FactSage-Based Design Calculations for the Production of High-Carbon Ferromanganese on Pilot-Scale

Joalet Dalene Steenkamp

Abstract The EU-funded PreMa project investigates the potential for a preheating stage to reduce the electrical energy requirement and CO_2 emissions produced, during the production of high-carbon ferromanganese in a submerged arc furnace. A pilot-scale campaign will be conducted at MINTEK in South Africa to demonstrate the potential effect of preheating on furnace operation. For the pilot-scale campaign, the design of the process flowsheet and sizing of the furnace and ancillary equipment were based on predictive mass and energy balance calculations. FactSage thermodynamic software and Microsoft Excel were utilised. The paper reports on the method applied and results obtained.

Keywords FactSage · High carbon · Ferromanganese · Pilot-scale

Introduction

High-carbon ferromanganese (HCFeMn) is an alloy consisting of 74–82% Mn, 7.5% C, 1.2% Si, 8–16% Fe, and minor impurities, i.e. P, S, As, Sn, Pb, and Cr [1]. It is mainly produced in electric submerged arc furnaces (SAFs), where the tips of the electrodes are submerged in a burden of raw materials, as illustrated in Fig. 1. Typical raw materials fed into the furnaces are manganese ores, carbonaceous reductants, and fluxes. The furnaces are typically round with three Söderberg electrodes, in equilateral triangular arrangement, supplying the electrical energy to the process. Electrical energy is converted to heat mainly through the resistive heating of the wet coke-bed. The wet coke-bed primarily consists of a mixture of liquid slag and coke. Alloy collects in the hearth of the furnace. Liquid slag and alloy are tapped intermittently through single- or bi-level tap-holes for further handling downstream.

J. D. Steenkamp (✉)
MINTEK, 200 Malibongwe Road, Randburg 2125, South Africa
e-mail: joalets@mintek.co.za

University of the Witwatersrand, 1 Jan Smuts Ave,
Johannesburg 2000, South Africa

Z. Peng et al. (eds.), *11th International Symposium on High-Temperature Metallurgical Processing*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-36540-0_67

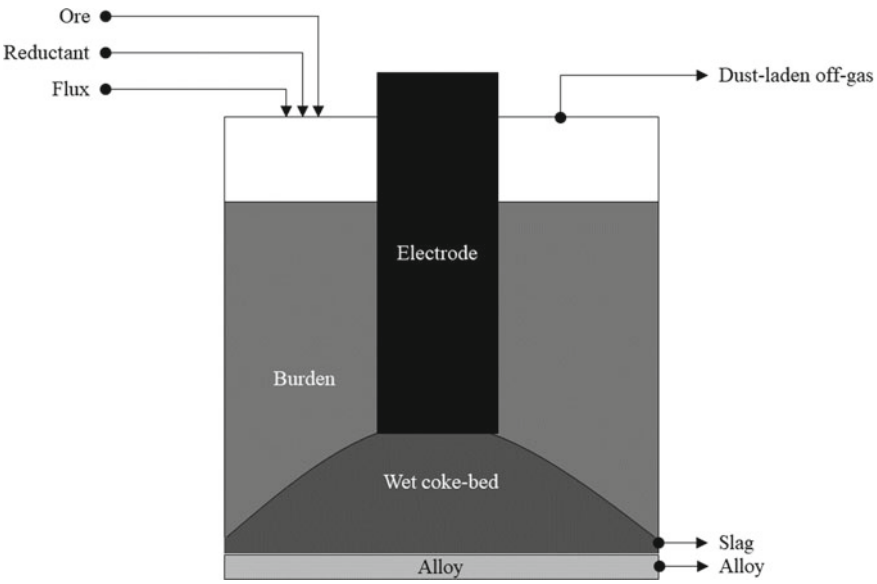

Fig. 1 Simple schematic of the process flow in a submerged arc furnace utilised in the production of high-carbon ferromanganese

Dust laden offgas is collected from the top of the furnace for further downstream treatment. Furnaces can be open, where a gap between the top of the sidewalls and the furnace roof allows for CO-rich offgasses to be combusted prior to cleaning and venting, or closed, where CO-rich offgas is cleaned and utilised downstream as a source of energy.

The HCFeMn production process is energy intensive with requirements ranging between 2.0 and 3.5 MWh per ton alloy [2–5]. The process is also a significant producer of CO_2 emissions, especially in countries where the electrical energy is supplied by coal-fired power stations.

