Wear analysis of a tap-hole from a SiMn production furnace

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In April of 2013 a 48 MVA submerged arc furnace producing silicomanganese was excavated in South Africa. One of the areas excavated systematically was the furnace tap-hole. The aim was to obtain a refractory wear profile of the tap-hole area, together with affected hearth and sidewall refractory. Subsequently, thermodynamic modelling was applied to quantify the potential for chemical reaction between refractory and slag and refractory and metal in the tap-hole area.

Keywords: Excavation, dig-out, post mortem, submerged arc furnace, silicomanganese, refractory, tap-hole

Introduction

Silicomanganese (SiMn) is an alloy used to add both Si and Mn to steel at low carbon contents. SiMn is produced in three-phase, alternating current (AC), submerged arc furnaces (SAFs) by carbothermic reduction of oxide raw materials. In a SAF the electrode tips are submerged in a porous charge mix, and electrical energy is liberated by micro-arcing to a slag-rich coke bed floating on top of a molten metal bath (Olsen and Tangstad, 2004; Matyas et al., 1993). Typical SAFs producing SiMn are rated at 15–40 MVA and produce 80–220 t of metal per day (Olsen and Tangstad, 2004). The furnaces are circular, with an external diameter of 11.6 m and height of 6.2 m being typical of a 40 MVA furnace (Brun, 1982).

In the duplex process for SiMn production, slag from high-carbon ferromanganese (HCFeMn) production is the primary source of manganese (Olsen, Tangstad, and Lindstad, 2007). In South Africa the discard route is applied in HCFeMn production, where the slag is discarded onto slag dumps. Manganese ores in the form of lump, sinter, and briquettes are therefore the primary source of manganese in SiMn production (Gous et al., 2014). In the duplex route the slag-to-metal ratio is typically 1.2 and tapping temperature 1600°C (Olsen, Tangstad, and Lindstad, 2007). In South Africa the slag-to-metal ratio is typically 0.8 (Gous et al., 2014).

Gous et al. (2014) reported on the methodology followed and main observations made when excavating a 48 MVA SiMn furnace in South Africa in April 2013. The paper presented here reports on the tap-hole wear profile in more detail, as well as on a thermodynamic study conducted to understand the potential for chemical reaction as a wear mechanism in the tap-hole area.

Background

Refractory design

The SAF under investigation was of circular design with an open roof and outer diameter of 12 m. The refractory design is indicated in Figure 1 and composition of refractory materials of interest in Table I.

In the hearth, fireclay was cast onto the steel shell to level the floor. Five layers of super-duty fireclay bricks were installed as back lining with high-grade carbon ramming as working lining. In the lower sidewall, a single layer of super-duty fireclay bricks was installed as back lining with high-grade carbon ramming as working lining. As safety lining, a low-grade carbon ramming was rammed between the steel shell and the back lining. In the upper sidewall, the lining design was similar to the lower sidewall but with the super-duty fireclay brick layer forming both the working lining and the back lining i.e. no high-grade carbon ramming installed. The two single-level tap-holes were built with SiC bricks supported by super-duty fireclay bricks.

The original lining was installed in April 2003. In September 2007 the refractory was partially demolished and rebuilt, including the tap-holes. Tap-hole A was partially repaired in March 2012 (the front two rows of SiC carbide bricks were replaced) but no repairs were done on tap-hole B. Finally, the complete lining was demolished and rebuilt.
in April 2013. During the excavation, tap-hole B was studied in detail. Since the partial reline in September 2007, 7520 taps had been made through tap-hole A and 1880 through tap-hole B.

![Diagram of furnace tapping](image)

**Figure 1. SiMn lining design – drawing to scale**

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw materials</th>
<th>Thermal conductivity</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon ramming – high grade</td>
<td>Carbon</td>
<td>11.0 W/mK at 1000°C</td>
<td>Al₂O₃ 1-5%</td>
</tr>
<tr>
<td>SiC – brick (nitride bonded)</td>
<td>Silicon carbide</td>
<td>15-20 W/mK at 1200°C</td>
<td>SiC 75</td>
</tr>
</tbody>
</table>

