Control of open slag bath furnaces at Highveld Steel and Vanadium Ltd: development of operator guidance tables

W. S. Steinberg[1] and P. C. Pistorius*[2]

Several electric furnaces, which are used to melt down partially prereduced vanadiferous magnetite at Highveld Steel and Vanadium, have recently been converted from submerged arc furnaces (SAFs) to open slag bath furnaces (OSBFs). The self-regulating nature of SAFs is largely absent from the OSBFs, and hence the OSBFs rely more strongly on process control. As a first step towards implementing a process control system, a mass and energy balance was drawn up for the OSBFs, and this was used to develop operator guidance tables. The tables show the required changes in feed rate and power, to accommodate changes in prereduction, and to correct overcharged and undercharged furnace conditions. Implementation of the tables has contributed to improved process stability.

Keywords: Process control, Ironmaking, Electric furnace, Mass and energy balances, Vanadium

Introduction

The ironmaking process at Highveld Steel and Vanadium is described briefly in this section, as background to the description of the development of charging tables for operator guidance; more complete descriptions of the process[1,2] and the conversion to open slag bath furnaces (OSBF)[3] can be found in the literature.

Highveld Steel and Vanadium processes titaniferous magnetite from the Bushveld Complex of South Africa; the ore is rich in vanadium (the ore typically contains 12–15%TiO_2, 1·4–1·9% vanadium expressed as V_2O_5 and 53–57%Fe).[2] All of the raw materials are fed into SL/RN rotary kilns, where prereduction of the ore and calcination of the fluxes take place. The reductant is coal. The kiln feed typically consists of 63% ore, 28% coal and 9% dolomite. Air injection into the kiln, and combustion of pulverised coal, serve to maintain the temperature inside the kiln close 1140°C. The prereduced mixture (prereduction typically 45%) is transferred hot to the electric furnaces. At this plant, ironmaking was originally performed in submerged arc furnaces (SAFs),[4] but the SAF process has a number of technical challenges, including the following:[3]

- low vanadium yield
- low iron yield, mainly due to low iron temperature
- low productivity, due to low power inputs. This is a result of erratic carbon contents in the furnace feed, which affect electrical control of the SAF.

Converting the smelting furnaces from submerged arc operations to open slag bath operation served to overcome these challenges; conversion to open slag bath operation followed plant trials (completed in September 2003), and following this furnace 5 was commissioned as the first OSBF in December 2005. The second and third OSBFs were commissioned in early 2007 and 2008. Plant management view the OBSF technology to be the future for the production of iron from the titaniferous magnetite.[5]

In SAFs, the electrical resistivity of the burden strongly affects the furnace performance; if the resistivity of the material between the electrode tips and the furnace hearth changes, the electrodes must be move vertically to maintain a constant resistance. In contrast, in the OSBF the electrodes arc on top of the furnace contents and are not submerged in the burden; some of the advantages of this include the following:[3]

- the electrical resistance is not influenced by the properties of the mixture inside the furnace, but rather by the arc length
- fines can be melted, since burden permeability is not a limitation, unlike in the SAF
- in the OSBF the superheated slag melts the furnace feed, so helping to separate the slag and metal
- it is possible to control the slag composition inside the furnace by adding millscale or ore ('correction material').

A potential disadvantage of the open slag bath operation is the inherently higher radiative heat losses to the roof of the furnace, resulting in lower energy efficiency and possibly high roof refractory wear rates. From plant experience, the roof cooling system which was designed

[1]Highveld Steel and Vanadium Ltd, PO Box 111, Witbank 1035, South Africa
[2]Department of Materials Science and Metallurgical Engineering, University of Pretoria, South Africa (now at Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA)