The PreMa project (2018–2022) aims at demonstrating a suite of innovative technologies to reduce the consumption of electrical energy and CO_2 emissions during the production of HCFeMn in SAFs. A preheating unit will be added to the flowsheet and various technologies are considered, the details of which lie outside the scope of this paper.

Included in the test program is a pilot-scale campaign where the effect of preheating ore to 600 °C on SAF operation will be evaluated. As part of the design of the process flowsheet for the pilot-scale facility, and to size the furnace and upstream and downstream equipment, a number of questions were raised:

1. What alloy specification will be targeted in terms of the major components (Mn, Fe, Si, and C)?
2. What raw materials will be selected?
3. What will the ore blend be to meet the selected alloy specification?

4. What will the stoichiometric reductant requirement be?
5. What will the flux requirement be to optimize the recovery of Mn, ensuring tapability of the slag at the same time?
6. What will the process energy requirement be at equilibrium?

Answers were obtained through a review of literature and predictive mass and energy balance calculations.

Alloy Specification

ASTM standard A99-03 [1] defines the typical grades for high-carbon ferromanganese (HCFeMn). The grades vary in terms of their Mn-content with Grade A ranging from 78 to 82% Mn, Grade B from 76 to 78% Mn, and Grade C from 74 to 76% Mn. For design purposes, the lower end of Grade A was targeted: 78% Mn, 7.5% C, 1.2% Si, and 12% Fe (calculated by difference), and a Mn/Fe ratio of 6.5.

Raw Materials

South Africa accounts for 78% of the world's identified manganese resources and 29% of the world's reserves [6]. In typical smelter operations, especially in South Africa, more than one type of commercially available manganese ore is utilised. This fact is explained by the geology of the Kalahari Manganese Field (KMF), the main source of manganese ores commercially available in South Africa.

Three ore types may be distinguished in the KMF deposit on the basis of their geological alteration styles and mineral assemblages [7–9]. Mamatwan-type represents the least altered, low-grade type of ore in the deposit, and typically contains between 20 and 38% Mn. Wessels-type represents hydrothermally altered, high grade type of ore and typically contains between 45 and 60% Mn. The third type of ore is supergene altered ore, which is of variable grade, depending on the degree of alteration.

Key to the definition of these ore types is their different mineral assemblages. Mamatwan-type ores are enriched in Mn-bearing carbonates, compared to Mn oxide-rich Wessels-type ores. The oxidation state of the manganese in both types of ores is limited to the bivalent and trivalent state. The supergene ores are defined by the presence of tetravalent Mn-oxide minerals, and are of intermediate grade [9].

Mamatwan ore accounts for the bulk of the commercial ore in the KMF (around 95%) and the supergene ore accounts for a very small portion of the deposit. Due to its abundance, the Mamatwan-type ore forms the basis of any HCFeMn smelting facility in South Africa. Due to its low Mn-content, and increasing smelting costs, the Mamatwan-type ore is blend with Wessels-type or supergene ore.

Table 1 Chemical compositions of raw materials in % by mass

Component	Al_2O_3	CaO	Fe	Fe_2O_3	MgO	Mn	SiO_2	Total	Mn/Fe
Ore #A	0.13	13.21	4.94	–	3.30	37.78	5.60	64.96	7.65
Ore #a	0.14	14.94	5.79	–	2.59	35.11	5.01	63.58	6.06
Ore #B	0.09	15.33	3.86	–	4.21	34.29	4.72	62.50	8.88
Ash in coke	17.01	20.53	–	33.04	2.25	–	27.17	100.00	–
Quartz	1.20	–	–	–	–	–	98.80	100.00	–

Producers of manganese ferroalloys typically operate their processes with a number of carbonaceous reductants (i.e., see [10]), and in South African operations, quartz is often added as flux.

For the pilot-scale campaign, five types of raw materials were considered: three types of ores, coke as carbonaceous reductant, and quartz as flux. Ore from Mine A formed the baseline, blended with ore from Mine B in order to meet the Mn/Fe requirement of the alloy due to its higher Mn/Fe ratio (see Table 1). Two grades of ore from Mine A were considered and referred to as Ore #A and Ore #a, respectively. Ore from Mine B was referred to as Ore #B. As carbonaceous reductant, only one coke was considered in order to simplify the process control during the campaign. The coke consisted of 2.62% volatile matter, 10.03% ash, and 87.35% fixed carbon (all dry basis) with 3.96% moisture being typical. Table 1 contains the chemical compositions of the manganese ores, ash in coke, and quartz considered in the design calculations.

