Abstract—Chrome ores from six locations across the Bushveld Igneous Complex in South Africa are used to investigate the effects of ore types on the smelting processes, such as the consumption of fluxes, reductant; and most importantly, the consumption of electricity.

The electric energy consumption is highly related to the SiO$_2$ content of chrome ores. The lowest electric consumption of 3.31 MWh/t is required when the SiO$_2$% of chrome ores is 6%. Considering the fact that the other contents do not change much in the selected 6 lumpy ores, an increase of SiO2 will decrease the contents of Cr and Fe oxides in the ores. As a result, it requires more ore and less quartzite to feed in the furnace. With the combined effect of more ores and less quartzite, the smelting process produces more slag and requires more electric energy to heat and melt the slag.

Keywords—Ferrochrome production, ferroalloy process optimization, chrome ore

I. INTRODUCTION

HIGH carbon ferrochrome (HCFeCr) is produced by carbothermic reduction of chrome ore. Electric power is generally used to supply the energy required to carry out the heating, melting and reduction reactions. The production process is energy intensive, and consumes approximately 3,300-3,800 kWh per ton of metal produced. The cost of electricity counts for about 35-40% of total production cost. Due to the shortage of power supply in South Africa, the cost of electricity has more than doubled since 2008, and a plan has been tabled to increase the electricity price by 16% every year from 2013 to 2018. South Africa, with 80% of world chrome reserves, is one of the major producers of ferrochrome, and its production accounts for about 34% of the total production in the world.

With a sharp increase in electricity cost, all ferrochrome producers in South Africa are looking for any alternatives that can use less electricity. An investigation of the effect of various chrome ores on the electric energy consumption is one of the alternatives. The selected chrome lumpy ores contains mainly Cr$_2$O$_3$, FeO, SiO$_2$, MgO, Al$_2$O$_3$, and small amount of CaO. The contents of MgO, Al$_2$O$_3$ and CaO have small changes in the selected chrome ores, particularly CaO with a range of only 1-2%. The major changes of the chrome ores appear in the contents of SiO$_2$, Cr$_2$O$_3$ and FeO.

Chrome ores produced in South Africa are mainly from the mines that operate in the Bushveld Igneous Complex. The Bushveld Complex contains a series of overlapping funnel shaped intrusions oriented from Doornvlei of North West Province to Steelpoort of Mpumalanga Province [1], covering an area of 180,000 km$^2$, see Fig. 1.

Most ferrochrome producers have its own mining and smelting operations and are located near the Bushveld Complex, in Rustenburg, Brits, Witbank, Lydensberg, and Steelpoort. Those producers include Xstrata, Samancorcr, Hernic, SAS Metals, Assmang Chrome, Mogale Alloys.

II. SOUTH AFRICA CHROME ORES

Chrome ores are selected from the following mining locations, which are located along the Bushveld Igneous Complex:

- Elandsdrift
- Millsell
- Mooinooi
- Tweefontein
- Lannex
- Steelpoort

The upper group two (UG2) concentrate from a platinum group metal (PGM) mine in Rustenburg is also selected. Each mine produces 3 grades of chrome ore, namely lumps, chips, and concentrates. The lumps and chips of chrome ores are used as raw material and are directly fed in submerged arc furnace, while the concentrates of chrome ore must undergo agglomerating treatment, such as sintering or pelletizing. Due
to the advantages of DC furnace process, chrome concentrates are fed in DC furnace directly without any agglomerating treatment. Considering the feature of chrome ore usage, the effect of concentrate ores on the production of ferrochrome will be conducted separately. From Table I, it is noticed that the difference in chemical composition between the lumpy ores and chip ores is limited, to such extent that it is worth to focus on lumpy ores only in the current phase of the investigation.

