Towards sustainable processing of vanadium-bearing titaniferous magnetite deposits – an overview of barriers and opportunities

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ABSTRACT

Efficient recovery of titanium from titaniferous magnetite ores continues to be a promising, yet unrealised opportunity, despite significant occurrences of titaniferous magnetite deposits worldwide and the existence of established industrial-scale practices. Current smelting processes only recover iron and vanadium, while the titanium is discarded in the waste slag. These slags are stockpiled and present massive environmental challenges, while still containing value as residual iron, vanadium and titanium. The complex mineralisation of these deposits does not allow for a significant opportunity to separate the titanium and magnetite minerals through normal physical upgrading processes. An upgrading process is therefore required to derive economic value. An efficient process technology could create an opportunity to unlock all three valuable commodities. South Africa’s Bushveld Complex, the largest known deposit of its kind in the world, is known for the high vanadium content but is also associated with relatively high concentrations of titaniferous magnetite. The quality of the Bushveld Complex was one of the drivers for the establishment of the Highveld Steel and Vanadium Company in the mid-1960s. The unfortunate demise of Highveld Steel and Vanadium created an opportunity to review current practices and evaluate the best available process for this complex ore in the context of the three elements of interest. Past and current processes, the nature of these deposits and the potential to recover titanium are assessed to highlight the potential of fluxless smelting of titaniferous magnetite to produce a titania-rich slag as feedstock to the pigment, titanium metal industry in conjunction with recovery of iron and vanadium. Ilmenite smelting practices are proposed as a suitable alternative to achieve the goal, namely sustainable processing.

Keywords: Titaniferous magnetite, titanomagnetite, smelting, titania slags, comprehensive processing
1. Introduction

The nature and occurrence of titaniferous magnetite (or titanomagnetite) deposits are well-known to be numerous and significant in size. Titanomagnetite is generically defined as magnetite, with more than 1% titanium dioxide (TiO$_2$); these deposits are characteristically vanadium-bearing (Fischer, 1975). The iron and titanium occur as a mixture of magnetite (Fe$_3$O$_4$) and ilmenite (FeTiO$_3$). For the majority of deposits, the ilmenite and iron minerals are intimately interlocked, which prevents clean separation of the magnetite and ilmenite via physical beneficiation (Henry et al., 1987; Rohrmann, 1985; Taylor et al., 2005). Titaniferous magnetite deposits contain iron, vanadium and titanium, but only iron and vanadium are routinely recovered, usually via a pyrometallurgical process during which the titania is discarded via the slag phase, together with unrecovered iron and vanadium, while iron and vanadium is recovered via the metal phase (Geldenhuys, 2020; Moskalyk and Alfantazi, 2003; Taylor et al., 2005). Titanomagnetite deposits suffer to an extent from a “paradox of plenty” (Awolusi, 2015). It could be likened to the difficulties that befall lottery winners who struggle to manage the complex side-effects of abundance. While abundantly endowed with iron, vanadium and titanium, titaniferous magnetite ores are complex to process efficiently and economically.

The objective of this paper is to review pyrometallurgical practices for the processing of titaniferous magnetite. Past, and present smelting practices are compared with the view to identify a possible opportunity to comprehensively process these ores. Unlocking the abundance of titanomagnetite has proved to be a multifaceted challenge, with current global practices only extracting partial value. Fluxless smelting in a direct-current (DC) furnace, namely an open-arc, open-bath operation, is proposed as a potential alternative approach to current practices.

2. Nature and occurrence of titanomagnetite

Characteristically titaniferous magnetite ores vary significantly in composition, containing from 16% to 60% Fe, 1.5% to 38% TiO$_2$ and 0.1% to 2% V$_2$O$_5$ and are also generally low in S and P (Fischer, 1975; Pang et al., 2010). Deposits of titanomagnetite are found in significant quantities throughout the world. Substantial and expanding resources are found in the Panzhihua Complex in Sichuan Province, China (Pang et al., 2010) and the Windimurra Complex, Australia (Ivanic et al., 2010). Most titaniferous magnetite deposits are vanadium-bearing, and many also contain inter-grown or spatially associated ilmenite (Peck and Huminicki, 2016). Titaniferous magnetite deposits account for about 90% of China’s titanium reserves (Chen and Chu, 2014a), while according to recent data, the Bushveld Complex accounts for about 16% of global demonstrated vanadium reserves, namely about 3.5 million metric tons. In recent years, Chinese and Australian stated reserves have surpassed the Bushveld Complex (U.S. Geological Survey, 2020, 2016). The trend is an indication of the economic interest in these deposits in China. A feature of the magnetite seam of the Bushveld Complex is the remarkable consistency with regards to the vanadium content, namely grades of about 1.6% V$_2$O$_5$, which is traceable for hundreds of kilometres; grades of 0.3% V$_2$O$_5$ is for example usual for titanomagnetite.
deposits (Goldberg et al., 1992). Titanomagnetite deposits are classed as magmatic iron-titanium deposits (Pang et al., 2010). It is noteworthy that Norwegian and Canadian hard-rock ilmenite deposits are also classified as magmatic iron-titanium deposits. Table 1 lists the most significant titanomagnetite deposits by the primary mineralogy of the ore, adapted from Pang et al. (2010), to include Russian and New Zealand deposits (Badmatsyrenova and Orsoev, 2005; Goldberg et al., 1992).