Ore Blend

To determine the types and ratios of the different manganese ores to utilise in the design calculations, the recovery of Mn was assumed to be 80% and of Fe 100%. These assumptions were based on a review of publications available in literature. Results for accounting balances, based on industrial (closed SAF) [2–4, 11, 12] or pilot (open SAF) [13, 14] plant data, as well as predictive balances [2, 5, 11, 15] were summarised in Table 2. Equation 1 defines basicity (B_3) where all components were expressed in % by mass.

$$B_3 = \frac{\%CaO + \%MgO}{\%SiO_2} \tag{1}$$

Taking the recoveries for Mn and Fe into account, the Mn/Fe ratio of the respective ores then reduces to 6.12 for Ore #A, 4.85 for Ore #a, and 7.11 for Ore #B. To produce an alloy with Mn/Fe ratio of 6.5, Ore #A and Ore #B have to be blend at a ratio of 61.38/38.62, and Ore #a and Ore #B at 26.90/73.10. As ore from mine A had to form the baseline and ore from mine B only had to be added as 'sweetener', the use of Ore #a was not further considered due to its unfavourable ratio to Ore #B.

Table 2 Summary of relevant parameters for mass and energy balance calculations mentioned in literature where raw material input temperatures were 25 °C in all instances except for *[11] where raw materials were preheated to 600 °C using an external rotary kiln. Where applicable, mass percent applies

Reference	Unit	[2]	[3]	[4]	[11]	[14]	[13]	[5]	[15]
Mn_{Rec}	(%)	70–80	82		85	43–68	82–83		
Fe_{Rec}	(%)	100	100		100	80–100	100		
Mn/Fe_{Ore}	(%/%)	>6				>6.2	5.4		1.0–2.7
C_{Excess}	(%)			10–30		<10			
$Energy_{Predict}$	(MWh/ton alloy)	2.196	2.207	2.3	2.413 (*1.878)		3.15		1.924–3.001
$Energy_{Actual}$	(MWh/ton alloy)	2.5–3.5	2.2	2.1–2.3	2.0			2.7	
$Energy_{Lost}$	(%)	27 (16–38)	20		20				20
T_{Alloy}	(C)	1500	1500		1500		1440, 1490, 1540		
T_{Slag}	(C)	1500	1500		1500		1440, 1490, 1540		1500
T_{Gas}	(C)	200–500	200		400				25
MnO_{Slag}		18.8	34.6	30	45.6	15.1–32.0	25.5–27.4		20
B_3		1.3–1.6	1.0		0.9	1.1	1.3		

Thermodynamic Calculations

As the South African process for the production of HCFeMn is considered to be near equilibrium [3], equilibrium mass and energy balance calculations were initially considered sufficient for design purposes, both in terms of the carbonaceous reductant and energy requirements.

The calculations were conducted in the Equilib module of the FactSage 7.2 thermodynamic software [16]. As solution databases, FToxid was applied for the oxide systems and a custom-made database (FeMn) [17] for the alloy systems. The pure specie database (FactPS) was also selected.

As the phase chemistry could play a role, the chemical analyses of the ores and reductant were converted to mineral phases available in the FactSage databases (see Table 3). The conversions were based on the following assumptions:

1. Braunite consisted of $MnSiO_3$ and $3Mn_2O_3$; all SiO_2 present as $MnSiO_3$.
2. Jacobsite consisted of $MnFeO_4$ and Fe is primarily present as $MnFeO_4$.
3. Hausmanite consisted of Mn_3O_4 and accounted for the remainder of the Mn.
4. Hematite consisted of Fe_2O_3 and accounted for Fe when Mn_3O_4 became negative.
5. Dolomite consisted of $CaMg(CO_3)_2$ and contained all Mg.