### TABLE I
CHEMICAL COMPOSITION OF CHROME LUMPY ORES PRODUCED IN SOUTH AFRICA (WT %)

<table>
<thead>
<tr>
<th>Chrome ores</th>
<th>Cr₂O₃</th>
<th>MgO</th>
<th>FeO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elandsdrift Lumps</td>
<td>39.59</td>
<td>10.49</td>
<td>23.51</td>
<td>7.9</td>
<td>14.24</td>
<td>1.13</td>
<td>3</td>
</tr>
<tr>
<td>Elandsdrift Chips</td>
<td>38.35</td>
<td>10.96</td>
<td>22.92</td>
<td>9.43</td>
<td>14.11</td>
<td>1.72</td>
<td>3</td>
</tr>
<tr>
<td>Millsell Lumpy</td>
<td>38.26</td>
<td>12.25</td>
<td>22.67</td>
<td>11.33</td>
<td>13.11</td>
<td>1.12</td>
<td>3</td>
</tr>
<tr>
<td>Millsell Chips</td>
<td>37.23</td>
<td>12.84</td>
<td>22.11</td>
<td>11.47</td>
<td>13.26</td>
<td>0.84</td>
<td>3</td>
</tr>
<tr>
<td>Mooiinooi Lumps</td>
<td>39.51</td>
<td>10.65</td>
<td>23.45</td>
<td>8.32</td>
<td>14.49</td>
<td>1.08</td>
<td>3</td>
</tr>
<tr>
<td>Mooiinooi Chips</td>
<td>39.61</td>
<td>10.77</td>
<td>23.54</td>
<td>8.16</td>
<td>13.86</td>
<td>1.04</td>
<td>3</td>
</tr>
<tr>
<td>Tweefontein Lumps</td>
<td>37.6</td>
<td>13.9</td>
<td>19.5</td>
<td>19.3</td>
<td>12.1</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>Tweefontein Chips</td>
<td>30</td>
<td>11.7</td>
<td>22.2</td>
<td>10.1</td>
<td>13.7</td>
<td>0.83</td>
<td>3</td>
</tr>
<tr>
<td>Lannex Lumps</td>
<td>40.9</td>
<td>10.9</td>
<td>23.9</td>
<td>5.8</td>
<td>14.3</td>
<td>0.74</td>
<td>3</td>
</tr>
<tr>
<td>Lannex Chips</td>
<td>37.5</td>
<td>12.2</td>
<td>22.6</td>
<td>9.5</td>
<td>13.4</td>
<td>0.9</td>
<td>3</td>
</tr>
<tr>
<td>Steelpoort Lumps</td>
<td>42.9</td>
<td>11.8</td>
<td>23.7</td>
<td>3.7</td>
<td>13.8</td>
<td>0.69</td>
<td>3</td>
</tr>
<tr>
<td>Steelpoort Chips</td>
<td>29.2</td>
<td>17.1</td>
<td>18.4</td>
<td>19.9</td>
<td>10.2</td>
<td>1.9</td>
<td>3</td>
</tr>
</tbody>
</table>

## III. SIMULATION OF HCFE₇CR PRODUCTION

An excel-based simulation, called Ferroalloy Simulation (Ferro-Sim), was used to evaluate the effect of different chrome ores on the electricity consumption used to produce high carbon ferrochrome (HCFeCr) in submerged arc furnace (SAF), which uses electric energy and is fed with raw materials of chrome ores, fluxes, reductant and electrode paste. The Ferrochrome Simulation is developed using the principles of mass balance and heat balance, the interface can be seen in Fig. 2. The simulation requires three inputs and generates the results of charge recipe, mass and composition for slag, metal, and off gas, with the energy consumption associated with the production process.

**Ferroalloy Simulation Inputs:**
- Chemical composition of chrome ores (%)
- Chemical composition of reductant (%)
  - Coke
  - Anthracite
  - Coal
- Chemical composition of fluxes (%)
  - Quartzite
  - Lime
  - Dolomite

**Ferroalloy Simulation Outputs:**
- Charge recipe (chrome ore/fluxes/reductant)
- Mass and composition of slag
- Mass and composition of metal
- Mass and composition of off gas (with or without CO combustion)
- Electric energy consumption
- Recovery rate of Cr, Fe

Fig. 2 Ferroalloy simulation used to calculate charge and electricity consumption of ferrochrome production in a submerged arc furnace