Table 1.
Significant titaniferous magnetite deposits grouped by primary mineralogy.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Primary ore mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tellnes (Norway), Lac Tio (Canada)</td>
<td>Hemo-ilmenite/titanomagnetite with or without apatite</td>
</tr>
<tr>
<td>Bushveld (South Africa)</td>
<td>Titanomagnetite with or without apatite</td>
</tr>
<tr>
<td>Windimurra (Australia)</td>
<td>Titanomagnetite with or without ilmenite</td>
</tr>
<tr>
<td>Panzhihua, Hongge (China)</td>
<td>Titanomagnetite with or without ilmenite or apatite</td>
</tr>
<tr>
<td>Kachkanar (Russia)</td>
<td>Titanomagnetite beach sand</td>
</tr>
<tr>
<td>Waikato North Head (New Zealand)</td>
<td>Titanomagnetite beach sand</td>
</tr>
</tbody>
</table>

3. Smelting of titaniferous ores

Current pyrometallurgical practices for titaniferous deposits are either ironmaking processes, to recover iron, or iron and vanadium or, in the case of ilmenite, iron removal processes, to produce a high-grade titania-slag. Smelting of titanomagnetite to produce iron is a well-established industrial practice, dominated by the following geographical regions, China (Panzhihua), Russia (Kachkanar), South Africa (Bushveld Complex) and New Zealand (Waikato North Head). These regions are associated with substantial deposits of vanadium-bearing titanomagnetite deposits.

Conventional ironmaking blast furnaces, have been adapted, mainly via judicious recipe and operational management, to minimize the impact of the higher than usual concentration of titanium in the slag. Operational problems are reported if the feed composition to blast furnaces is not managed very carefully. The highly reducing conditions in blast furnaces, contribute to the formation of highly refractory titanium compounds which requires careful management to avoid operational difficulties such as hearth build-up and tuyeres blockages. Other challenges reported include poor burden permeability, low productivity and foaming slag. If not managed, long periods of idling may be required to clear build-up or accretions in the blast furnaces (Lazutkin et al., 2001; Smirnov et al., 2000; Steinberg et al., 2011). Recipe interventions include dilution with high-grade iron ore, fluxing, and where possible, lowering the titania content of the feed, through physical beneficiation (Chen and Chu, 2014a; Zhang et al., 2007). All of these interventions have a negative impact on the recovery of the elements of economic importance.

Electric smelting of titaniferous magnetite is also a well-established ironmaking process, albeit significantly smaller in scale if compared to blast furnaces. The titania content is less of a challenge in an electric furnace. In an electric smelter, higher titania concentrations in the slag can be tolerated, thus less fluxing is required, if compared to a blast furnace, and recoveries improve (Bleloch, 1949; Kelly,
Titaniferous magnetite smelters thus discard a substantial portion of the contained value of the ore via the titania-bearing slag by-product. The Panzhihua blast furnace operation reportedly recovers about 70% of the Fe, and 47% of the V in the feed, the difference reporting to the discard slag phase. These ironmaking slags, therefore, also contain significant quantities of residual iron and vanadium, which is discarded as waste slag with the titanium and other gangue components (Chen and Chu, 2014b).

4. Ironmaking history

The earliest evidence of pyrometallurgical processing of titanomagnetite ore dates back to the Late Iron Age (the period ranging from about 1000 to 1880 calibrated Common Era) in South Africa. The early ironmakers in the Lowveld region of South Africa adapted their bloomery furnaces to produce iron from the readily available titanomagnetite. The early settlers were likely attracted to the northern Lowveld region due to copper and salt and not by the vast quantities of titanomagnetite and magnetite, but would have needed iron. Archaeological evidence shows that these early settlers adapted bloomery smelting methods to produce the much-needed iron from the magnetite deposits. Because the reduction of magnetite to iron metal is much slower than similarly sized lumps of iron ore, and the titanium in titanomagnetite stabilises the spinel structure, the intrepid iron makers adjusted their smelting processes. One adaptation is the use of finer ores to ensure the adequate reduction of iron was achieved in the short shafts of the bloomery furnaces (which only about 1 m high). Slags recovered from the Lowveld bloomery furnaces were found to contain 12% to 25% TiO₂ and is reportedly the first evidence of titaniferous magnetite smelting (Killick and Miller, 2014; Park and Ostrovski, 2003).