**Tapping practice**

Slag and metal were tapped simultaneously through the same, single-level tap-hole. The furnace was tapped every three hours, and tapping duration varied between 30 and 45 minutes. The tapping temperatures, as measured at the tap-hole, varied between 1420 and 1520°C. Operational practices included the sampling of slag and metal at each tap. The slag sample was taken with an oxygen lance in the launder and the metal sample in the metal ladle with a ‘lollipop–sample dipstick’. Slag and metal compositions were determined by powdered X-ray fluorescence spectrometry (XRF). The carbon content of metal samples was determined by LECO. For the purpose of the second part of the study, the chemical compositions of slag and metal were normalized per tap for the six-component slag system (MnO, SiO₂, MgO, CaO, FeO, and Al₂O₃) and four-component metal system (Mn, C, Si, and Fe). The average and standard deviation of the normalized results were calculated over a 4-month period (November 2012 to February 2013) and are reported in Table II and Table III. To correct the slag composition for entrained metal, it was assumed that all FeO in the slag was associated with entrained metal droplets with average composition in Table III. Mass balance calculations were conducted to correct the slag composition for FeO, SiO₂ and MnO also reported in Table II.
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Table II. Average and standard deviation of as-received slag analyses and slag composition (percentage by mass) corrected for metal inclusions

<table>
<thead>
<tr>
<th></th>
<th>MnO</th>
<th>SiO₂</th>
<th>MgO</th>
<th>CaO</th>
<th>FeO</th>
<th>Al₂O₃</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (as-received)</td>
<td>13.3</td>
<td>46.0</td>
<td>6.0</td>
<td>25.3</td>
<td>0.5</td>
<td>5.9</td>
<td>97.0</td>
</tr>
<tr>
<td>Average (normalized)</td>
<td>13.7</td>
<td>47.4</td>
<td>6.2</td>
<td>26.1</td>
<td>0.5</td>
<td>6.1</td>
<td>100.0</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.8</td>
<td>0.8</td>
<td>0.4</td>
<td>1.0</td>
<td>0.3</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>Corrected</td>
<td>11.9</td>
<td>48.3</td>
<td>6.4</td>
<td>27.1</td>
<td>0.0</td>
<td>6.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table III. As-received metal composition (percentage by mass)

<table>
<thead>
<tr>
<th></th>
<th>Mn</th>
<th>C</th>
<th>Si</th>
<th>Fe</th>
<th>Total</th>
<th>Mn:Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (as-received)</td>
<td>66.2</td>
<td>1.8</td>
<td>17.0</td>
<td>14.8</td>
<td>99.8</td>
<td></td>
</tr>
<tr>
<td>Average (normalized)</td>
<td>66.3</td>
<td>1.8</td>
<td>17.1</td>
<td>14.8</td>
<td>100.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.5</td>
<td>0.2</td>
<td>0.8</td>
<td>0.6</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Thermodynamic modelling approach

The Equilibrium model in FACTSage 6.4 was applied (Bale et al., 2012) in the thermodynamic modelling. Depending on the type of calculation the FToxid and/or FSstel and FACTPS databases were selected. Default gas, liquids, and solids were selected as pure species, and duplicates were suppressed with the order of preference being FToxid, FSstel, FACTPS databases. The results obtained were plotted as equilibrium phase distributions, phase chemical compositions, and element balances as functions of temperature.

In all calculations the temperature range was 1500–1700°C at 25°C intervals and at 1 atmosphere pressure, although the ambient pressure at the plant is typically 0.85 atmosphere (Anon., 2014). The temperature range was selected based on the following:

- The process temperature required for the production of SiMn with 17.0% Si in equilibrium with slag with an activity of 0.2 (typical of SiMn production) is calculated as 1600°C (Olsen, Tangstad, and Lindstad, 2007)
- Actual tapping temperatures measured at the plant ranged between 1420 and 1520°C. A difference of 50–100°C between tapping temperature and process temperature is typical of plant operations (Olsen, Tangstad, and Lindstad, 2007)
- The actual temperature experienced by the hot face refractories would therefore have been 1600°C or more
- A first indication of the effect of lancing on tap-hole wear was to be obtained (albeit not a detailed investigation).

Method

Tap-hole wear profile

For the macro-scale investigation, photographs were taken of the refractory in situ. Photographs were taken with a Canon EOS 30D camera installed on a tripod and triggered by remote trigger. The camera settings for aperture and shutter speed were adjusted manually based on the lightmeter readings on the camera. Lighting was provided by free-standing floodlights and no flash was used. The refractory thickness was measured with a tape measure and/or laser measurement device. The original design drawing was marked up with the measured wear profile.