*Correspondence author, email pistorius@cmu.edu
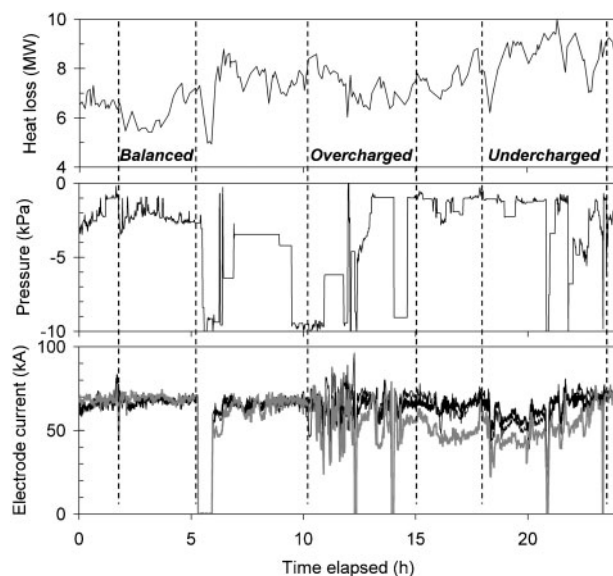
1 **Variations in heat loss, furnace gauge pressure, and current in each of three electrodes over time, illustrating periods of balance, overcharged and undercharged conditions**

for the OSBF successfully avoided excessive refractory wear, though.

For the work reported in this paper, a key difference between the SAF and the OSBF is the importance of the feed rate control. The SAF is a self-regulating furnace, with choke feed (so the contents of the furnace are automatically replenished). In contrast, the inventory of unmelted material is smaller in the OSBF, and the furnace control system must balance the feed rate with the melting rate, with a smaller buffer inside the furnace. In the OSBF, this unmelted inventory is present as banks of unreacted material between the electrodes and the furnace wall, so shielding the furnace wall from thermal radiation, and increasing the energy efficiency of the process.[3]

If the feeding rate to the furnace exceeds the rate at which material is melted, the resulting build-up of material leads to an 'overcharged' condition, where the banks approach the electrode tips, and interfere with electrical control. Conversely, if the feed rate is too low, the banks are melted away, leading to excessive heat losses to the furnace sidewalls ('undercharged' condition). The aim is to match the feed rate with the power input, to achieve a 'balanced' condition. Figure 1 shows examples of the effects of these types of behaviour on process signals, from a period of 24 h operation of one of the OSBFs. Figure 1 illustrates that in the balanced condition, the heat loss is relatively low, and the electrode currents stable. In the overcharged condition, the electrode currents are highly variable. In the undercharged condition, the heat loss is high. (In Fig. 1, the heat loss for the overcharged period is higher than that for the balanced period, which is unexpected; the likely reason for this was the excessive offgas suction rate during the overcharged period, as evident from the larger negative furnace pressure during the overcharged period.)

In this process, there are two main manipulated variables, namely the ratio of furnace power to feed rate, and the balance between reductant and feed. The latter
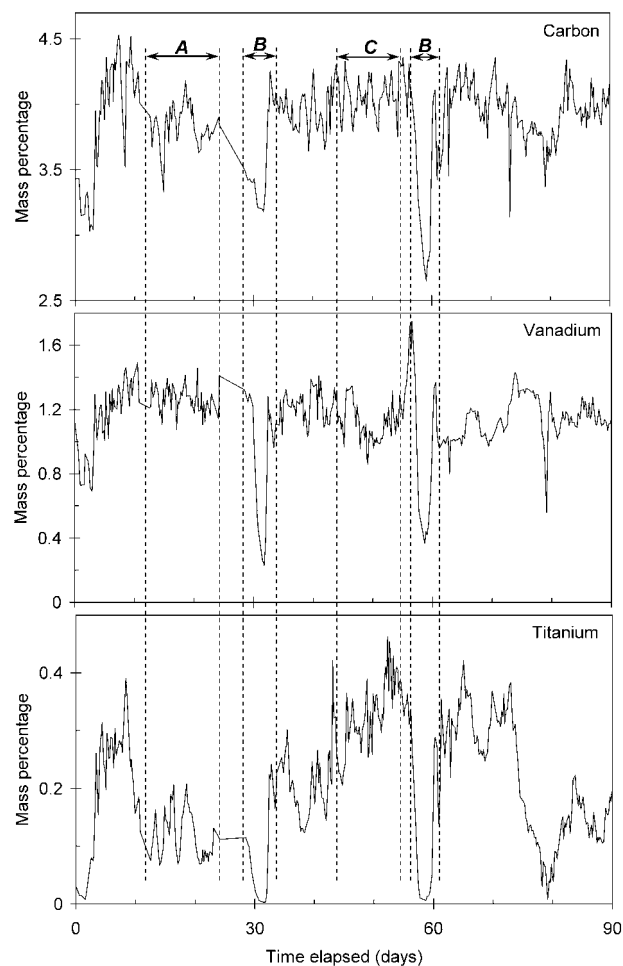
2 **Illustration of ways in which vanadium and titanium contents of iron product can vary in both coupled (B) and uncoupled (C) ways**