The United States Bureau of Mines published a report in 1913 reviewing the chemical and economic value of titaniferous magnetite deposits of the United States (Singewald, 1913). The report describes early endeavours processing titanomagnetite ores in England, Norway, Sweden and the United States dating back to the 1860s. The blast furnaces were challenging to operate and found not to be economically competitive. The report concludes as follows: "Electric smelting of iron ores is still in its infancy, and its full possibilities have not yet been demonstrated. Electric smelting is of special interest in this connection since there is a confident feeling in many quarters that herein lies the hope of utilisation of the titaniferous ores." (Singewald, 1913, p. 15).

In Russia, blast furnace smelting technology was already implemented for the production of vanadium-bearing iron and a titanium-bearing slag in 1925. The iron was processed to produce steel in a Bessemer converter, while the slag was used by the paint and lacquer industry (Lazutkin et al., 2001). Lazutkin et al. (2001) describe blast furnace smelting of titanomagnetite as follows: "...we must still concur with the assessment of Academician M. A. Pavlov: Titanomagneties cannot be as easily smelted as conventional ores – this much must be acknowledged beforehand."

Electric furnace processes, yielding pig iron, were commonplace at the beginning of the twentieth century, especially in Sweden and Norway, where low-cost electrical power was readily available due to the prevalence of hydroelectric power. During this era, the renowned South African metallurgist,
Dr William Bleloch, suggested that the ‘atypical iron ore’ from the Bushveld Complex could be a candidate for electric smelting (via alternating current or AC furnaces). His research halted as a result of World War II, but in the post-war years, his attention returned to metallurgy and in particular, electric smelting projects. In 1948 he masterminded the smelting of 100 tons of Bushveld magnetite in Norway, and successfully demonstrated the production of pig iron and recovery of vanadium from the Bushveld Complex’s magnetite (Bleloch, 1949). Dr Bleloch proposed that the electric furnace would not replace blast furnace ironmaking, but that some iron ores, such as magnetite and magnetite ores containing other oxides (for example titanium, chromium and vanadium), could benefit from electric smelting. It was his work that ultimately led to the establishment of Highveld Steel & Vanadium in South Africa (Steinberg et al., 2011).

5. Titanium perspective

The titanium industry is young, especially in comparison to the ironmaking industry. Pigment production emerged in the 1920s and titanium metal extraction only developed in the 1950s via the Kroll Process. Titanium dioxide was first used as a pigment in 1908 when the French metallurgist A.J. Rossi mixed the material with salad oil and brushed out the mixture. In 1916 the Titanium Pigment Company was formed in New York. During the same period, the Norwegian government initiated a process to investigate commercial uses for the extensive titaniferous magnetite and ilmenite deposits in Norway. Although focussed on recovery of iron, the work led to the discovery of titanium dioxide pigments, and by 1912 Norway commenced production of TiO2 pigment (Fisher, 1997; Gambogi and Gerdemann, 2013). Russian blast furnace operators started processing titaniferous magnetite for ironmaking in 1925 with that the slag from the ironmaking process was processed for pigment production (Lazutkin et al., 2001). In the 1950s, large electric furnaces were commissioned at Sorel in Canada with the purpose to smelt the atypical titaniferous deposits in Quebec (Habashi, 2010). These furnaces were designed to operate with open-arcs, partially shielded by feed, producing high-titania slags in the absence of slag modifiers and produce slag with about 80% TiO2 (Sorel Slag) from the hard rock ilmenite feedstock with a starting grade of about 34% TiO2. The Sorel facility was replicated in South Africa, at Richards Bay Minerals in the mid-70s, processing beach sand concentrate, containing about 49% TiO2, to produce furnace slag with 85% TiO2 content in four, six-in-line alternating current electric arc furnaces (Williams and Steenkamp, 2006). Combined, the two Rio Tinto owned facilities has a furnace slag design capacity of over 2 million tons per annum. AC smelting technology is also used, with some variation, by TiZir Titanium and Iron (TTI) formerly TINFOS at Tyssedal in Norway (Gilman and Taylor, 2001).