Lumpy chrome ores from six different locations of the Bushveld Igneous Complex are used. Quartzite is added as flux, and coke is used as reductant. The chemical composition of quartzite and coke are listed in Table II. Based on the production of ferrochrome in South Africa, the following conditions are used as major smelting parameters:
- 6% FeO in slag
- 12% Cr₂O₃ in slag
- 45% SiO₂ in the 3-component slag of SiO₂-MgO-Al₂O₃
- 8% carbon in metal
- 4% silicon in metal
- Slag temperature 1700 °C
- Metal temperature 1600 °C
## Table II

<table>
<thead>
<tr>
<th>Name</th>
<th>Coke Nuts (Newcastle)</th>
<th>Delmas Quartzite (Chert lumpy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Carbon</td>
<td>76.07</td>
<td>0</td>
</tr>
<tr>
<td>H₂O</td>
<td>6.63</td>
<td>0</td>
</tr>
<tr>
<td>S</td>
<td>0.59</td>
<td>0</td>
</tr>
<tr>
<td>FeO</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td>SiO₂</td>
<td>10.5</td>
<td>98.4</td>
</tr>
<tr>
<td>CaO</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>MgO</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### IV. RESULT AND DISCUSSION

#### A. Smelting Parameters

The main parameters, used to produce high carbon ferrochrome in a submerged arc furnace, are selected and listed in Table III, including raw material consumption, energy consumption, mass of metal, slag and offgas. They are expressed in terms of kilogram per ton of produced metal (kg/t):

- Ore consumption, ore-kg/t
- Flux, quartzite consumption, quartzite-kg/t
- Reductant, coke consumption, coke-kg/t
- Electric energy consumption, MWh/t
- Metal produced, t
- Slag produced, slag-kg/t
- Offgas produced, offgas-kg/t

#### B. Composition of SA Chrome Lumpy Ores

The selected chrome lumpy ores contains mainly Cr₂O₃, FeO, SiO₂, MgO, Al₂O₃ and small amount of CaO. The range of chemical composition is 29-43% of Cr₂O₃, 20-24% of FeO, 4-20% of SiO₂, 11-17% of MgO, 10-14% of Al₂O₃, 1-2% of CaO, see in Fig. 3.

#### C. Raw Material Consumption

The consumption of ores, flux quartzite, reductant coke, and the produced mass of slag and CO gas are shown in Fig. 5, with left axis in terms of kg per ton of metal (kg/t). The electric energy consumption is also shown the same figure with right axis in mega watt hour per ton of metal (MWh/t).

When producing one ton of high carbon ferrochrome in SAF, the Tweefontein lump ore has the highest ore consumption at 3200 kg/t, 22% and more than 30% higher than the consumption of Millsell and other ores. At the same time, the Tweefontein lump ore requires the lowest quartzite consumption at 160 kg/t. It is 205%-225% lower than the quartzite consumption comparing the ores of Millsell, Elandsdrift, and Moooinooi, and it is 277%-251% lower when comparing the ore of Steelpoort and Tweefontein ore.

### Table III

<table>
<thead>
<tr>
<th>ore names</th>
<th>ore kg/t</th>
<th>quartzite kg/t</th>
<th>coke kg/t</th>
<th>slag kg/t</th>
<th>CO kg/t</th>
<th>MWh/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelpoort</td>
<td>2202.02</td>
<td>455.73</td>
<td>490.86</td>
<td>1350.10</td>
<td>684.61</td>
<td>3.33</td>
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<tr>
<td>Lannex</td>
<td>2265.62</td>
<td>413.24</td>
<td>488.43</td>
<td>1369.81</td>
<td>680.29</td>
<td>3.31</td>
</tr>
<tr>
<td>Elandsdrift</td>
<td>2338.73</td>
<td>371.27</td>
<td>486.67</td>
<td>1405.82</td>
<td>678.95</td>
<td>3.32</td>
</tr>
<tr>
<td>Moooinooi</td>
<td>2339.57</td>
<td>372.90</td>
<td>487.49</td>
<td>1423.85</td>
<td>678.63</td>
<td>3.33</td>
</tr>
<tr>
<td>Millsell</td>
<td>2460.79</td>
<td>338.00</td>
<td>489.06</td>
<td>1563.55</td>
<td>679.01</td>
<td>3.41</td>
</tr>
<tr>
<td>Tweefontein</td>
<td>3196.63</td>
<td>164.69</td>
<td>483.11</td>
<td>2017.23</td>
<td>670.50</td>
<td>3.63</td>
</tr>
</tbody>
</table>

