone of the SAF which is at lower temperature
(ii) bottom zone of the furnace where smelting reduction takes place at high temperature in vicinity of the electric arc.

Phase transformations and various reactions occurring in these areas and their effect of the overall furnace performance are discussed below with the help of results of experimental work and thermodynamic computations.

Analysis of furnace top zone

An increase in the specific power consumption and coke rate generally raise the temperature of the reaction zone, which in turn increases the temperature of the exhaust gas. The high exhaust gas temperature then raises the temperature of the furnace top zone. When the charge drops in the furnace from the chutes, the sudden increase in temperature promotes decrepitation of certain types of Mn ore. The decrepitation properties depend on its phase composition and phase association. In Mn ores the gangue phases are mainly present in the form of layers (Fig. 1) which are loosely bound together. Depending on the composition (especially oxyhydroxide content), these phases decompose in the temperature range 300–600°C and causes breaking or cracking of the

Table 1 Chemical composition of raw materials samples provided by FAP, Joda, wt-%

<table>
<thead>
<tr>
<th>Ore</th>
<th>Mn</th>
<th>Fe</th>
<th>$\text{Al}_2\text{O}_3$</th>
<th>$\text{SiO}_2$</th>
<th>$\text{MgO}$</th>
<th>$\text{CaO}$</th>
<th>$\text{TiO}_2$</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine-A (+48)</td>
<td>53.73</td>
<td>5.20</td>
<td>2.75</td>
<td>2.65</td>
<td>0.31</td>
<td>0.54</td>
<td>0.05</td>
<td>11.40</td>
</tr>
<tr>
<td>Mine-A (-48)</td>
<td>53.90</td>
<td>3.55</td>
<td>3.45</td>
<td>2.54</td>
<td>0.41</td>
<td>0.63</td>
<td>0.03</td>
<td>12.29</td>
</tr>
<tr>
<td>Mine-A (-46)</td>
<td>47.11</td>
<td>9.64</td>
<td>4.80</td>
<td>2.62</td>
<td>0.28</td>
<td>0.62</td>
<td>0.02</td>
<td>12.44</td>
</tr>
<tr>
<td>Mine-B</td>
<td>41.04</td>
<td>6.65</td>
<td>3.52</td>
<td>16.54</td>
<td>2.47</td>
<td>5.76</td>
<td>0.10</td>
<td>8.76</td>
</tr>
<tr>
<td>Mine-C</td>
<td>36.00</td>
<td>8.63</td>
<td>2.39</td>
<td>16.15</td>
<td>0.32</td>
<td>0.60</td>
<td>0.01</td>
<td>2.10</td>
</tr>
<tr>
<td>Mine-D</td>
<td>42.00</td>
<td>10.45</td>
<td>2.72</td>
<td>9.96</td>
<td>0.53</td>
<td>0.80</td>
<td>0.03</td>
<td>8.90</td>
</tr>
<tr>
<td>Mn ore fines</td>
<td>34.10</td>
<td>14.24</td>
<td>5.68</td>
<td>8.36</td>
<td>0.76</td>
<td>0.90</td>
<td>0.08</td>
<td>15.14</td>
</tr>
<tr>
<td>Coke</td>
<td>0.50</td>
<td>1.60</td>
<td>5.55</td>
<td>14.85</td>
<td>2.26</td>
<td>2.88</td>
<td>0.38</td>
<td>...</td>
</tr>
<tr>
<td>Dolomite</td>
<td>...</td>
<td>0.60</td>
<td>1.55</td>
<td>10.27</td>
<td>18.63</td>
<td>26.95</td>
<td>...</td>
<td>41.23</td>
</tr>
</tbody>
</table>