Table 3 Input parameters for thermodynamic calculations in FactSage 7.2—composition normalised, i.e., mass in grams equals per cent by mass

Item	Al_2O_3	C	CaO	$CaCO_3$	CH_4	Fe_2O_3	H_2O	MgO	$(Ca, Mg)(CO_3)_2$	$MnO{\cdot}SiO_2$	Mn_2O_3	Mn_3O_4	$MnFe_2O_4$	SiO_2	Total
1	0.12	–	–	23.15	–	1.35	–	–	16.56	11.49	41.53	–	5.80	–	100.00
2	0.16	–	16.39	–	–	1.77	–	4.09	–	15.15	54.77	–	7.65	–	100.00
3	0.08	–	–	25.47	–	–	–	–	21.16	9.70	35.05	2.85	5.69	–	100.00
4	0.12	–	20.12	–	–	–	–	5.53	–	13.51	48.83	3.97	7.93	–	100.00
5	1.2	–	–	–	–	–	–	–	–	–	–	–	–	98.8	100.00
6	1.6	83.9	2.0	–	2.5	3.2	4.0	0.2	–	–	–	–	–	2.6	100.00
7	Solid-1 gamma	Solid-1 graphite(s)	Solid lime	–	Gas	Solid-1 hematite	Liquid	Solid periclase	–	Solid rhodonite	Solid-1 bixbyite	Solid-1 solid-A	Solid	Solid-1 quartz(l)	–
8	FToxid	FeMn	FToxid	–	FactPS	FToxid	FactPS	FToxid	–	FToxid	FToxid	FactPS	FactPS	FactPS	–
9	25	25	25	25	25	25	25	25	25	25	25	25	25	25	–
10	25	25	25	25	25	25	25	25	25	25	25	25	25	25	–
11	600	–	600	600	–	600	–	600	600	600	600	600	600	–	–

Where items are
1. Ore #A with calcite and dolomite
2. Ore #A with CaO and MgO
3. Ore #B with calcite and dolomite
4. Ore #B with CaO and MgO
5. Quartz
6. Coke
7. Phase selected in FactSage
8. Database selected in FactSage
9. Temperature #1 (°C)—All raw materials
10. Temperature #2 (°C)—Coke and quartz
11. Temperature #2 (°C)—Ore

6. Calcite consisted of $CaCO_3$ and accounted for the remainder of the Ca.
7. Volatile matter in the coke only consisted of CH_4.

Each of these streams were predefined in the Mixture module of the FactSage 7.2 thermodynamic software. The ore streams were specified at two temperatures: 25 and 600 °C. In all calculations the initial conditions of the phases were specified as indicated in Table 3.

In the Equilib module, all ideal gas species were selected as well as all pure solids and pure liquid species, with duplicates suppressed and the solution databases having priority over the pure specie database. For the oxide systems, all solution phases were selected, except in cases where more than one option existed, for which the A-phase was selected, i.e., Slag-A. For the alloy system, all solution phases were selected. Equilibrium was calculated for normal and transition states.

Other input conditions were summarised in Table 4 on a case-by-case basis. The results of the calculations were summarised in Table 5 which can be found just before the sub-section on sensitivity analysis.

Stoichiometric Reductant Requirement

As a first iteration, a flux-less operation was analysed by reacting 100 g of ore blend with 0–100 g coke, at intervals of 10 g at 1500 °C. Two cases were evaluated. In Case #1, all input materials were considered to be at 25 °C. In Case #2, the ore blend were input at 600 °C and coke and quartz at 25 °C. Products were produced at 1500 °C.

The results were analysed in terms of mass of alloy (FEMN-Liqu) and graphite (FEMN-C(s)) phases formed per 100 g ore blend, as a function of coke additions. The reductant requirement was estimated as the point just before the formation of graphite as reaction product, as it was assumed that the formation of graphite indicated a surplus of coke. For both Case #1 and Case #2, 22.03 g of coke is required per 100 g of ore blend forming 38.87 g of alloy. Preheating of the ore streams neither influenced the reductant requirement nor the formation of alloy phase.

Process Energy Requirement at Equilibrium

To determine the process energy requirements, the thermodynamic calculations in FactSage 7.2 were done in three steps:

1. In the first step, the phases produced at 1500 °C when reacting Ore #A and Ore #B, and coke were calculated. Also calculated, was the energy required to produce these phases at 1500 °C. The amounts and compositions of the gas and alloy phases produced were saved as streams to be used in subsequent calculations.