Equilibrium phase composition of slag and of metal

To obtain a preliminary understanding of the system under investigation, the equilibrium phase distributions of both slag and the metal were calculated. The FToxid and FACTPS were selected for the slag, and for the metal the FSstel and FACTPS databases. The composition of the slag is given in Table II, and for the metal in Table III. Initial conditions were not specified. For the slag calculations only liquid slag (SLAGA) was selected as solution species and 0.00001 g of argon was added to allow for the calculation to converge. For the metal only liquid metal (LIQU) was selected as solution species.
Reaction of slag with refractory

The equilibrium phase distribution of the reaction products for the reaction of 100 g of slag with 100 g of refractory was calculated as a function of temperature. Although this simplification was made to obtain a balanced view of slag/refractory interactions, it is important to remember that considering the tap-hole specifically – but also furnace refractory material in general – the refractories are exposed to large volumes of process materials (slag, metal) that are continuously being replenished by fluid flow past the hot face, and due to new process material being continuously produced. This means that the effective ratio of process material to refractory material is usually very large, which has an effect on refractory consumption – see the discussion on refractory consumption that follows.

The compositions of the slag and initial conditions specified are stated in Table IV and Table V. The refractory was assumed to be 100% C or 100% SiC. As solution species, liquid slag (SLAGA) and liquid metal (LIQU) were selected.

Table IV. Material compositions and initial conditions applied in free energy minimization calculations where slag is reacted with either C- or SiC-based refractory material

<table>
<thead>
<tr>
<th>Composition [g]</th>
<th>Slag</th>
<th>Refractory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MnO</td>
<td>SiO₂</td>
</tr>
<tr>
<td>13.7</td>
<td>47.4</td>
<td>26.1</td>
</tr>
<tr>
<td>Database</td>
<td>FToxid</td>
<td>FToxid</td>
</tr>
<tr>
<td>Reference states</td>
<td>Liquid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Pressure [atm.]</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table V. Material compositions (slag corrected for entrained metal) and initial conditions applied in free energy minimization calculations where slag is reacted with either C- or SiC-based refractory material

<table>
<thead>
<tr>
<th>Composition [g]</th>
<th>Slag</th>
<th>Refractory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MnO</td>
<td>SiO₂</td>
</tr>
<tr>
<td>11.9</td>
<td>48.2</td>
<td>27.1</td>
</tr>
<tr>
<td>Database</td>
<td>FToxid</td>
<td>FToxid</td>
</tr>
<tr>
<td>Reference states</td>
<td>Liquid</td>
<td>Liquid</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Pressure [atm.]</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Reaction of metal with refractory

Then the equilibrium phase distribution of the reaction products for the reaction of 100 g of metal with 100 g of refractory was calculated as a function of temperature. The FSstel and FACTPS databases were selected. The composition of the metal and initial conditions applied are stated in Table VI. To study the effect of slag specifically, the refractory was assumed to be 100% C or 100% SiC. As solution species, liquid metal (LIQU) was selected.
Table VI. Material compositions and initial conditions applied in free energy minimization calculations where metal is reacted with either C- or SiC-based refractory material

<table>
<thead>
<tr>
<th>Composition [g]</th>
<th>Metal</th>
<th>Refractory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mn</td>
<td>C</td>
</tr>
<tr>
<td>66.3</td>
<td>1.8</td>
<td>17.1</td>
</tr>
<tr>
<td>Database</td>
<td>FSstel</td>
<td>FSstel</td>
</tr>
<tr>
<td>Reference states</td>
<td>Liquid</td>
<td>Solid</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Pressure [atm.]</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Refractory consumption

Finally, refractory consumption as a function of temperature was calculated. In the case of C-based refractory material, two sets of data were generated. In the one set it was assumed that SiC formed detached from the refractory, causing wear. In the other set it was assumed that SiC formed as an in-situ refractory material attached to the carbon, therefore protecting it (Lee and Moore, 1998).

Results and discussion

Tap-hole wear profile

In Figure 2 the dimensions of the worn lining are superimposed onto the refractory design drawing. The dimensions of the red-line drawing were obtained at the centre of the tap-hole in elevation. Included in the figure are three photographs highlighting aspects of the tap-hole area.

Wear of the tap-hole was extensive. More than 50% of the SiC brick was worn away with most of the wear occurring at the hot face (sidewall). In the SiC brick, wear was more extensive above the tap-hole than below.

Not only did the SiC brick wear, but also the carbon ramming above the SiC brick. A channel 500 mm wide formed all the way to the top of the carbon ramming. In plan view (not indicated), the wear pattern was in the form of a channel with fairly straight sidewalls rather than funnel-shaped as is typical of the wear pattern in open-bath furnaces. The channel depth is indicated on the redline drawing.

Below the tap-hole, not only did the SiC-brick wear, but also the carbon ramming paste in the hearth in front of the tap-hole.