The application of DC smelting of ilmenite emerged in the mid-90s as an alternative to the existing six-in-line AC furnace technology. The development of the technology was led by Mintek and Anglo American Corporation and was first implemented at Namakwa Sands on the west coast of South Africa. The DC smelters are economically operated despite smaller furnace capacities if compared to the Rio Tinto furnaces, offering a flexible alternative to the mega-scale six-in-line furnace technology.
The South African DC furnaces produce slags with more than 85% TiO$_2$ from beach sand deposits. The combined DC smelting capacity, owned by Tronox, namely Namakawa Sands and KZN Sands (previously Ticor) is about 430 million tons per annum (Gous, 2006; Williams and Steenkamp, 2006). Ilmenite smelters in China and Saudi Arabia are the most recent entries to the slag market. The facility owned by China Yunnan Metallurgical Company (CYMCO), started operating in 2010, with a design capacity of 85 000 tons of slag per annum (De Jong and Mitchell, 2010). The Saudi Arabian facility has been marred by operational and start-up challenges and has yet to ramp up to full production (Perks, 2018).

Smelting of titaniferous feedstock to produce a furnace slag is basically an iron extraction process resulting in the concentration of the titanium oxide in the slag. Ilmenite smelters, unlike the titanomagnetite operations, are not principally ironmakers. Iron is an economic boon, rather than the object of the process. The titaniferous feed is intentionally processed in the absence of additives and contaminants to maximise the titania grade of the furnace slag (the primary product). Iron is removed from the oxide ore via carbothermic reduction to metallic iron. The reaction takes place in the liquid state at a temperature of around 1650°C in an open-arc electric furnace (either direct current or alternating current). In some cases, some of the iron is reduced to the metallic state in a pre-treatment step (solid-state reduction) to reduce the electrical energy requirement (Gamar and Stanaway, 1994; Gilman and Taylor, 2001; Pistorius, 2008).

The iron extraction process offers little opportunity for removal of minor impurities which may naturally be present in the titanium-bearing mineral, and it is the mainly the quality of the feedstock that determines the composition of the slag product. This is true regardless of whether the titania feedstock is hard rock ilmenite, beach sands, or titaniferous magnetite. For this reason, titania slag smelters will preferentially process titaniferous feedstock with the lowest gangue component. It is possible to reduce virtually all the iron oxide from the slag, and the remaining oxides are thus proportionally concentrated in the slag, including the titania; modern ilmenite smelters avoid dilution of the slag product at all cost (Pistorius, 2008).

Furnace slags from titaniferous magnetite smelting processes contain high amounts of gangue components in part from the ore, and in part from the flux additions. While the slag from current titanomagnetite smelting operations contains economic value, these slags cannot compete with slag produced by ilmenite smelters, due to the lower starting grade and the intentional dilution of the titania via additives. A typical furnace slag destined for pigment production contains from 78% to 87% TiO$_2$ compared to the slags from titaniferous magnetite slags containing less than 36% TiO$_2$.

6. Titaniferous magnetite smelters

Current smelting practices for ironmaking is dominated by blast furnace operations. According to Chen et al. (2015), Panzhihua Steel produces about 10 million tons of crude steel per annum from vanadium-bearing titanomagnetite. The capacities of the electric smelters, in comparison, is about a tenth of the Chinese blast furnace operations (Hall, 1980; Kelly, 1993). Table 2 lists prominent
titaniferous magnetite smelters. Ironmaking slags from titanomagnetite smelting can be described via the TiO₂-SiO₂-Al₂O₃-MgO-CaO slag system, regardless of whether the ore is processed in a blast or electric furnace. The relative proportions of these components are determined by the gangue components in the ore and the fluxing regime (typically via the addition of lime and silica). The typical chemical compositions of titaniferous magnetite ores, as processed by prominent commercial smelting operations, are summarised in Table 3, with the corresponding slag compositions presented in Table 4; noting that Highveld Steel is no longer in operation. The current smelting practices of titaniferous magnetite ores produce slags that offer little incentive as a source of titania.

Table 2.
Prominent titaniferous magnetite smelters

<table>
<thead>
<tr>
<th>Plant</th>
<th>Process description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highveld Steel &amp; Vanadium (South Africa)</td>
<td>Rotary kilns, submerged-arc furnaces converted to open-arc, open-bath furnaces in 2006, closed in 2015</td>
</tr>
<tr>
<td>New Zealand Steel (New Zealand)</td>
<td>Multi-hearth furnaces (since 1972), rotary kilns, open-arc rectangular furnaces (changed from circular open-arc)</td>
</tr>
<tr>
<td>Nizhniy Tagil Metallurgical Plant (NTMK) (Russia)</td>
<td>Blast furnace route (since about 1925)</td>
</tr>
<tr>
<td>Chengde Xinghua Vanadium Chemical Company (China)</td>
<td>Blast furnace route, with pelletizing</td>
</tr>
<tr>
<td>Panzhihua Iron and Steel Company (China)</td>
<td>Blast furnace (expansions in the 2000s)</td>
</tr>
</tbody>
</table>

Table 3.
Chemical composition of titanomagnetite concentrate as processed by industrial smelters, mass %