Table 4 Inputs for various cases evaluated using the Equilib module in FactSage 7.2 with the FACTPS, FToxid, and custom alloy database. For ease of reference, the variables that changed from the previous case was indicated in *italics* for each case

Case	Ore #A (g)	Ore #B (g)	Quartz (g)	Coke (g)	H_2O (g)	$T_{Mix\ A/B}$	$T_{Mix\ C}$	$T_{Mix\ D}$	T_{H_2O}	T_{Slag}	T_{Gas}	T_{Alloy}
#1	61.38	38.62	–	22.03	–	25	–	25	–	1500	800	1400
#2	61.38	38.62	–	22.03	–	*600*	–	25	–	1500	800	1400
#3	61.38	38.62	*12.86*	*21.54*	–	*25*	*25*	25	–	1500	800	1400
#4	61.38	38.62	12.86	21.54	–	*600*	25	25	–	1500	800	1400
#5	61.38	38.62	–	*23.49*	–	*25*	–	25	–	1500	800	1400
#6	61.38	38.62	–	23.49	–	*600*	–	25	–	1500	800	1400
#7	61.38	38.62	*10.24*	*23.06*	–	*25*	*25*	25	–	1500	800	1400
#8	61.38	38.62	10.24	23.06	–	*600*	25	25	–	1500	800	1400
#9	61.38	38.62	10.24	*21.91*	–	25	25	25	–	1500	800	1400
#10	61.38	38.62	10.24	*21.33*	–	25	25	25	–	1500	800	1400
#11	61.38	38.62	10.24	*20.75*	–	*25*	25	25	–	1500	800	1400
#12	61.38	38.62	10.24	*19.60*	–	25	25	25	–	1500	800	1400
#13	61.38	38.62	10.24	*18.45*	–	25	25	25	–	1500	800	1400
#14	61.38	38.62	*15.36*	*23.06*	–	25	25	25	–	1500	800	1400
#15	61.38	38.62	*5.12*	23.06	–	25	25	25	–	1500	800	1400
#16	61.38	38.62	*10.24*	23.06	–	25	25	25	–	*1450*	*750*	*1350*
#17	61.38	38.62	10.24	23.06	–	25	25	25	–	*1400*	*700*	*1300*
#18	61.38	38.62	10.24	23.06	–	25	25	25	–	1500	*700*	1400
#19	61.38	38.62	10.24	23.06	–	25	25	25	–	1500	*600*	1400
#20	61.38	38.62	10.24	23.06	–	25	25	25	–	1500	*500*	1400
#21	61.38	38.62	10.24	23.06	–	25	25	25	–	1500	*400*	1400
#22	61.38	38.62	10.24	23.06	*1.00*	25	25	25	*25*	1500	*800*	1400
#23	61.38	38.62	10.24	23.06	*2.00*	25	25	25	25	1500	800	1400
#24	61.38	38.62	10.24	23.06	*4.00*	25	25	25	25	1500	800	1400
#25	61.38	38.62	10.24	23.06	*8.00*	25	25	25	25	1500	800	1400

2. In the second step, the phases produced and energy required when cooling the gas to 800 °C were calculated. This was done to quantify the effect of the gas cooling, as it percolates through the burden, on the energy required.
3. In the final step, the phases produced and energy required when cooling the alloy to 1400 °C were calculated. This was done to quantify the effect of alloy typically leaving the process at a lower temperature, on the energy required.

The process energy requirements for Case #1 and Case #2 calculated in this manner were 3.301 and 2.932 MWh/ton alloy, respectively.

Table 5 Results of various cases evaluated using the Equilib module in FactSage 7.2 with the FACTPS, FToxid, and custom alloy database. Where applicable, mass percent applies

