Prereduction and DC open-arc smelting of carbon-based ilmenite pellets

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The smelting of ilmenite to produce valuable titania slag and pig iron is an energy-intensive process. At process temperatures of about 1700°C, roughly 1 MWh of electricity per ton of ilmenite feed is consumed. Following successful laboratory-scale test work, a pilot-scale operation was undertaken to demonstrate prereduction and subsequent smelting of carbon-based ilmenite pellets. Five metric tons of carbon-based micropellets of 2 to 5 mm in size, consisting of ilmenite, anthracite, and an organic binder, were prepared for prereduction in batches of 250 kg. Prereduction was conducted in a fixed-bed furnace under a controlled atmosphere using CO gas at temperatures between 900 and 1100°C. The resulting prereduced pellets were successfully smelted in a 200 kW DC arc pilot furnace. The pilot test work and the prior laboratory test work demonstrated that consistent prereduction could be achieved due to improved heat and mass transfer within the carbon-based pellets, as well as diffusion of CO gas reactant to the reaction sites. Smelting of prereduced ilmenite appeared technically feasible and efficient; the furnace operation during the smelting process was stable with no visible sign of foaming. On average, furnace electricity consumption was measured at 0.6 MWh per ton of prereduced ilmenite pellets (extent of prereduction between 74–80%, with 65–73% metallization). Production of titania slag containing as little as 1.3% FeO and as high as 95% TiO₂ is achievable by this process. The test work demonstrated the technical feasibility, viability, and robustness of the smelting of prereduced carbon-based ilmenite pellets as one of the many alternatives to the current ilmenite smelting process.

INTRODUCTION

Electric smelting of 48–52% TiO₂-grade ilmenite is carried out for the production of 85–90% TiO₂ titania slag. This energy-intensive process operates at high temperatures of approximately 1700°C, and consumes around 1.0–1.3 MWh per ton ilmenite. An amount of 4.5 Mt of titania slag is produced globally per annum, of which South Africa contributes 1.5 Mt (Gous, 2006; Kotze, Bessinger, and Beukes, 2006; Williams and Steenkamp, 2006). In South Africa, production is carried out in DC arc furnaces at Tronox Heavy Mineral Sands (previously Namakwa Sands) and Exxaro KZN Sands, while AC furnaces are used at Richards Bay Minerals (RBM). Altogether these furnaces have an installed capacity of 435 MW, which currently represents close to 1% of the national grid (Gous, 2006; Kotze, Bessinger, and Beukes, 2006; Williams and Steenkamp, 2006; Zietsman and Pistorius, 2006). The DC open-arc smelting process was jointly developed in South Africa by Mintek and Anglo American, while the QIT process used by RBM was developed by Quebec Iron and Titanium (QIT), Canada (Gous, 2006; Kotze, Bessinger, and Beukes, 2006; Williams and Steenkamp, 2006).
The availability and cost of energy (for example, the availability and price of electricity, coal, and natural gas) play a significant role in the development, implementation, and operation of energy-intensive processes. At national and global levels, this ultimately dictates the size of the industry as well as its capacity to create jobs and generate income. The gradual decrease in the global competitiveness of the South African ferroalloys industry can be cited as one example of the effect of rising costs and tight supply of electricity on the local industry. A gradual decrease in alloy production and increasing exports of raw ores are being observed. This business model decreases the prospect for production capacity expansion and job creation.

From a number of options evaluated to stimulate the ilmenite smelting industry, preheating and prereduction of ilmenite prior to smelting are able to mitigate, to some extent, the impact of electricity price and tight supply on this industry. There is no existing plant where ilmenite is preheated prior to smelting in the furnace, as preheating may create more operational challenges such as severe slag frothing (Kotze, Bessinger, and Beukes, 2006). Smelting of cold prereduced ilmenite pellets has been practised by Tinfos Titan KS in Norway (Murty, Upadhyay, and Asokan, 2007). Although it is a successful process, the Tinfos process uses an elaborate feeding system in which bentonite-bound pellets are reduced in a rotary kiln using coal in excess of the stoichiometric requirements. The lumpy pellets are then magnetically separated from fines and unreacted coal, and are smelted in electric furnaces. The Tinfos process produces a low-grade slag of about 77% TiO₂ with the main impurities being MgO and SiO₂ (Nell, 2007).