<table>
<thead>
<tr>
<th>Country</th>
<th>Highveld Steel South Africa</th>
<th>New Zealand Steel New Zealand</th>
<th>Panzhihua Steel China</th>
<th>NTMK Russia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Fe</td>
<td>54.8</td>
<td>58.0</td>
<td>51.6</td>
<td>61.3 - 64.9</td>
</tr>
<tr>
<td>FeO</td>
<td>16.5</td>
<td>-</td>
<td>32.0</td>
<td>-</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>60.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TiO₂</td>
<td>12.7</td>
<td>7.8</td>
<td>12.7</td>
<td>~3</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>1.65</td>
<td>0.56</td>
<td>0.58</td>
<td>0.57 - 0.66</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.8</td>
<td>3.7</td>
<td>4.9</td>
<td>-</td>
</tr>
<tr>
<td>CaO</td>
<td>0.10</td>
<td>0.67</td>
<td>1.43</td>
<td>-</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>1.6</td>
<td>3.0</td>
<td>3.1</td>
<td>-</td>
</tr>
<tr>
<td>MnO</td>
<td>0.3</td>
<td>0.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.0</td>
<td>2.9</td>
<td>4.7</td>
<td>-</td>
</tr>
<tr>
<td>P</td>
<td>-</td>
<td>0.04</td>
<td>0.03</td>
<td>-</td>
</tr>
</tbody>
</table>

References: (Steinberg et al., 2011) (Kelly, 1993) (Hu et al., 2013; Taylor et al., 2005) (Moskalik and Alfantazi, 2003)
Table 4.
Typical chemical compositions of slag produced by titanomagnetite smelters, mass %

<table>
<thead>
<tr>
<th>Site</th>
<th>FeO (1 - 1.5 - 1.0)</th>
<th>TiO₂</th>
<th>V₂O₅</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>SiO₂</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highveld Steel, submerged-arc &amp; open-arc</td>
<td>1.0</td>
<td>32.0</td>
<td>0.9</td>
<td>14.0</td>
<td>17.0</td>
<td>22.0</td>
<td>0.17</td>
</tr>
<tr>
<td>New Zealand Steel, current</td>
<td>(1.26)</td>
<td>35.6</td>
<td>0.9</td>
<td>18.0</td>
<td>14.1</td>
<td>18.3</td>
<td>0.12</td>
</tr>
<tr>
<td>Panzhuhua Iron and Steel 2005 &amp; 2015</td>
<td>1.1</td>
<td>32.3</td>
<td>0.22</td>
<td>17.0</td>
<td>15.5</td>
<td>20.0</td>
<td>0.12</td>
</tr>
<tr>
<td>Nizhniy Tagil Metallurgical</td>
<td>1.8</td>
<td>22.2</td>
<td>0.22</td>
<td>15.2</td>
<td>29.0</td>
<td>27.9</td>
<td>0.23</td>
</tr>
<tr>
<td>Reference</td>
<td>(Rohrmann, 1985)</td>
<td>(Steinberg et al., 2011)</td>
<td>(Kelly, 1993)</td>
<td>(Taylor et al., 2005)</td>
<td>(Zhou et al., 2015)</td>
<td>(Smirnov et al., 2000)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Concentrations reported in brackets converted by the author from original reference to match table convention. Total Ti reported as TiO₂ and total Fe reported as FeO.

Notable is the significant difference in the titania-content of the slags for the various smelting practices (Table 4). The relative amounts of the various oxides is a result of the fluxing strategies and the feed composition, and in turn, determines the slag properties. Of interest is the upgradability of the slags, if current smelting constraints are removed. The concentrate analyses presented in Table 3 was used to estimate an approximate fluxless slag composition by proportionally upgrading the titania and other gangue components, as iron is reduced. The idealised slag compositions, assuming a residual FeO of 5%, is presented in Table 5 and is compared with the actual slag compositions reported in Table 4.

Table 5.
Simplified slag compositions of prominent titaniferous magnetite smelters, mass %

<table>
<thead>
<tr>
<th>Site</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highveld Steel</td>
<td>36</td>
<td>18</td>
<td>14</td>
<td>16</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>New Zealand Steel</td>
<td>32</td>
<td>17</td>
<td>16</td>
<td>18</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>Panzhuhua</td>
<td>21</td>
<td>14</td>
<td>28</td>
<td>26</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Idealised slag compositions assuming fluxless smelting of current ironmaking concentrates, mass %

<table>
<thead>
<tr>
<th>Site</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>FeO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highveld Steel</td>
<td>57</td>
<td>22</td>
<td>0.4</td>
<td>9</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>New Zealand Steel</td>
<td>41</td>
<td>19</td>
<td>4</td>
<td>15</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Panzhuhua</td>
<td>45</td>
<td>17</td>
<td>5</td>
<td>17</td>
<td>11</td>
<td>5</td>
</tr>
</tbody>
</table>

It is worth noting that the concentrate compositions, as listed in Table, are not optimised for fluxless smelting. It is reasonable to assume that the TiO₂ concentration could be increased during
preconcentration. The Highveld Steel concentrate, for example, without any effort to maximise titania, has an upgrade potential of 1.6 (from 36% to 57% TiO₂) mainly due to the higher titania-to-gangue ratio. There is clearly potential for the titaniferous magnetite from the Bushveld Complex to become a source of titania slag if processed differently.