is adjusted in two ways – by changing the proportion of coal in the feed to the kilns (which takes several hours to affect the furnace), and by adding unreduced material (millscale or ore) into the furnace (which gives a much more immediate effect). Both the power/feed ratio and the reductant/feed ratio are important, but the work reported in this paper focused on the power/feed ratio as a first goal. Stabilising the power/feed ratio control was the first goal, because variations in vanadium recovery were observed which were clearly not related to the reductant input only. Such variations are illustrated by Fig. 2 (period C). When the carbon content of the furnace feed is insufficient (periods B in Fig. 2), both the titanium and vanadium contents drop, as would be expected, since both titanium and vanadium are reduced from the slag by carbon, to report to the iron. In Fig. 2, period A shows the desired behaviour, with a high vanadium content in the iron, and a low and fairly stable titanium content. A high vanadium content is desired, because vanadium is the main product of this plant; titanium in the metal only increases power consumption, and may cause some difficulties in steelmaking. Period C in Fig. 2 shows an increasing titanium content in the metal, while the vanadium content was somewhat low. It is thought that decoupling of titanium reduction and vanadium reduction is observed in period C because the interior of the furnace is not homogeneous, and the tapped metal reflects the combined effect of the different

Table 1   Empirical partitioning coefficients, giving ratios in which each element reports to metal, slag and dust

Element	Metal	Slag	Dust
Fe	0·93	0·05	0·02
Si	0·03	0·92	0·05
Ti	0·02	0·98	0·00
V	0·79	0·20	0·01
Cr	0·73	0·26	0·01
S	0·11	0·89	0·00
Ca	0·00	1·00	0·00
Mg	0·00	1·00	0·00
Al	0·00	1·00	0·00

extents of reaction within the furnace (indeed, unreacted feed material is sometimes observed in the tap stream). Maintaining the proper balance between feed rate and power will promote more homogeneous conditions inside the furnace, and was hence the first goal. Also, some procedures are already in place to compensate for variation in the degree of prereduction and carbon content of the furnace feed.

Process quantification

Mass balance

The approach in this project was to compile a mass and energy balance of the open slag bath process, and to summarise the results of the mass and energy balance in simple charging tables, for use by furnace operators to match the furnace power to the feed rate. The furnace mass balance was based on a separate mass balance for the prereduction kilns, and empirical partitioning coefficients. The partitioning coefficients give the relative amounts of each element reporting to the three condensed phase furnace output streams, namely metal, slag, and dust. The partitioning coefficients were based on plant experience, and are listed in Table 1.

A summarised mass balance, which results from the partitioning coefficients and the composition of the kiln product, is given in Table 2. The metallic iron content of the slag was based on plant experience and the amount of metal recovered by processing the solidified furnace slag.

The mass balance shows that the kiln discharge product is assumed to contain ~11%C. This number was tested by sampling the kiln discharge with a steel container (with a capacity of ~4 dm^3), which was covered with a lid and flushed with argon immediately after capturing the sample from the kiln discharge. After cooling, the carbonaceous portion of the material was

separated with a dense liquid (2000 kg m^{-3} density), and the float fraction analysed for total carbon content. Based on four such samples, the average carbon content of the kiln discharge was found to be 15·4 ± 3·5% (95% confidence interval), which is somewhat higher but similar to the carbon content estimated from the kiln mass balance.