Through extensive investigation of the solid-state reduction of ilmenite, the smelting of prereduced ilmenite in a DC arc furnace was developed at Mintek. In this process, provisionally patented as the ‘Impril process’ (SA Patent 2015/08501), carbon-based ilmenite micro-pellets 2-5 mm in size consisting of ilmenite, anthracite, and organic binder are heated in a fixed-bed configuration, at high temperatures in the range of 900–1100°C in the presence of CO gas. CO could potentially be replaced by other reducing gases such as syngas, hydrogen, and natural gas. This process would be able to produce consistent prereduced ilmenite pellets for direct smelting in the furnace.

Following successful laboratory-scale tests, the Impril process was demonstrated at pilot scale. The results are summarized in this paper. The aim of the test work was to demonstrate the technical feasibility of the smelting of prereduced carbon-based ilmenite pellets in a DC open-arc furnace and the benefits that this could generate. Preparation of carbon-based ilmenite pellets and their prereduction in a fixed-bed configuration, as well as the smelting of the resulting prereduced carbon-based ilmenite pellets in the DC open-arc furnace, were evaluated individually.

**TEST MATERIALS**

Five tons of ilmenite concentrate and one ton of anthracite required for the test work were sourced locally. The as-received ilmenite was sampled using a riffle splitter and a representative sample was used for characterization - the methodologies are described in the next section. The ilmenite had a particle size in the 38–150 µm range. The chemical analysis of the concentrate is summarized in Table I. The concentrate is composed mainly of iron oxides and TiO₂. Iron is present as Fe²⁺ and Fe³⁺. The chemical analyses of the anthracite used is summarized in Tables II and III. The anthracite was milled to 85% passing 106 µm to facilitate its incorporation into the ilmenite pellet recipe. The brand name and composition of the organic binder used for the pellets are not disclosed since it is proprietary.

| Table I. Bulk chemical composition of the raw ilmenite (mass %). |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| MgO | Al₂O₃ | SiO₂ | CaO | TiO₂ | V₂O₅ | Cr₂O₃ | MnO | FeO | Fe²⁺ | Fe³⁺ | Fe⁰ | Fe/T |  |
| 0.28 | 0.44 | 0.57 | 0.05 | 46.6 | 0.25 | 0.09 | 1.08 | 47.87 | 1 | 0 | 5 | 1.33 |  |

<0.05%: The analyte concentration could not be accurately quantified as it is below the limit of detection (LOD)
Total Fe in the sample is expressed as %FeO
Table II. Summary of the bulk chemical composition of the anthracite (mass %).

<table>
<thead>
<tr>
<th>Moisture</th>
<th>Ash</th>
<th>Volatiles</th>
<th>Fixed carbon</th>
<th>Total carbon</th>
<th>Total sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.57</td>
<td>4.74</td>
<td>6.19</td>
<td>89.1</td>
<td>90.7</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table III. Bulk chemical composition of the anthracite ash (mass %).

<table>
<thead>
<tr>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>CaO</th>
<th>TiO₂</th>
<th>V₂O₅</th>
<th>Cr₂O₃</th>
<th>MnO</th>
<th>FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.43</td>
<td>6.42</td>
<td>18.78</td>
<td>2.74</td>
<td>1.43</td>
<td>1.61</td>
<td>1.25</td>
<td>1.07</td>
<td>65.27</td>
</tr>
</tbody>
</table>

Total Fe in the sample is expressed as %FeO

Analytical and characterization methods

The bulk ilmenite material was sampled using a riffle splitter. A subsample was characterized by particle size distribution (PSD), X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM), and bulk chemical analysis. The raw materials and products were chemically analysed by appropriate accredited methods using inductively coupled plasma optical emission spectroscopy (ICP-OES) and X-ray fluorescence (XRF). Phosphorus content was determined by spectrophotometry, and carbon and sulphur by combustion methods (LECO). Wet chemistry for speciation was carried out to determine the content of the respective iron species by selective leaching. SEM analysis was carried out for the determination of the textural relationships between phases and the evaluation of the morphology of the grains and pores, as well as any features that may affect the gas-solid interactions.