Table 2 Results of decrepitation test of Mn ores

<table>
<thead>
<tr>
<th>Ore</th>
<th>Decrepitated</th>
<th>% fines formed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine-A (+48)</td>
<td>No</td>
<td>...</td>
</tr>
<tr>
<td>Mine-A (-48)</td>
<td>No</td>
<td>...</td>
</tr>
<tr>
<td>Mine-A (-46)</td>
<td>Yes</td>
<td>14%</td>
</tr>
<tr>
<td>Mine-B</td>
<td>Yes</td>
<td>12%</td>
</tr>
<tr>
<td>Mine-C</td>
<td>No</td>
<td>...</td>
</tr>
<tr>
<td>Mine-D</td>
<td>No</td>
<td>...</td>
</tr>
</tbody>
</table>
ore lumps. If the passage for escape of the product gas formed during decomposition is blocked then it exerts pressure on the layers and develops the cracks and consequently breaks them into pieces. This process generates fines, which are generally rich in siliceous gangue phases. The fines generated by decrepitation either escape with the exhaust gas and block the gas cleaning system or, if locked in the charge, then they reduce the permeability of the bed. The longer travel path of the exhaust gas due to blockage aids transfer of sensible heat of gas to the charge which in turn increases the temperature of the top charge.

Although the exhaust gas coming from the reaction zone raises the charge temperature in the top zone, which is a common phenomenon, the main reason for overheating and sintering of charge is due to the type of Mn ore used in the process. The mineral pyrolusite (MnO₂) is a major constituent and thermodynamically MnO₂ is not stable at high temperature and in reducing atmospheres, and decomposes into suboxides via the following reactions

\[
\begin{align*}
4\text{MnO}_2 & \xrightarrow{T=873\, \text{K}} \text{Mn}_2\text{O}_3 + 2\, \text{O}_2 & (1) \\
2\text{Mn}_2\text{O}_3 + \text{O}_2 \quad & [G_T = 169 - 0.22\, T\, (\text{kJ})] \\
6\text{MnO}_3 & \xrightarrow{T=1173\, \text{K}} 4\text{Mn}_2\text{O}_4 + 2\, \text{O}_2 & (2) \\
2\text{Mn}_3\text{O}_4 & \xrightarrow{T} 6\text{MnO} + \text{O}_2 \quad [G_T = 487 - 0.25\, T\, (\text{kJ})] & (3)
\end{align*}
\]

In the SAF top zone, the atmosphere is highly reducing as the exhaust gas coming from reaction zone is CO. The reducing atmosphere further enhances the decomposition of MnO₂ in the ore. The predominant area diagram of Mn–O system, computed using FACT-Sage programme is shown in Fig. 2, which shows the stability of various Mn oxides at different temperatures and oxygen partial pressures. The oxygen formed during decomposition reacts instantaneously with CO in exhaust gas in the SAF top zone and combustion of CO gas generates excessive heat in the top zone

\[
2\text{CO} + \text{O}_2 \xrightarrow{T} 2\text{CO}_2
\]

The thermodynamic phase equilibrium composition of the Mn–O system at different temperatures is shown in Fig. 3. Decomposition of MnO₂ liberates 9-2% oxygen in reaction (1) at 600°C. The calculation of thermal energy generated by these reactions revealed that decomposition of 1 tonne Mn ore at 600°C temperature and burning of CO gas by liberated oxygen generates ~300 kWh, i.e. ~1080 MJ energy. This localised generation of excessive energy increases the temperature of the charge surface and triggers the sintering of the charge by forming siliceous liquid phase with gangues. In siliceous Mn ores (MOIL), Mn is present in the form of MnO₂SiO₂ therefore excessive heating due to decomposition is not possible in these ores. Part of the oxygen and CO₂ formed during these reactions in turn react with coke in the charge and form CO gas, which leads to a rise in specific coke consumption

\[
\text{CO}_2 + \text{C} \xrightarrow{T} 2\text{CO}
\]

\[
\text{O}_2 + 2\text{C} \xrightarrow{T} 2\text{CO}
\]

In summary, the principal cause for high temperature and sintering of the charge in the top zone is generation of excessive heat by burning of CO gas with oxygen liberated via the decomposition reaction of MnO₂ minerals in the ores. The fines generated by decrepitation of ore and high top temperature leads to the sintering of the charge.