Tables 1 and 2 show that a significant portion (2%) of the iron in the furnace feed reports to the slag, based on the empirical partitioning coefficients. The resulting calculated FeO content of the slag (2·8%) is much higher than it would be at equilibrium. This prediction was tested by taking spoon samples of the furnace slag from the slag tapping stream of two different OSBFs, and having these analysed for total iron content, and the distribution of iron between different valencies. The results in Table 3 show a significant FeO content in the slag, even higher than assumed in the mass balance, and quite different for the two samples. This significant and variable departure from equilibrium is in line with the proposed effect of inhomogeneous conditions inside the furnace, resulting in tapping of unreacted feed. For comparison, the equilibrium FeO content of the slag was estimated by using the FactSage 'SlagA' slag model, assuming equilibrium between carbon saturated iron, slag and CO (1 atm) at the iron tapping temperature of 1360°C; the calculated equilibrium content of FeO was 0·07%, much lower than the observed level. While the carbon content of the iron is generally slightly below saturation, the effect of this is far too small to account for the difference between the observed and equilibrium FeO levels.

Energy balance

Published values of the enthalpies of pure species were used in calculating the energy balance.[6] The heat of mixing of the slag was estimated using a published model.[7] FactSage can be used to calculate the slag enthalpy, but it is more convenient for plant control to have a spreadsheet based method available. The approach of Björkvall *et al.*[7] can be used to find the enthalpy of SiO$_2$–Al$_2$O$_3$–CaO–FeO–MgO–MnO slags with spreadsheet calculations, but this model does not include parameters for TiO$_2$ and Ti$_2$O$_3$. The approximation used was to calculate the enthalpy of the slag – but excluding TiO$_2$ and Ti$_2$O$_3$ – with the Björkvall approach, and then to assume that liquid TiO$_2$ and liquid Ti$_2$O$_3$ mix ideally with this mixture; the results of this method were compared with the FactSage predictions to test its validity. The enthalpies of the liquid titanium oxides were taken from the literature

Table 2   Summary of typical mass balance (basis: 1000 kg metal)

		FeO	Fe	TiO$_2$	SiO$_2$	CaO	MgO	Al$_2$O$_3$	V$_2$O$_3$	Cr$_2$O$_3$	C	S	Total
Kiln discharge	Mass, kg	1097	174	274	171	158	133	129	29	7	265	4	2446
	mass-%	44·8	7·1	11·2	7·0	6·5	5·5	5·3	1·2	0·3	10·8	0·2	
Slag	Mass, kg	66	27	269	157	158	133	129	6	2	0	3	952
	mass-%	6·9	2·8	28·2	16·5	16·6	14·0	13·6	0·6	0·2	0·0	0·4	
Dust	Mass, kg	26·4	0·0	0·0	8·5	0·0	0·0	0·0	0·3	0·1	5·3	0·0	41
	mass-%	65	0	0	21	0	0	0	1	0	13	0	

		Fe	C	V	Ti	Cr	Si	S						Total
Metal	Mass, kg	930·0	45·8	15·3	2·8	3·4	2·4	0·4						1000
	mass-%	93·0	4·6	1·5	0·3	0·3	0·2	0·04						

compilation[8] as also used within FactSage. In both cases – with this approximate procedure and with the FactSage approach – the slag composition was normalised as follows: Cr_2O_3 and sulphur were excluded; V_2O_5 (as reported in the plant analyses) was recalculated as V_2O_3, and the V_2O_3 was taken as Ti_2O_3 for the energy balance (this was necessary because the FactSage slag model does not include V_2O_3). From this comparison, the combined Björkvall-ideal-mixing approach gave values which were only slightly larger than the FactSage values, which confirmed the utility of this approach (the values were larger by 120–140 kJ per kg slag, compared with the typical slag enthalpy around 10 MJ kg^{-1}). It was also confirmed that the slag enthalpy is not a strong function of the trivalent titanium content of the slag. This was convenient: while the slag contains some $10\%Ti_2O_3$ (that is, some of the titanium reported as TiO_2 in Table 2 is in fact Ti_2O_3), the trivalent content of the slag is variable, and not readily determined by routine in plant chemical analysis.