PELLET PRODUCTION AND TESTING

Pellet preparation

Pellets were prepared in a pilot-scale pelletizing unit. This unit is comprised of an inclined rotating pan of 985 mm diameter and 170 mm depth, a feeding system, and a water spraying system. It is equipped with a variable-angle mechanical system and a variable-speed electric motor which is used by operators to set the angle and speed of the rotating pan. A blend of solid materials consisting of raw ilmenite, milled anthracite, and binder was fed to the rotating pan. Each blended batch was prepared by mixing 200 kg of ilmenite, a stoichiometric amount of milled anthracite, and 1% of the organic binder in a Jones mixer for about 30 minutes. The stoichiometric amount in this case is defined as the amount of pure carbon required to reduce all the iron oxides to metallic iron without any co-reduction of titanium oxides. Water was sprayed onto the blend in the rotating pan, thus binding and rolling the grains together into pellets. The feed rates of the blend of solid materials and process water were manually regulated during the pelleting process in order to produce micro-pellets of 2–5 mm size. The pellets were intermittently discharged from the rotating pan using a steel scoop once they were of required size and physical quality.

In total, about 4.5 t of carbon-based ilmenite pellets were produced. The green pellets were indurated by drying in an ambient environment for 24 hours, stockpiled for 4 days and packed into 1 m³ bags. The mechanical strength of the pellets was measured using a basic compression test machine. The procedure consisted of randomly selecting 10 to 15 pellets and subjecting these pellets to the standard compression test. The weight, mean diameter, and the force to crack each pellet were recorded. Based on the force and mean diameter, the compressive stress/strength of each pellet was calculated. The average compression strength of the pellets was about 1.50 MPa. This value may be considered as a reference value for future work.

Prereduction of ilmenite pellets

The pilot prereduction unit is presented schematically in Figure 1. This unit is a top-hat furnace with an internal muffle. The pellets were loaded at a height of 100 mm (250 kg pellets) in a single tray of dimensions 1700 mm × 900 mm. The loading area was a mesh screen which acted as a distribution plenum for the reducing gas and argon gas that were blown through the muffle load throughout the
operation. Firing commenced once the loaded tray was placed inside the furnace. Two K-type thermocouples were used to monitor the process: one was used to measure and control the muffle temperature and the second measured the internal temperature at the coldest part of the load, which was located in the centre of the tray at 450 mm from the edge, 50 mm deep into the product. The burden thermocouple was used to follow the progress of the heating.

CO gas, supplied from cylinders, was fed through a pipe connected at the bottom of the furnace tray. Due to operational challenges related to the logistics and supply of gaseous reductant to the process, CO was only used intermittently to flush the furnace atmosphere every 12 minutes. An amount of 5 kg CO was used per firing cycle, or about 18 g/min/m² if CO is spread over the 3-hour blowing cycle. Each firing cycle lasted for about 3–5 hours. The process gases from the furnace were released through an exhaust pipe. CO was replaced by Ar once the prereduction period was completed. The furnace was then switched off and the prereduced material was left to cool inside the furnace in the argon gas environment.

Batches of indurated pellets of 250 kg each were heated in the muffle furnace. A typical profile of the furnace temperature (TOP °C) and the burden temperature (BOTTOM °C) is presented in Figure 2. The furnace temperature was gradually raised over a period of about 2 hours to 1100°C; this was subsequently followed by a 2-hour stable operation period at 1100°C. The muffle furnace operation was consistent and stable. With these operating conditions, the burden temperature was measured at between 800 and 1050°C. A drawback of the test conditions is that CO was blown through the burden only intermittently, as explained earlier. Overall, the furnace operation was consistent, resulting in fairly uniform prereduction conditions for the carbon-based ilmenite pellets.
Figure 2. Typical temperature profile during the prereduction process (red=muffle temp; blue=burden temp).

Figure 3 shows a top view of the cooled tray of prereduced carbon-based ilmenite pellets. There was no visible disintegration or sintering of the pellets, and burden permeability was therefore preserved throughout the prereduction test. This also demonstrates that the carbon-based pellets are able to withstand high temperatures of up to 1100°C, suggesting that prereduction in a fixed-bed configuration is possible for these particular carbon-based pellets.

In total, about 3.6 t of prereduced pellets were produced. The pellets were bagged in 1 m³ bags, from which five composite samples were collected using a pipe sampling technique. The samples were characterized by both chemical and mineralogical analyses. The chemical analyses of the five composite samples are given in Table IV.