Fig. 3 Chemical Composition of Chrome Lumpy Ores of South Africa, with main contents of Cr₂O₃, FeO, SiO₂, MgO, Al₂O₃, and 1-2% of CaO.

Fig. 4 Chemical composition of chrome lumpy ores, with increase of SiO₂% and decrease of Cr and Fe oxides from Steelpoort ore to Tweefontein ore.
Fig. 5 Raw material consumption, when producing one ton of high carbon ferrochrome using different chrome lumpy ores of South Africa, with left axis for kg/t, and right axis for MWh/t

With the combination of high ore consumption and low quartzite consumptions when using lump ore from Tweefontein, the production process generates the most slag, about 2000 kg/t. It is 22% more than that of Millsell ore, and 29-33% more than the others.

D. Electric Energy Consumption

The electric energy consumption ranges from 3.31 to 3.63 MWh per ton metal produced (MWh/t), when using the selected 6 different chrome lumpy ores. Tweefontein lumpy chrome ore requires the highest electric energy, with amount 3.63 MWh/t, as shown in Fig. 7. Millsell lumpy ore requires the second highest energy at 3.41 MWh/t, and the rest of 4 chrome ores consumes similar amount electric energy from 3.31 to 3.33 MWh/t.

The total consumption of electric energy can be broken into 3 different categories, namely heating, reduction of oxides, forming molten slag and metal, considering the cooling of the off gas from reduction temperature 1700 °C to the roof temperature 800 °C before exiting the submerged arc furnace.

Among the three categories, heating and reduction require the most electric energy, about 97% of the total electric energy. The energy used for heating and reduction counts for 52% and 45% respectively. Only about 3% of the electric energy is used to forming molten slag and metal, see Fig. 8.

The electric energy consumption is highly related to the SiO2 content of chrome ores, ranging from 4 to 20%. The lowest electric consumption of 3.31 MWh is required to produce one ton of high carbon ferrochrome, when the SiO2% of chrome ore is about 6%. When the SiO2 content increases from 6% to 19%, the electric energy consumption increases from 3.31 to 3.63 MWh/t, see in Fig. 9. Furthermore, based on the limited data, it seems that the energy consumption increases from 3.31 to 3.33 MWh/t, when SiO2 content decreases from 6% to 4%. The electric energy consumption with the SiO2 content in the selected six chrome lumpy ores can be seen in Fig. 10.
The chemical composition of ores is one of the main factors that result in different consumption of electric energy. Less amount of quartzite is required when a chrome ore has higher SiO$_2$, and more ore is required when the ore contains less Cr and Fe oxides.

With the combination of higher SiO$_2$ and lower contents of Cr$_2$O$_3$ and FeO, more tonnage of ore and less tonnage of quartzite are needed to feed into the submerged arc furnace. The net combined effect results in a higher slag mass, and consequently a higher electric energy required to heat and melt the slag, see Fig. 11. The similar results have been reported in various investigation [2-6].

Electric consumption of 3300-3400 kWh is reported [2] to produce one ton of high carbon ferrochrome using submerged arc furnace in India. The raw materials include chrome ore with 50% of Cr$_2$O$_3$, quartzite of 98% SiO$_2$, and coke with 80% fixed carbon.

Another investigation reported that the electric energy consumption is highly liked to the content of Cr$_2$O$_3$ of the Iranian chrome ores [3]. When the Cr$_2$O$_3$ content is between 43 to 46%, the production can achieve 95% Cr recovery with the lowest consumption of electric energy. Their investigation was based on actual experiences obtained from Fayab Ferroalloy Plant over a period of three years. Other similar investigations have been conducted on the effects of chrome ores on the production of ferrochrome [4-6].