7. Electric smelting of titaniferous magnetite

The closure of South Africa’s EVRAZ Highveld Steel and Vanadium (Highveld Steel) in 2015, after almost 50 years of operation resulted in tremendous hardship for the surrounding communities and is a devastating blow for the South African economy (EVRAZ Highveld Steel and Vanadium, 2015). The Bushveld Complex’s titaniferous magnetite deposit is particularly abundant in vanadium and titanium and remains a resource of strategic importance. The closure of this smelting complex, which was the world’s second-biggest vanadium producer at the time (with reportedly a market share of 14%), changed the character of global vanadium supply. Vanadium is, however, not a particularly scarce element and the market response has been relatively muted. The Mapochs mine from which the primary ore for the Highveld Steel smelter was extracted also closed as part of the business rescue process. The mine has subsequently been sold to International Resources Limited (IRL), signalling that the Bushveld Complex’s vanadium continues to attract interest, and value (Mining Weekly, 2017).

Highveld Steel’s process flowsheet, originally consisted of co-current rotary kilns (for prereduction of the concentrate), followed by feeding of the hot-reduced concentrate into submerged-arc furnaces, to produce vanadium-bearing pig iron. At the time of decision-making, the use of conventional blast furnace technology had been regarded as being too high risk due to the high concentration of titanium in the Bushveld Complex ores. The purpose of the kilns is to reduce the relevant metal oxide, in this instance mainly the iron, using a low-cost energy source, such as pulverised coal (New Zealand Steel, 2018, 2017). The prereduction step lowers the electrical energy requirement of the smelting step. The kilns roughly represent the process that occurs within the shaft of the blast furnace. The aim is to reduce the magnetite to metallic iron and to feed the hot, prereduced ore into the electric furnace to produce vanadium-bearing iron that separates from the fluxed titanium-bearing slag. Vanadium is recovered post-taphole from the metal as a vanadium-rich slag (Hukkanen and Walden, 1985; Rohrmann, 1985; Steinberg et al., 2011).

The furnaces at Highveld Steel were designed to operate in submerged-arc mode, a divergent approach from the growing ilmenite smelting industry in Canada and compatriot, New Zealand Steel. Steinberg et al. (2011) lists poor control of slag chemistry and recovery of vanadium, operational instability due to kiln feed variability (degree of reduction), and a high burden conductivity (due to the high titania content of the ore), which limited the power input due to characteristic low resistance of the burden, as some of the operational challenges associated with submerged-arc smelting. A process to convert four of the eight furnaces from submerged-arc to open-arc started in 2004 and was completed in 2010, thereby eliminating the dependence of the power input on the burden and slag composition. Operational and process improvements included improved vanadium recovery, lower electrode
consumption, improved reductant utilisation and ability to process more fines. The slag compositions, before and after the conversion of the furnaces, are compared in Table 4. Of interest is the change in the titania content. In open-arc mode, the smelting recipe was optimised for metallurgical benefits, as opposed to electrical properties of the burden. The resulting slag from the open-arc operation is an outcome of lower flux additions, and would naturally result in improved recovery and lower energy consumption per ton of metal, as reported by Steinberg et al. (2011).

Due to the highly conductive nature of high-titania slags, an open-arc operation is the preferred embodiment; evidenced by the earliest of ilmenite smelters. Open-arc operation requires that the power-to-feed balance control is managed well as the buffer created by a burden is no longer available to absorb minor power or feed imbalances. The conversion to open-arc mode at Highveld Steel, required new roof designs, and the plant also had to modify control systems, operating practices and feed systems to adapt to the new mode of operation. The upgrades brought Highveld Steel closer to the benchmark for high-titania smelting practices, but while the improvements were dramatic, the investment fell short, with no further upgrades implemented before the demise in 2015.