Both the raw and prereduced ilmenite materials were chemically analysed; specifically, the analysis of the oxidation state of iron (Fe³⁺, Fe²⁺, and Fe⁰) is used to calculate the prereduction and metallization yields for the reduced pellets.
Negligible reduction of titanium oxides is assumed throughout and the prereduction yield was therefore calculated based on the mass balance of oxygen associated with each gram of iron before and after prereduction. Equations [1] and [2] were used for the calculation of the prereduction and metallization yields, respectively.

$$\text{Prereduction yield} = 100 \times \frac{(\text{Oxygen removed by the prereduction process})}{(\text{Oxygen associated with each gram of iron in ilmenite sample})} \quad [1]$$

$$\text{Metallization yield} = 100 \times \frac{\text{Fe}^0}{\text{Fe}_{\text{total}}} \quad [2]$$

The calculated degrees of prereduction and metallization for the five composite samples are presented in Table V.

Table IV. Chemical compositions of the prereduced pellets.

<table>
<thead>
<tr>
<th></th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>CaO</th>
<th>TiO₂</th>
<th>V₂O₅</th>
<th>Cr₂O₃</th>
<th>MnO</th>
<th>Total Fe</th>
<th>Fe₀</th>
<th>Fe²⁺</th>
<th>C</th>
<th>Ti³⁺</th>
<th>Fe/Ti ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bag 1</td>
<td>0.53</td>
<td>0.33</td>
<td>0.31</td>
<td>0.10</td>
<td>44.4</td>
<td>0.36</td>
<td>0.07</td>
<td>1.05</td>
<td>34.92</td>
<td>25.55</td>
<td>9.37</td>
<td>7.23</td>
<td>6.55</td>
<td>1.32</td>
</tr>
<tr>
<td>Bag 2</td>
<td>0.55</td>
<td>0.30</td>
<td>0.26</td>
<td>0.07</td>
<td>44.5</td>
<td>0.36</td>
<td>0.08</td>
<td>1.06</td>
<td>35.23</td>
<td>25.44</td>
<td>9.79</td>
<td>7.72</td>
<td>6.76</td>
<td>1.32</td>
</tr>
<tr>
<td>Bag 3</td>
<td>0.50</td>
<td>0.30</td>
<td>0.24</td>
<td>0.15</td>
<td>43.5</td>
<td>0.33</td>
<td>0.07</td>
<td>1.03</td>
<td>33.60</td>
<td>21.90</td>
<td>11.70</td>
<td>7.97</td>
<td>5.45</td>
<td>1.29</td>
</tr>
<tr>
<td>Bag 4</td>
<td>0.48</td>
<td>0.32</td>
<td>0.39</td>
<td>0.11</td>
<td>42.4</td>
<td>0.33</td>
<td>0.07</td>
<td>1.05</td>
<td>34.46</td>
<td>22.66</td>
<td>11.80</td>
<td>8.01</td>
<td>4.78</td>
<td>1.35</td>
</tr>
<tr>
<td>Bag 5</td>
<td>0.36</td>
<td>0.45</td>
<td>0.64</td>
<td>0.18</td>
<td>41.9</td>
<td>0.33</td>
<td>0.07</td>
<td>1.08</td>
<td>36.01</td>
<td>24.21</td>
<td>11.80</td>
<td>7.20</td>
<td>4.66</td>
<td>1.43</td>
</tr>
<tr>
<td>Average</td>
<td>0.48</td>
<td>0.34</td>
<td>0.37</td>
<td>0.12</td>
<td>43.3</td>
<td>0.34</td>
<td>0.07</td>
<td>1.05</td>
<td>34.84</td>
<td>23.95</td>
<td>10.89</td>
<td>7.63</td>
<td>5.64</td>
<td>1.32</td>
</tr>
<tr>
<td>St dev</td>
<td>0.07</td>
<td>0.06</td>
<td>0.16</td>
<td>0.04</td>
<td>1.17</td>
<td>0.02</td>
<td>0.004</td>
<td>0.02</td>
<td>0.90</td>
<td>1.64</td>
<td>1.21</td>
<td>0.39</td>
<td>0.98</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Tables IV and V show that pellets prereduced to a consistent extent were produced as a result of the uniform furnace operating conditions. This would also suggest that within the range of operating conditions and pellet recipes investigated, the fixed-bed prereduction configuration would be appropriate for the prereduction of the prepared pellets. Design and operation of a controllable smelting process for prereduced pellets is possible in these conditions.