Slag was present as a mixture of slag and coke bed and/or raw materials, depending on the level at which the sample was obtained. In the worn tap-hole, slag was present as a mixture of slag and carbon reductant (typical coke bed). Higher up in the channel, ore briquettes and quartz could also be distinguished. Metal was present in the tap-hole below the slag layer. Of interest were the remnants of the clay mushroom – formed when clay forced through the tap-hole spreads in a vertical direction when in contact with burden – to the hot face of the tap-hole but slag and metal channelled around it. According to clay manufacturers the clay mushroom should assist with tap-hole rebuilt, but this was not the case.

In the remainder of the paper the potential for chemical reaction as a wear mechanism is further investigated by calculating the potential for slag or metal to react with carbon- or SiC-based refractory materials. The effect of increased temperature caused by lancing was also investigated to some extent. The effect of lancing on slag composition and the effect of flow on tap-hole wear were not addressed.
Equilibrium phase distribution of slag

The predicted equilibrium phase composition, in both as-received slag not corrected for metal entrainment and slag corrected for metal entrainment as a function of temperature in the range 1500–1700°C, was 100% liquid.

Equilibrium phase distribution of metal

At temperatures below 1635°C the metal is saturated in SiC (see Figure 3). This is in agreement with the calculated carbon/SiC solubility for MnFeSiC alloys with a fixed Mn/Fe ratio of 5.1 (as opposed to 4.5 by mass for this system) at 1600°C (Olsen, Tangstad, and Lindstad, 2007).

Figure 3. Predicted (a) phase composition of as-received metal and (b) chemical composition of liquid metal phase as a function of temperature

Equilibrium phase distribution of slag reacted with refractory

Slag will react with both C- and SiC-based refractory material to form metal, gas, SiC (for C-based refractory material), and residual slag. The difference in phase composition of slag not corrected for metal entrainment and slag corrected for metal entrainment was insignificant. The remainder of the discussion will focus on slag corrected for metal entrainment only.
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Figure 4. Predicted phase composition of 100 g slag reacted with 100 g of (a) SiC-based and (b) C-based refractory material as a function of temperature. Solid lines represent the borders for phase composition calculated from the as-received slag analysis and dotted lines calculated from the analysis of the slag after reaction.

Figure 5. Predicted chemical composition of (a) slag, (b) metal, and (c) gas phases that form when reacting 100 g slag with 100 g of SiC-based (grey symbols) or C-based (black symbols) refractory material as a function of temperature. Only the species that partake in some form of reaction were selected.
For SiC-based refractory, metal formed even at 1500°C when in contact with slag (see Figure 4). At 1500°C metal formed due to the reduction of MnO by SiC and subsequent dissolution of SiC to increase the Si and C contents of the alloy. As the temperature increased the equilibrium MnO content of the slag reduced (see Figure 5).

An O-mole balance confirmed that no reduction of SiO₂ occurred at 1500°C to contribute Si in the alloy. As the temperature increased (Figure 6) the amount of metal formed increased and the effect of gas formation – not only CO as reduction product but also gaseous Mn and SiO to a lesser extent – became significant. The Si balance indicates that as temperature increased the Si reporting to the metal phase increased significantly, with only a small amount reporting to the gas phase.

At temperatures of 1550°C or less, a small amount of carbon precipitates as the metal is saturated in carbon at these temperatures. This is in agreement with the calculated carbon/SiC solubility for MnFeSiC alloys with a fixed Mn/Fe ratio of 5.1 (as opposed to 4.5 by mass for this system) at 1600°C (Olsen, Tangstad, and Lindstad, 2007). From 1575°C upwards the reporting of C to the gas phase as CO increases significantly.

Wear of the SiC in the refractory was therefore primarily due to reduction of MnO from the slag to produce SiMn and CO gas as by-product.

![Figure 6](image-url) Mass balances indicating the distribution of Mn, Si and C between the different equilibrium phases that form when slag reacted with SiC-based refractory

For C-based refractory, reaction with slag became significant only from 1575°C, when metal started to form. From 1600°C not only metal formed as reduction product, but also SiC. As the temperature increased the amounts of metal, SiC, and gas increased.

From a mass balance perspective the decrease in manganese reporting to the slag could initially be explained by metal formation only, but from 1600°C upwards the Mn reporting to gas also increased slightly. In the case of both metal and gas the Mn reporting to these phases increased as temperature increased. The decrease in Si content of the slag was initially due to the formation of metal at 1575°C. From 1600°C upwards Si reported to SiC also, with the increase in Si reporting to SiC with increase in temperature much more significant than the increase in Si reporting to metal. At 1675°C and higher, SiO gas formed, although the amount was insignificant.