For the energy balance, the temperatures as listed in Table 4 were assumed.

The heat loss from the furnace was calculated from the cooling water flow rates and temperature increases;

Table 3   Iron content of furnace slag (spoon samples), mass-%

Sample	Fe°	FeO	Fe$_2$O$_3$
Furnace 5	3·6	6·7	0·02
Furnace 6	1·1	11·2	0·01

Table 4   Temperatures assumed in energy balance

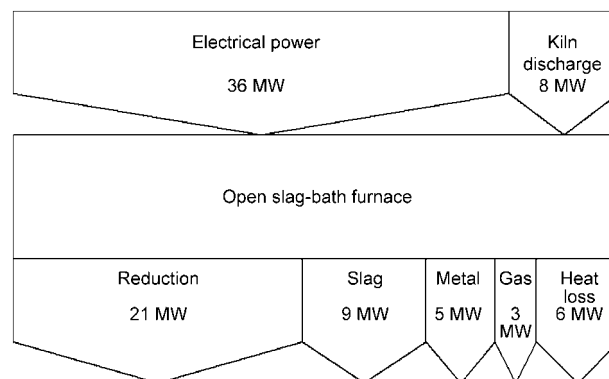| Stream	T, °C
Prereduced feed	550
Slag	1460
Metal	1360
Offgas	1000

Table 5   Operator guidance table: required change in feed rate, for changes in prereduction in furnace feed, and in addition rate of correction material

		Correction material, t h^{-1}	
		0	3
Prereduction, %	30	−4	−8
	40	0	−4

3 Energy balance for OSBF at feed rate of 48 t h^{-1}: heat flow rates assigned to different process streams (kiln discharge, slag, metal and gas) are their sensible and latent heats

this gave a typical heat loss of 6 MW, although as Fig. 1 illustrates, the actual heat loss is variable.
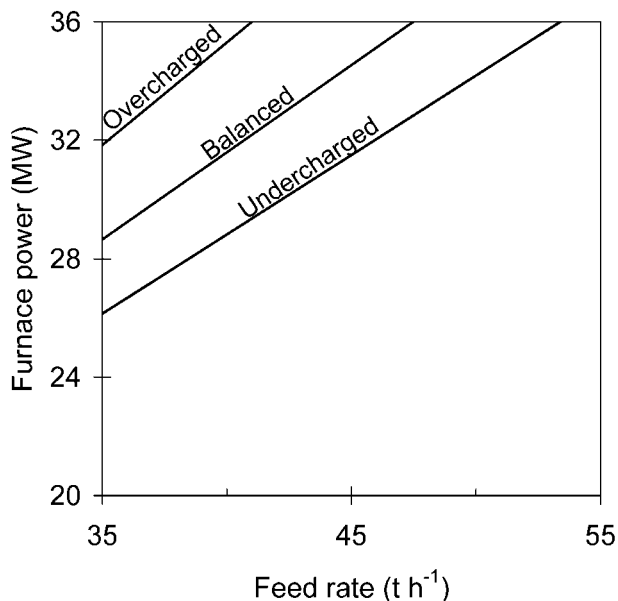
The furnace offgas analysis was used to calculate the amount of entrained air; online gas analyses are performed on samples taken after the gas is quenched in the venturi scrubber, analysing for H_2, O_2, CO, CO_2 and N_2.

For typical process conditions, the resulting energy balance is summarised in the Sankey diagram of Fig. 3.

Operator guidance tables

The results of the mass and energy balance were used to develop two operator guidance tables. The tables indicate the required changes in feed rate if the prereduction of kiln feed changes, and the required furnace power to recover from overcharged or undercharged conditions.