As per the prior laboratory test work results, the actual yields can be improved. In the laboratory test work, reduction yields of over 95% were achieved when a continuous CO flow was maintained and prereduction was carried out at a temperature of 1000 °C. The lower prereduction yields achieved in the pilot-scale work were attributed to lower firing temperatures recorded in the burden, as well as the significantly lower and intermittent flow of CO blown through the burden.
DC SMELTING OF PRE-REDUCED ILMENITE PELLETS

Pilot smelting set-up
Mintek’s 200 kW DC arc furnace facility, used for the smelting phase of the work, is schematically presented in Figure 4. It consists of a cylindrical 1 m outer diameter steel shell which is water-spray cooled and lined with a single layer and three rows of magnesite-chrome bricks, and a hearth consisting of a rammable magnesia refractory. The refractory design resulted in a furnace crucible internal diameter (ID) of 0.656 m. The furnace is equipped with an alumina-lined conical roof, and the shell is bolted onto a domed base. A single tap-hole was used for this test, with molten slag and metal tapped together and allowed to separate in the ladle. The furnace is equipped with a single, centrally-located graphite electrode of 40 mm diameter operating as a cathode, and an anode consisting of steel pins embedded in the hearth refractory. The feed system comprises individual hoppers used to feed raw ilmenite, anthracite, and prereduced ilmenite pellets through a feed pipe connected to a feed port located in the furnace roof. The furnace is linked with an off-gas system for the cleaning of process gases prior to their release to the atmosphere.

Smelting
Continuous smelting of partially reduced ilmenite pellets (approx. 70% prereduction yield) was carried out in a 200 kW DC open-arc furnace. The aim of the pilot smelting test was to demonstrate stable furnace operation as well as production of a consistent slag quality, in particular, a slag TiO₂ grade above 85%. The test work also had the objective of confirming the process specific energy requirement.

In total, 28 furnace batches were completed, producing 2.4 tons of titania slag and 1.1 tons of pig iron.

Two conditions were particularly interesting in this process: direct melting, and smelting of the as-received pre-reduced pellets. The results of these conditions were compared to those of the carbothermic smelting of raw ilmenite.

Smelting Conditions
As can be seen in Figure 5, the residual slag FeO content varied with the reducing conditions. The smelting process was controlled using the tapping temperature and the residual FeO content in the tapped slag.
Titania Slag Analyses

Operation of smaller pilot furnaces is generally challenging. Eroded refractory contaminated the final slag and metal with chromium and magnesium species (oxide and metal). The standard and weighted averages of the chemical compositions of the slag produced per condition were calculated and are summarized in Table VI.

Slag containing a weighted average of 22% FeO was produced in test conditions during which the pellets were processed as-is (melting of prereduced pellets). However, this test condition did not achieve steady state due to acute erosion of the furnace crucible. Pyrosim, Mintek’s in-house thermochemical simulation software, was used to calculate the degree of metallization that would result in production of a slag containing about 20% FeO. This was found to be about 70% metallization (Jones, 1992), indicating that the pilot prereduction results were acceptable.

As the efficiency of the furnace shell water-spray cooling was fairly low, increasing the reduction of FeO and thus increasing the slag liquidus temperature was expected to aid building of a freeze lining, which would also limit refractory erosion.

Subsequent smelting tests were carried out with the addition of 5% anthracite to the smelting recipe, which resulted in the expected lowering of FeO in the slag to below 10%. The composition of the slag produced in this period is given in Table VII. Slag FeO contents as low as 1.3–4.9% were achieved without visible signs of slag foaming. This condition was maintained for a longer period (Batch 10 to Batch 17) during which stable furnace operation was demonstrated and slags of consistent FeO content were produced.

The concentration of TiO₂ in the slag was affected by a combination of factors, including the contamination of the slag with foreign species from the refractory, ilmenite ore grade, and the extent of reduction in the smelting process (or residual slag FeO content). However, considering a specific smelting operation the TiO₂ content is a function of the level of residual FeO in the slag. The FeO level should be such that it ensures both optimal slag chemistry and optimal furnace operation (such as developing a freeze lining and preventing foaming).