**Analysis of reaction zone of the furnace**

The sintering of the charge in the top zone of the furnace blocks the passage of the product gas from reaction zone. As a result, pressure of CO gas formed during reduction reaction (7) increases, which disturbs the gas–slag–metal phase equilibria in this zone

\[
\text{MnO} + \text{C} \xrightarrow{T} \text{Mn} + \text{CO} \uparrow (7)
\]

\[
K = \frac{a_{\text{Mn}}} {a_{\text{MnO}} \, a_{\text{C}}} (8)
\]

High partial pressure of CO gas affects the activities of other reactants and products in equation (8) and thereby shifts the equilibrium conditions and retards the rate of reduction of the MnO. As a result, additional energy and coke are required to increase the rate of forward reaction.

The slag chemistry is also a major cause of operational problems. Since the Mn ores used are high alumina type ores, the proper adjustment of slag chemistry is vital to maintain the required gas–slag–metal phase equilibrium in the reaction zone. Use of a charge with low silica and high alumina content altered the slag chemistry and liquidus temperature significantly. The high alumina and low silica in the slag also increased its viscosity. Unfortunately, thermodynamic data (phase diagrams, liquidus temperature) for the FeMn process was not available at the plant, which created difficulty for controlling/adjusting the composition of slag. Therefore, binary and ternary phase diagrams of MnO–Al₂O₃–SiO₂–MO (M=Ca, Mg) system specifically used at FAP, Joda were computed using FACT-Sage thermodynamic programme. The ternary phase diagrams of the multicomponent system (MnO–Al₂O₃–SiO₂–CaO–MgO) specific to plant conditions were also computed. The effect of change in alumina concentration and temperature on the slag properties was examined using FACT-Sage. For computation the alumina concentration was varied from 0 to 30% in 100 g slag (37% MnO, 30% SiO₂, 6% MgO, 8% CaO and 2% Fe₂O₃) and the equilibrium phase composition was computed using the Equilib module of the FACT-Sage. The results of the computation are presented in Fig. 4. At 1300°C, slag can absorb up to 18% alumina as seen from Fig. 4. Addition of excess alumina results in the precipitation of MnAl₂O₄ spinel phase and hence the amount of MnO, MgO and Al₂O₃ reporting to the slag decreases. The change in composition of slag and formation of spinel phase raises the slag viscosity and liquidus temperature. The solubility limit of alumina in the slag in the temperature range from 1200 to 1500°C is presented in Fig. 5, which shows that solubility of alumina increases from 12% at 1200°C to more than 30% at 1500°C.
Dolomite, commonly used as a flux, adds CaO and MgO to the slag phase. The effect of CaO and MgO addition on phase equilibria of the slag used at FAP, Joda was computed by FACT-Sage and results are presented in Fig 6a and b. The addition of CaO below 5% has a detrimental effect as it enhances the precipitation of MnAl₂O₄ spinel phase (i.e. decreases the solubility of alumina in slag) as seen from Fig. 6a, however more than 6% addition of CaO gives a beneficial effect by increasing the solubility of alumina (i.e. reduces the amount of MnAl₂O₄ spinel phase) and thereby increases the fluidity of the slag. Although MgO is used for adjusting basicity of the slag, the presence of more than 3% MgO in the slag decreases the solubility of alumina by forming thermodynamically more stable (Mg,Mn)Al₂O₄ spinel solid solution phase. Therefore, the concentration of MgO and CaO in the charge needs to be evaluated critically, w.r.t. alumina level in the charge, to control the properties of the slag and thereby the operating conditions of the SAF. The change in the liquidus of binary MnSiO₃–Al₂O₃ by the addition of 3, 6 and 9% CaO and MgO is shown in Fig. 7a and b.

Thus, variations in the composition of slag alter its liquidus temperature and physical properties, which affect the performance of the smelting reduction process. The precipitation of the MnAl–spinel phase increases the viscosity of the slag and thereby restricts the flow of the slag during tapping. Accumulation of slag in the reaction zone of the SAF and high energy input leads to slag boil. The slag boil in turn blocks the path of the CO gas as the temperature in the middle zone of the furnace is below the slag liquidus temperature. These conditions disturb the normal operation of the SAF and lead to major eruptions of the charge.
In summary, the major cause for the problems in the reaction zone of the SAF is high pressure of CO due to blockage of the path and poor slag chemistry. A root cause analysis map was prepared based on these investigations and the same is presented in Fig. 8.