Case	Energy (MWh/ton ore)	Energy (MWh/ton alloy)	Alloy (g)	Mn_{Alloy} (%)	Fe_{Alloy} (%)	Si_{Alloy} (%)	C_{Alloy} (%)	Mn/Fe (g/g)	Mn_{Rec} (%)	Fe_{Rec} (%)	Slag/Alloy (g/g)	MnO_{Slag} (%)	$Solids_{Slag}$ (%)	B_3
#1	1.279	3.301	38.8	82.8	10.0	0.0	7.2	8.28	95	100	0.79	3.1	93.5	3.73
#2	1.137	2.932	38.8	82.8	10.0	0.0	7.2	8.28	95	100	0.79	3.1	93.5	3.73
#3	1.318	3.566	36.9	81.9	10.5	0.7	6.9	7.83	89	100	1.23	7.8	0.0	1.33
#4	1.175	3.180	36.9	81.9	10.5	0.7	6.9	7.83	89	100	1.23	7.8	0.0	1.33
#5	1.147	2.158	53.1	83.3	9.5	0.0	7.2	8.77	97	100	0.61	3.0	92.8	3.75
#6	1.022	1.923	53.1	83.3	9.5	0.0	7.2	8.77	97	100	0.61	3.0	92.8	3.75
#7	1.187	2.304	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#8	1.062	2.061	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#9	1.152	2.323	49.6	83.1	10.1	0.3	6.5	8.23	90	100	0.93	10.4	0.0	1.35
#10	1.133	2.340	48.4	83.3	10.3	0.2	6.1	8.08	89	100	0.98	12.4	0.0	1.34
#11	1.115	2.363	47.2	83.5	10.6	0.1	5.8	7.91	86	100	1.03	14.6	0.0	1.34
#12	1.078	2.422	44.5	83.7	11.1	0.1	5.1	7.52	82	100	1.16	19.2	0.0	1.33
#13	1.040	2.506	41.5	83.5	11.9	0.0	4.6	7.03	76	100	1.32	24.2	0.0	1.33
#14	1.223	2.447	50.0	81.6	10.1	1.9	6.4	8.11	90	100	1.00	10.8	0.0	1.13
#15	1.156	2.197	52.6	83.4	9.6	0.1	7.0	8.71	96	100	0.72	6.1	67.8	1.56
#16	1.088	2.189	49.7	82.7	10.1	0.1	7.0	8.17	90	100	0.94	11.4	1.3	1.33
#17	0.982	2.065	47.5	82.5	10.6	0.0	6.9	7.79	86	100	0.98	17.5	4.1	1.29
#18	1.060	2.058	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#19	0.946	1.837	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#20	0.892	1.730	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#21	0.866	1.681	51.5	82.7	9.8	0.6	7.0	8.46	93	100	0.86	6.9	0.0	1.38
#22	1.196	2.382	50.2	82.9	10.0	0.4	6.7	8.27	91	100	0.91	9.2	0.0	1.36
#23	1.204	2.475	48.6	83.3	10.3	0.3	6.1	8.05	89	100	0.97	11.8	0.0	1.34
#24	1.211	2.582	46.9	83.5	10.7	0.2	5.6	7.78	86	100	1.05	14.6	0.0	1.34
#25	1.218	2.706	45.0	83.6	11.2	0.1	5.1	7.48	83	100	1.14	17.7	0.0	1.33

Calculated Mn and Fe Recovery

From the results of the calculations in FactSage 7.2, the amount of alloy produced as well as the composition and Mn/Fe ratio of the alloy was derived. The recoveries of Mn and Fe at equilibrium conditions were calculated as follows:

1. The molar compositions of each of the phases formed were extracted from the dataset.
2. From the set of results, the number of moles of Fe and number of moles of Mn per phase was derived, totalized, and the recovery of the Fe and Mn to the alloy phase was calculated.
3. Calculated in this manner, the mass and molar recovery will be the same.

Flux Requirement

The other product phases that formed for both Case #1 and Case #2 were 40.9% gas, 1.7% liquid slag, and two types of solid phases: 12.5% monoxide and 12.5% (Ca, Mg, Mn)$_2$SiO$_4$. Of the monoxide phase formed, 1.0% was associated with the gas phase formation, the remainder of the oxide phases would be considered as 'slag' phase. The 'slag'/alloy mass ratio is calculated at 0.9, which is similar to the 0.8 typically associated with South African operations [18] or pilot-scale testwork [13]. The solids content of the 'slag' phase is very high at 93.5% by mass, which means that the 'slag' will not be able to tap from the furnace and 'slag'/alloy separation will be difficult amongst other problems.

At South African operations, quartz is used as a flux and is also considered here. The calculations in FactSage 7.2, were based on Case #1, to which 0–20 g quartz was added at 2 g intervals, with equilibrium calculated at 1500 °C. The quartz requirement is estimated as the point where no solids (excluding graphite) are formed as reaction product and was found to be 12.86 g quartz per 100 g ore blend. The reductant requirement will also be less as indicated by the formation of graphite. To account for the effect of flux addition, the results obtained for Case #1 were subsequently revised as Case #3 and Case #2 as Case #4, taking the reduction in reductant requirement into account.