Results for this particular test work suggest that smelting of partially reduced ilmenite and operating the furnace with lower FeO content in the slag is technically possible.
<table>
<thead>
<tr>
<th>Batch</th>
<th>2-7</th>
<th>8–20</th>
<th>10–17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remelting</td>
<td>Weighted av.</td>
<td>60.02</td>
<td>85.86</td>
</tr>
<tr>
<td></td>
<td>Av.</td>
<td>60.96</td>
<td>87.25</td>
</tr>
<tr>
<td></td>
<td>St dev</td>
<td>4.81</td>
<td>11.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% anthracite</td>
<td>Weighted av.</td>
<td>87.12</td>
<td>87.25</td>
</tr>
<tr>
<td></td>
<td>Avg</td>
<td>2.67</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>St dev</td>
<td>2.67</td>
<td>1.35</td>
</tr>
</tbody>
</table>

In conventional DC ilmenite smelting, FeO content in the final slag is 8–12% (Zietsman, 2004). The content of both TiO₂ and FeO is about 96% in typical South African commercial ilmenite smelting operations, the balance being the impurities. A slag with greater than 90% TiO₂ would be produced by lowering the FeO below 6%, while a level of 86% TiO₂ in the slag may be achieved with an FeO content of about 10%. Production of a higher TiO₂ slag leads to increased reductant and energy requirements, increased refractory wear, tapping issues, and foaming (Maharajh, 2015).

Smelting of prereduced ilmenite can avoid these challenges, at least partially. Slag foaming under current smelting conditions is a result of two main factors: the amount of reaction gas generated, and slag properties such as surface tension, viscosity, and density. Through smelting of prereduced ilmenite (approx. 70% prereduction yield), the amount of reaction gas is decreased by as much as 70% compared to conventional ilmenite smelting processes. Decreasing the reaction gas volume to this degree is expected to have a significant effect on the likelihood and intensity of foaming incidents during abnormal operating conditions in the furnace. The physical properties of slag were investigated and were found not to be significantly different within the range of composition investigated. Modelling of a binary slag composed of TiO₂ and FeO was carried out to illustrate that the surface tension is relatively insensitive to the slag composition. Slag foaming or slag foaming intensity is therefore expected to depend primarily on the amount of reaction gas released by the process.

Conditions used in conventional DC ilmenite smelting in South Africa can be applied to the present process test work to remove the effects of refractory erosion and ilmenite ore quality on the slag TiO₂ grade. By targeting a residual slag FeO content lower than 6%, the Impril process should be able to produce a slag TiO₂ grade of at least 90%. Due to the benefit of prereduction, this process may be able to operate stably with slag containing less than 6% FeO. As can be seen in Table VII, this was largely achieved.
However the ultimate goal of the Impril process is to process fully prereduced ilmenite pellets with at least a 90% prereduction yield to reduce the electrical energy requirement. It is postulated that a favourable effect on the quality of the final products will also be achievable.

**Pig Iron Analyses**

Iron alloy was successfully produced during both the direct melting and smelting of prereduced carbon-based ilmenite. The Fe content varied between 91% and 97% due to contamination by Ti, Cr, Si, and Mn. Apart from Cr, which comes mainly from the furnace refractory lining, the other elements present in the alloy come from the ore. These contaminants can, however, be removed through refining of the raw pig iron. The content of the minor elements C, P, and S met the requirements of commercial pig iron. C was below 2% on average, the requirement being 3.5–4.5%. S and P were both low and within the requirements for pig iron, namely below 0.05% and 0.12%, respectively. The contents of S and P are related to their concentrations in the raw ilmenite.

**Furnace Electrical Consumption and Operation**

The 200 kW DC open-arc furnace was operated at a power level in the range of 115–140 kW and corresponding voltage of 100–115 V. Consistent furnace heat losses in the range between 60–90 kW were measured, and the specific energy requirement (feed rate ratio at constant power) was varied to produce molten material at a temperature of about 1750°C. Average tapping temperatures were scattered within a range between 1670 and 1780°C.

The specific energy requirement (SER) for the direct melting and subsequent smelting of prereduced carbon-based ilmenite pellets was measured between 0.6 and 0.7 kWh/kg prereduced ilmenite. The SER of the direct melting was closer to the lower value, while smelting required more energy with the SER closer to the higher limit as expected. The energy requirement for smelting of prereduced ilmenite is dependent on the degree of prereduction and the extent of the reduction in the smelting furnace at a given temperature.