**Process modification to improve process**

The systematic analysis of the raw materials, slag and ferromanganese samples, and various stages involved in SAF operations was carried out. Based on these studies followings options were tested for improving the performance of the SAF and also minimising the operating difficulties:

(i) charge selection: the Mn ores with high decrepitation index were rejected which helped to reduce the generation of fines inside the furnace. This also reduced the SAF shutdown time and thereby increased the availability of furnaces. Screening of the charge was also considered for reduction of fines in the charge but during trials it was observed that the concentration of silica was high in the finer fractions, thus screening of fines reduced the total concentration of silica in the charge. For utilisation of ore fines as a source of silica, it was recommended to agglomerate the Mn ore fines by using pot sintering technique or briquetting. Briquetted fines were trialled and found suitable for the operation.

(ii) monitoring of the temperature and pressure in the top zone of the furnace: continuous monitoring of the top gas temperature and pressure helped operator to detect the symptoms of eruption conditions. This also helped to maintain the safe operating conditions and gave sufficient time for the operating staff to take necessary precautionary majors.

(iii) preheating of Mn ores: the major reasons for the excessive generation of fines and high top temperature in the furnace were decrepitation and decomposition of certain types of Mn ores. Preheating of the Mn ores in heating ovens or vertical shaft furnace at 600 to 800°C using SAF gas was recommended to eliminate these problems in the top zone of the furnace. The oxygen generated during decomposition of the MnO₂ will burn CO gas which will help to maintain the required temperature of the furnace. The laboratory results also revealed that during decrepitation of Mn ore layers of the gangue minerals separate out and accumulate in the fines which can be screened to reduce the concentration of gangue minerals, especially alumina, in the charge. This is technoeconomically feasible process as it will use the sensible heat and chemical energy of the furnace exhaust gas; hence no additional energy is required.

(iv) adjustment of slag chemistry: from phase diagrams of the slag system (MnO–Al₂O₃–SiO₂), as shown in Fig. 9, it can be observed that the liquidus of the slag depends on ratio of
MnO/SiO$_2$ and alumina content. Maintaining the MnO/SiO$_2$ ratio is more important for better slag properties. The lowest liquidus temperature region is highlighted in the centre of the MnO–Al$_2$O$_3$–SiO$_2$ ternary phase diagram (Fig. 9). It is essential to maintain the slag composition in this region for better operating conditions. Slag in this region can take up to 30% alumina below 1300°C temperature by adjusting the ratio of MnO/SiO$_2$.

Various options for silica addition were examined and are compared in Table 3. The most common and economic technique for adjusting MnO/SiO$_2$ is the addition of quartz as employed in FeCr production. However, dissolution of quartz lumps in the slag needs high temperature and is a sluggish process due to large particle size. The operating temperatures in FeMn production are relatively lower than in the FeCr process and hence dissolution of quartz lump is limited. Although reduction in particle size of quartz can enhance the rate of dissolution but charging of fines is not possible in SAF. Therefore this option is not feasible.

Presently at FAP, Joda, high silica Mn ores are used for adjusting the ratio of MnO/SiO$_2$. The silica in these ores is present in the form of MnO. SiO$_2$ which has a
lower melting point compared to quartz. Since Mn is present as MnO, it does not decompose and liberate oxygen in the top zone. Hence, these kinds of ores are blended in the feed mix.

Addition of BF grade lime is another option. The advantage of this material is its low melting temperature, which helps to adjust the ratio of MnO/SiO$_2$ below 1200°C. The addition of dolomite in the present practice also increases the MgO content in the slag. Although, addition of MgO reduces the liquidus temperature, it also reduces the solubility of alumina in the slag. Therefore, the addition of BF grade slag with high silica content will be better and effective alternative to the dolomite. However, quality of lime and its performance needs to be evaluated in detail.