The degree of prereduction of the kiln product is variable, because of changes in kiln operational conditions. The degree of prereduction is found by chemical analysis, and millscale (or unreduced ore) is used as correction material in the furnace, to match the amount of unreduced material in the total furnace feed with the carbon content in the kiln product. Increased prereduction decreases the energy requirement in the furnace (hence increasing the allowable feed rate at constant power), whereas addition of correction material increases the energy requirement. These effects were quantified, and summarised in an operator guidance table, of which an extract is given in Table 5. The table gives the required change in feed rate relative to normal operation (expressed as a percentage change), for changes in prereduction and addition rate of correction material. The normal

Table 6   Comparison of average iron analysis before and after implementation of operator guidance tables: values shown are mass percentages; based on 516 samples before implementation, and 453 samples after

		C		V		Ti		Si	
		Before	After	Before	After	Before	After	Before	After
Average*	Furnace 5	3·97±0·02	3·76±0·03	1·17±0·01	1·18±0·02	0·20±0·01	0·13±0·01	0·16±0·005	0·13±0·007
	Furnace 6	3·81±0·03	3·73±0·03	1·12±0·01	1·13±0·02	0·25±0·01	0·15±0·01	0·21±0·005	0·15±0·006
Standard deviation	Furnace 5	0·28	0·31	0·13	0·15	0·10	0·07	0·06	0·06
	Furnace 6	0·34	0·32	0·14	0·20	0·09	0·09	0·06	0·06

*With 95% confidence interval.

4 Required relationship between furnace feed rate and power, if furnace is operating in balanced condition, or needs to recover from overcharged or undercharged conditions

operation was considered to be 40% prereduction, 0 t h^{-1} correction material and 36 MW power input.

From the energy balance, the energy requirement – excluding heat losses – for normal operation was calculated to be 0·62 MWh per ton of furnace feed. To recover from an overcharged condition, the power input (relative to feed rate) must be increased over this value, and for an undercharged condition the ratio of power input to feed rate must be decreased. From plant experience, it was found that recovery from an undercharged condition requires the ratio to be 0·55 MWh ton^{-1}, and to recover from an overcharged condition 0·72 MWh ton^{-1} is required. These required changes were also captured in an operator guidance table; the relationships are shown in graphical form in Fig. 4.

These guidance tables were combined with detailed operating procedures (prescribing, amongst others, how long changed ratios of power to feed rate should be maintained, and how overcharged and undercharged conditions are recognised), and implemented at the plant.[9]

Results – furnace product and stability

The effect of the improved furnace operation procedures was assessed by comparing the product composition and slag tapping temperature from a period before the procedures were implemented (September 2007–December 2007), with the immediately subsequent period when the new procedures were first used (January 2008–March 2008). The results are summarised in Table 6 (product composition) and Table 7 (slag temperatures). These show that the vanadium content of the metal remained unchanged, but that there were significant

Table 7 Comparison of average slag temperatures (°C) before and after implementation of operator guidance tables: based on 416 measurements for furnace 6, and 326 measurements for furnace 5

		Before	After
Average*	Furnace 5	1437±4	1442±4
	Furnace 6	1439±3	1448±2
Standard deviation	Furnace 5	41	34
	Furnace 6	33	24

*With 95% confidence interval.

decreases in the titanium and silicon content of the metal; the situation where the titanium and vanadium contents become uncoupled (labelled C in Fig. 2) has hence been avoided with the improved operator guidance system. From Table 7 there does appear to be an increase in the slag temperature (with statistical significance in the case of furnace 6), but the most obvious effect is a decrease in the variability of the slag temperature (smaller standard deviations), which also indicates that the mass and energy balance is under better control.

The lower titanium and silicon contents of the hot metal should give lower energy requirements, and there are preliminary indications of this in the plant data. However, the available data were affected by variable degrees of furnace availability. Heat losses while the furnace is not producing increase the overall energy requirement, and so variable furnace availability can obscure differences in real process energy requirements; whether the changed procedures did lower the process energy requirement will be studied further in future.

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