It is somewhat perplexing why the change from submerged- to open-arc was only implemented nominally in the new millennium, especially in light of the fact that Highveld Steel’s only compatriot, New Zealand Steel and all ilmenite smelting operations, operated with an open-arc. Highveld Steel’s kilns were notoriously inefficient, and while this had been identified as an area that required investment, the investment never realised. An electric smelting process, such as the ironmaking furnaces at Highveld Steel, can only be competitive if the pretreatment is effective. This is required to offset the cost of electricity against the benefits of electric smelting. In the case of Highveld Steel, the combination of submerged-arc smelting and inefficient prereduction capacity, together with external factors such as commodity volatility, decline in demand and rising costs likely all contributed towards the closure.

In New Zealand titanomagnetite concentrate (referred to as ‘ironsand’) is processed to recover iron and vanadium at the New Zealand Steel Limited (New Zealand Steel) smelting complex. New Zealand Steel was incorporated in 1965 by the New Zealand Government and later became BHP New Zealand Steel Limited, but demerged from BHP in 2002 (Kelly, 1993; New Zealand Steel, 2018). The iron concentrate processed by New Zealand Steel is mined from the Waikato North Head site, south of Auckland, as well as from the Tahāroa deposit on the west coast of the North Island of New Zealand. The mined ores are subjected to fairly typical minerals concentration processes in order to improve the iron and vanadium grades through rejection of gangue. The gangue elements are mostly locked in the magnetite structure, as is typical for titanomagnetite deposits. Typical chemical composition of the concentrate (per Kelly, 1993), is presented in Table . New Zealand’s ironsand is lower in titanium than the South African and Chinese concentrates - the variation is typical of titanomagnetite mineralisation (Fischer, 1975; Pang et al., 2010).

The original New Zealand Steel plant consisted of a coal-based pre-reduction step linked to electric furnaces. Rotary kilns were designed to produce the direct reduced iron (DRI) by feeding coal together with the iron ore to a rotary kiln. The coal is gasified, and the iron ore is reduced. The
technology is known as the SL/RN (Stelco-Lurgi/Republic Steel-National Lead) process and is also well-known for being able to process a wide range of iron-bearing ores. The process generates significant amounts of residual gas. Notably, coal consumption is considerably higher than for a blast furnace, and the energy efficiency of individual plants depends on how efficient the residual gas is incorporated into the plant (Kelly, 1993). New Zealand Steel initially fed green unfired titanomagnetite pellets directly to the rotary kiln. It was found that the green pellets deteriorated in the kiln, resulting in excessive fines generation, and the waste gas handling system could not handle the excess dust, which limited the throughput of the reduction step. In 1972, the plant resorted to feeding iron concentrate directly (abandoning the pellets), but high waste gas volumes and velocities as a result of the combustion of volatiles from the coal continued to restrict throughput (Kelly, 1993; Richards and Davies, 1980). These challenges led to the development of multi-hearth furnaces as a pre-treatment step.

Currently, the New Zealand Steel flowsheet includes multi-hearth furnaces in which the primary concentrate, mixed with limestone (CaCO₃) and coal is processed first. The volatiles from the coal is used to generate heat in the multi-hearth furnaces. The concentrate is dried, preheated, and the coal is charred, before being fed to the kilns. The waste gas from the multi-hearth furnaces is used to generate electricity on the plant. The hot product from the multi-hearth furnaces, about 650°C, is fed to the rotary kilns to produce DRI, which is processed in electric furnaces. The furnaces were converted from the original three-electrode circular AC furnaces to rectangular furnaces. Vanadium rich slag is produced as a by-product of the ironmaking process. The design improvements implemented by New Zealand Steel in the 80s were substantial (New Zealand Steel, 2018; Taylor et al., 2005). New Zealand Steel’s efforts to optimise the pretreatment stages, resulted in process improvements that sustained the company in tough economic times.