Wear of the carbon in the refractory was therefore not only due to the formation of SiMn through the reduction of MnO and SiO₂ from the slag, but also to the production of SiC through reduction of SiO₂ in the slag forming CO gas as by-product.
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Figure 7. Mass balances indicating the distribution of Mn, Si, and C between the different equilibrium phases that form when slag reacted with C-based refractory

Equilibrium phase distribution of metal reacted with refractory

Both C- and SiC-based refractory material would react with metal from 1500°C, but wear will be significantly lower than reaction with slag.

Figure 8. Predicted phase composition of 100 g metal reacted with 100 g of (a) SiC-based and (b) C-based refractory material as a function of temperature
For SiC-based refractory at temperatures of 1550°C and below there was a net increase in the amount of SiC as SiC precipitated from the metal. From 1600°C upwards the solubility of SiC in the metal increased. From a mass balance perspective, the manganese distribution did not change as manganese reported only to metal. Both Si and carbon initially reported to SiC, and as the temperature increased, increasingly reported to metal.

For C-based refractory the formation of SiC – initially causing wear – decreased from 1550°C to disappear at 1700°C. From a mass balance perspective manganese distribution did not change as manganese reported only to metal. Both Si and carbon initially reported to SiC and increasingly reported to metal as the temperature increased.
Figure 11. Mass balances indicating the distribution of Mn, Si, and C between the different equilibrium phases that form when metal reacted with C-based refractory.

Refractory consumption

The potential for reaction between slag and SiC refractory and metal and C-based refractory exists at temperatures ranging between 1500 and 1575°C, but not for reaction between slag and carbon refractory and metal and SiC refractory.

At temperatures ranging between 1600°C and 1700°C the potential for reaction between metal and carbon refractory remains fairly constant, while the potential for reaction between metal and SiC becomes significant at higher temperatures. The potential for reaction between slag and SiC-based refractory increases significantly with an increase in temperature, and for reaction between slag and C-based refractory, extensively.

The consumption of C-based refractory by slag would be less significant in the case where SiC formed as an in-situ refractory material rather than a wear product. Experimental work done on similar systems indicated that SiC does form when industrial SiMn slag is exposed to C-based refractory material at 1600°C. First indications are that the SiC detached from the refractory rather than forming an in-situ refractory material (Mølnås, 2011; Steenamp et al., 2013).
Conclusions

- In the furnace excavated the tap-hole was one of two high refractory wear areas, the other being the furnace hearth.
- Not only did the SiC with which the tap-hole was built undergo wear, but also the carbon ramming paste in front of, above, and below the tap-hole.
- If refractory consumption of C-based refractory by metal is used as norm (6.3 kg refractory per ton of metal at 1600°C and 5.7 kg/ton at 1700°C), consumption of SiC-based refractory by metal is zero at 1600°C and is increased two-fold at 1700°C. Consumption of SiC-based refractory by slag is increased two-fold at 1600°C and six-fold at 1700°C. Consumption of C-based refractory by slag is increased eight-fold at 1600°C and 22-fold at 1700°C.
- Between SiC-based refractory and slag, wear is due to the reduction of MnO and SiO$_2$ in the slag to form Mn- and Si-containing metal and gas rich in CO also containing Mn and SiO. Further wear is caused by dissolution of SiC into the metal phase that forms. Between C-based refractory and slag, wear is further due to the formation of a SiC reaction product.
- Between both C-based and SiC-based refractory and metal, wear is due to the increased solubility of SiC in metal with increase in temperature.
- At temperatures of 1600°C, both SiC-based and C-based refractory will wear to some extent when in contact with slag.
- As lancing increases the tapping temperature, the potential for wear of the tap-hole refractory increases significantly, especially for C-based refractory in contact with slag. Further investigation into the effect of the lancing process on tap-hole wear would add significant value to the understanding of tap-hole wear.

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References


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**Joalet Dalene Steenkamp, PhD student (metallurgical engineering), University of Pretoria**

I worked in South African pyrometallurgical industry as process engineer from 1996 to 2009 and as senior lecturer in pyrometallurgy at the University of Pretoria from 2009 to 2012. My operational / pilot scale experience include secondary steelmaking at Iscor Pretoria Works and Saldanha Steel, ilmenite roasting and smelting at what is now referred to as Tronox KZN Sands and Richards Bay Minerals and production of high carbon ferromanganese at Exxaro’s Alloystream project. I have been working full-time towards my PhD since 2012 under supervision of Professors Chris Pistorius and Merete Tangstad. The title of PhD is: *Investigation into the chemical wear of carbon-based refractory materials in a SiMn furnace tap-hole*. It was during the early stages of the PhD project that I identified the need for a conference dedicated to the tapping of furnaces.