Table VIII gives a summary of the furnace operation for the various smelting conditions investigated. There are minor variations of power and voltage between the conditions. Stable furnace operation was achieved irrespective of the condition investigated, and with no visible sign of slag foaming. This continued to be the case even after increasing the FeO reduction.

As expected, the degree of reduction achieved will impact the electricity consumption during smelting. A 30–40% reduction in furnace electricity required relative to the conventional smelting process can be achieved in the Impril process, assuming that a prereduction yield of at least 70% can be achieved.
Achieving a specific energy requirement of 0.45–0.50 kWh/kg prereduced ilmenite may be possible under optimized conditions. Additional large-scale test work would enable confirmation of these estimates.

Compared to conventional ilmenite smelting, different furnace behaviour may be expected when smelting or melting prereduced ilmenite since titania slag is highly conductive. These differences may include arc length, power, and stability, and electrode movement effects not observed during the small-scale pilot test. Arc resistivities were measured for the various conditions investigated (melting and smelting) in order to predict the furnace arc stability. Arc resistivity was found to be in the range of 0.0168 and 0.0240 Ω cm, close to 0.0175 Ω cm, a typical value for arc resistivity in smelting processes with CO-rich atmospheres.

**CONCLUSION**

Through extensive investigations, Mintek has developed the ‘Impril’ process, an improved version of the original Mintek-patented process for DC smelting of ilmenite. The new process consists of DC arc smelting of prereduced carbon-based ilmenite pellets. The objectives of Impril are to decrease furnace electricity consumption, improve product quality, and improve furnace operability.

Carbon-based ilmenite pellets were successfully prepared. They were composed of the as-received ilmenite, milled anthracite, and an organic binder. A mechanical strength of up to 1.5 MPa was achieved for indurated pellets under ambient environmental conditions.

Hybrid prereduction of carbon-based ilmenite pellets was successfully carried out in a fixed-bed configuration at temperatures of about 1000°C. The tests used a CO reducing gas environment and a residence time of 1–4 hours. This prereduction process was successfully demonstrated at laboratory and pilot scale. Process performances appeared to be strongly related to the operating temperature, CO flow rate, and residence time. Consistent prereduction and metallization yields were achieved, which are important parameters for designing a controllable smelting process. Prereduction yields greater than 90% were achieved as a result of the combined actions of solid carbonaceous reductant, carbon-based binder, and CO.

Smelting of cold prereduced pellets with a prereduction yield ranging from 74 to 80 % in a 200 kW DC arc furnace was successfully completed. The test results successfully demonstrated the Impril process concept, and the indicative results supported the theoretical calculations and laboratory results. A residual slag FeO content in the range of 1.3–4.9% was achieved with a 5% additional anthracite addition to the recipe. Direct melting of the prereduced pellets was also successfully carried out with
the slag composition in line with the expected outcome, based on the degree of prereduction achieved during the pretreatment step. The furnace operated consistently with no major challenges such as slag foaming or furnace instability. The measured arc characteristics showed that the electrical behaviour in smelting of prereduced ilmenite is expected to be similar to the conventional smelting processes. A specific energy requirement (SER) of about 0.6–0.7 MWh/ton prereduced ilmenite was measured, which represents about 30–40% electricity savings compared with conventional smelting.

The Impril process may also enable production of higher TiO₂ grade slag (above 90%) due to the reduction of FeO in slag, and it was demonstrated that a saleable pig iron quality could be produced. Relative to other existing ilmenite smelting processes, the Impril process may also contribute towards a reduction in the occurrence of slag foaming as a result of the significantly lower quantity of gas generated. Producing high TiO₂ grade slags will have a positive impact on the downstream processes for the production of TiO₂ pigments and Ti metal and alloys.

The pilot-scale test work demonstrated the technical feasibility, viability, and robustness of the smelting of prereduced carbon-based ilmenite pellets as one of the many enhancements to the current ilmenite smelting process.

REFERENCES


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Kabwika has vast experience of more than 25 years in the field of Pyrometallurgy covering the operation and management of commercial plants, as well as research and development for the production of the following commodities: copper, cobalt, ferroalloys, ilmenite, rare earths, and coal. He joined Mintek in 1997 and since then has worked at various capacities in the Pyrometallurgy Division where he heads the New Technology group. His main research activities are directed towards but not limited to energy saving, minimisation of CO₂ emissions, beneficiation of complex ores as well as the minimisation of wastes.