8. The case for fluxless smelting of titaniferous magnetite

The slag produced from the blast furnaces at Panzhihua is added of slag dumps estimated by Chen et al. (2014a), to contain in excess of 70 million tons of slag. The Panzhihua slag dumps are located on the riverbanks of the Jinsha River, and apart from the fact that the resource is inefficiently processed, is a growing environmental concern. The sheer scale of production at the Panzhihua site is worth noting. According to Liu et al. (2008), Panzhihua produces more than three million tons of the blast furnace slag per annum. The slag dumps at Highveld Steel contain reportedly about 45 million tons of waste slag produced over about 50 years of operation (Avertana, 2017). Efforts continue to extract value from the dump, including the titanium for pigment production. The slags produced from titaniferous magnetite ores are often referred to as ‘steelmaking slag’, despite not being typical steelmaking slags. Millions of tons of low-grade titania-bearing slag are produced annually, adding to enormous stockpiles of discard slag already in existence around the world. These slag dumps will need to be reprocessed eventually, and many options have been considered to recover value from the low-grade slag. The proposed processes include variations of hydrometallurgical extraction, direct reduction (via fluidized beds, rotary kilns or rotary hearth furnaces) and electric smelting (Chen and Chu, 2014a, 2014b; Fu and
Xie, 2011; Hu et al., 2013). The processes usually suffer from low-recovery, high input cost and process complexity as a result of the grade of the slag. While there are ongoing efforts to extract the value from the stockpiled slag dumps, there is currently no commercial implementation. It is technical feasible to extract titania from low-grade sources, the challenge is that the gangue components contribute towards the scale, the complexity and costs of the process. Slag with higher titania content is favoured, and as such, slag from titaniferous magnetite via fluxless smelting could be ideal feedstock for the numerous slag upgrading processes that are proposed. A more efficient smelting process would also improve the overall utilisation of the titaniferous magnetite, as higher iron, and vanadium recoveries can be achieved in an open-bath operation. Stanaway (1994a, 1994b) reviewed the properties of titanium dioxide feedstocks in the context of minor elements and the impact on the production of pigment. It provides a useful reference to assess the criteria applied to furnace slags in the context of pigment production. It appears feasible that slags from titanomagnetite with lower iron per ton of slag if compared to ilmenite slags, and the absence of radioactive elements, could offer possible process benefits for pigment producers which could offset the lower grade.

There is likely significant scope to upgrade the concentrate (TiO₂ grade), if ironmaking is not the primary objective. Table 6 presents a summary of the relevant smelting processes and contextualise the opportunity for vanadiferous titanomagnetite as it relates to ilmenite smelting and ironmaking.

### Table 2
Delineation of the smelting processes for iron, titaniferous magnetite and ilmenite

<table>
<thead>
<tr>
<th>Primary Industry</th>
<th>Ironmaking</th>
<th>Titania slag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock</td>
<td>Iron</td>
<td>Ilmenite</td>
</tr>
<tr>
<td>Smelting process</td>
<td>Blast furnace</td>
<td>Electric furnace</td>
</tr>
<tr>
<td></td>
<td>Fluxed</td>
<td>(open-arc) DC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluxless</td>
</tr>
<tr>
<td>Primary product</td>
<td>Iron</td>
<td>Titania slag</td>
</tr>
<tr>
<td></td>
<td>Iron &amp; vanadium</td>
<td>iron &amp; vanadium</td>
</tr>
<tr>
<td>By-product</td>
<td>Ironmaking slags</td>
<td>Diluted titania slags</td>
</tr>
<tr>
<td>Users</td>
<td>Global</td>
<td>China, Russia, New Zealand, South Africa</td>
</tr>
</tbody>
</table>

9. Conclusion

Titaniferous magnetite ore is currently predominantly treated as complex iron ore, resulting in the creation of titania-bearing, low-grade slag dumps. Reprocessing of the diluted, low-grade slags, has proven to be challenging with minimal economic incentive due to the complex and low-grade nature of the slags.

The exploitation of titanomagnetite is of interest as these deposits represent a significant proportion of known global resources of vanadium, iron and titanium. The association of iron with

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titanium, however, restricts processing options, especially if the primary objective is ironmaking. In order to achieve the goal of comprehensive processing, processing practices would have to change to process the ore with a different agenda or primary directive to facilitate unlocking of titanium.

Fluxless smelting of titaniferous materials is technically feasible, regardless of the grade of the feedstock. Current ilmenite smelting practices serves as a reference point in this regard. There is an opportunity to process titaniferous magnetite to produce a titania-rich slag, but high-grade titania materials are readily available. The slag from a titaniferous magnetite feedstock would have to offer additional benefits to pigment producers to be competitive or desirable. As with ilmenite smelting, a good quality iron product can be co-produced during smelting, while recovering vanadium as a by-product from the ironmaking process.

The unfortunate demise of Highveld Steel in South Africa offers an opportunity to reflect on the most appropriate technology for the future, namely a process that comprehensively extract iron, vanadium and titanium. Fluxless smelting of the titaniferous magnetite in a DC furnace to produce a high-grade titania slag is proposed as a technology solution for the Bushveld Complex, known for high titania content as it creates an opportunity to economically extract the full value of the ore.

The review of titaniferous smelting processes identifies that practices used by ilmenite smelters, concentrate beneficiation, pretreatment and smelting, can be adapted to titaniferous magnetite to unlock the potential of these deposits. Notwithstanding the challenges, such as the complex and widely varied mineralisation fluxless smelting offers a step-change opportunity towards comprehensive processing of these deposits. The continued successful operation of ilmenite smelters worldwide and specifically in South Africa, indicate that there is an opportunity to categorise titaniferous magnetite as a primary source of titanium, rather than as iron ore. Historically, these ores have been categorised as difficult iron ores, but changing this perspective could lead to sustainable unlocking of this complex resource, instead of creating growing environmental legacies.

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