The addition of synthetic slag can be the most technoeconomically suitable option. Synthetic slag can be generated in selective campaigns using a low alumina charge. Fine quartz can be added in the molten slag during tapping. The computation of phase equilibria for
addition of quartz (at 25°C) in 100 g slag (FAP, Joda composition) at 1200°C, in Fig. 10a and b, revealed that the sensible heat of the slag can dissolve up to 25% of silica. The addition of silica reduces the liquidus of the slag by dissolving the MnAl–spinel phase back into the slag, which helps to maintain the required fluidity of slag during processing. If slag is not able to dissolve all the silica added, it helps to agglomerate the fine quartz particles. When this slag is charged in the furnace, the rise in temperature inside furnace will aid faster dissolution of these agglomerated quartz particles. This way it is possible to charge fine quartz particles in the

Table 3 Comparison of various materials considered for adjustment of silica in slag

<table>
<thead>
<tr>
<th>Material</th>
<th>High Si Mn ore</th>
<th>Synthetic slag</th>
<th>BF grade lime</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Market</td>
<td>In-house</td>
<td>Market</td>
<td>Market</td>
</tr>
<tr>
<td>Relative cost</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Rate of reaction</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Restricted</td>
</tr>
<tr>
<td>Furnace operations</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Top zone</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fine generation</td>
<td>Low</td>
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<td>Low</td>
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<tr>
<td>Charge sintering</td>
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<td>Med</td>
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<td>Reaction zone</td>
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<td></td>
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<td></td>
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<tr>
<td>Dissolution in slag</td>
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<td>Higher</td>
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<td>Low</td>
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<tr>
<td>Alumina effect</td>
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<td>Low</td>
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<td>High</td>
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<td>Power consumption</td>
<td>Low</td>
<td>Same</td>
<td>Low</td>
<td>Higher</td>
</tr>
<tr>
<td>Slag volume</td>
<td>Low</td>
<td>High</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Product quality</td>
<td>Better</td>
<td>Good</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Refractory erosion</td>
<td>Same</td>
<td>Low</td>
<td>High</td>
<td>Same</td>
</tr>
<tr>
<td>Operational difficulties</td>
<td>Same</td>
<td>NA</td>
<td>NA</td>
<td>High</td>
</tr>
</tbody>
</table>
furnace. However, careful burden calculations are required when synthetic slag is used for adjustment of silica as it will also contain other gangue oxides. The thermodynamic study of synthetic slag production process shows encouraging results, however, detailed study of the process will be required to fine-tune the process conditions and also to examine its behaviour in the SAF.

Plant performance after modifications

The various options were studied and it is found that the findings should be applied in two phases. In the first phase, the suitable charge mix, monitoring of the temperature and pressure in the top zone of the furnace and adjusting the slag chemistry were found feasible for the plant to implement. Preheating of the charge, addition of synthetic slag and lime in the furnace was cost-intensive hence these were considered for the second phase. The first phase findings were implemented and it is found that for one year the plant did not face any critical charge eruption, crust formation and slag metal separation problem. The slag composition was MnO: 34–40%, SiO₂: 23.5–27.5%, Al₂O₃: 17.5%, CaO: 8–9.5%, MgO: 5–6.5%. Daily production is in the range of 142–146 Mt/day and power consumption is in the range of 2550–2600 kWh t⁻¹. The taphole life is almost 15 days (200 heats). The second phase options are to be implemented now to further improve the process to study the power consumption, coke consumption and metal recovery.

Conclusions

The mineralogical properties of the Mn ore play a vital role in the smooth operation of the SAF. The decrepitation and decomposition of high oxides of Mn in Mn ores reduces the permeability of the bed and increases the temperature of the top charge. The lower bed permeability and sintering of charge increases the pressure of the product gas in the reaction zone of the SAF, which retards the rate of reduction reaction. As a result, the specific power and coke consumption increases and also disturbs the operating conditions of SAF. Therefore, proper selection and pretreatment of the Mn ores and use of synthetic slag were recommended as necessary steps to be incorporated in the existing process flow sheet/operation to overcome the operating problems and to exploit the captive Mn ores. Some of the recommendations, such as selection of Mn ores, monitoring of top temperature, and adjustment of slag chemistry improved the SAF operations. The smooth operations were reported at the plant for last one year without any violent charge eruptions.

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