Revising Raw Material Phase Composition

Comparing the results obtained for Cases #1 to #4 in terms of energy required, the results were significantly higher than those published in literature (see Table 2). The results reported in literature varied between 1.8 and 3.2 MWh/ton of alloy whilst the energy required for Cases #1 to #4 ranged between 2.9 and 3.6 MWh/ton of alloy. It was therefore decided to disregard the energy required for the decompositioning

of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Dolomite still contained all MgO but it now consisted of CaO and MgO in a molar ratio of 1:1. Calcite accounted for the remainder of the CaO and consisted of CaO only. The calculations for Cases #1 to #4 were subsquently revised as Cases #5 to #8.

Sensitivity Analysis

A sensitivity analysis was conducted to study the effects of the changes listed below on the energy requirement, product amount and quality, manganese recovery, and amount of slag. Case #7 formed the base case for the analysis. The following changes were considered:

1. Reducing the amount of coke by 2.5, 5, 7.5, 10, 15, and 20% to account for the effect of reaction kinetics (Cases #9 to #13). As FactSage calculates the equilibrium conditions only, and it is known that the manganese reduction in HCFeMn production is not at equilibrium, the amount of coke fed to the process was reduced. According to the training material provided with the software, this is typically done when using FactSage for mass and energy balance calculations when processes are not at equilibrium.
2. Increasing and decreasing the amount of flux by 50% to study effect of flux additions on solids in slag (Cases #14 and #15).
3. Reducing the output temperatures of all products by 50 and 100 °C (Cases #16 and #17), and the temperature of the offgas only at intervals of 100 °C up to 400 °C (Cases #18 to #21) to study effect of output temperatures.
4. Introducing moisture at intervals of 1 g up to 8 g to study the effect of moisture associated with wet ore (Cases #22 to #25).

The effect of the reduction on manganese recovery and energy required were presented in Fig. 2a. The conditions typical of operating conditions (80% recovery) will therefore probably be met at between 15 and 20% reduction in coke, which is within the range of excess carbon added typically for coke-bed management. For mass and energy balance calculation purposes, the stoichiometric reductant requirement was selected to be 15% less than the base case, i.e., 19.601 g/100 g ore instead of 23.06 g/100 g ore. The associated increase in process energy requirement would be between 5.1 and 8.7%. The increase in process energy requirement, when expressed as MWh/ton alloy, was not due to an actual increase in energy but due to a decrease in alloy produced though as can be seen in Fig. 2b. The actual reduction in process energy requirement was also evident when expressed as MWh/ton ore.

The process energy requirement for the base case was calculated for ore and quartz on a dry basis. In reality, the ore fed into the SAF would probably contain some moisture. The effect of ore containing moisture on the process energy requirement was therefore calculated. Addition of moisture significantly influenced the process energy requirement as well as the manganese recovery (Fig. 3a), with 4% moisture resulting in a 17.4% increase in process energy requirement and 11.7% decrease in

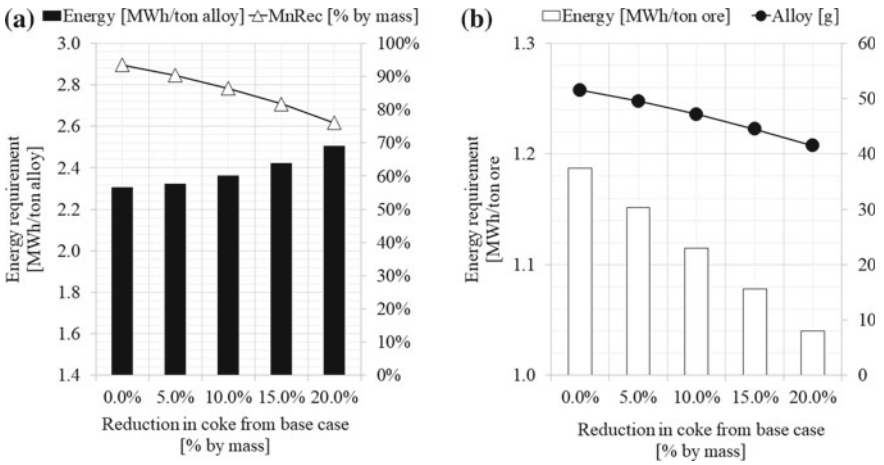

Fig. 2 Effect of reduction in coke on **a** energy requirement and manganese recovery and **b** energy requirement and alloy produced, where the baseline was 23.06 g coke/100 g ore (Case #7)

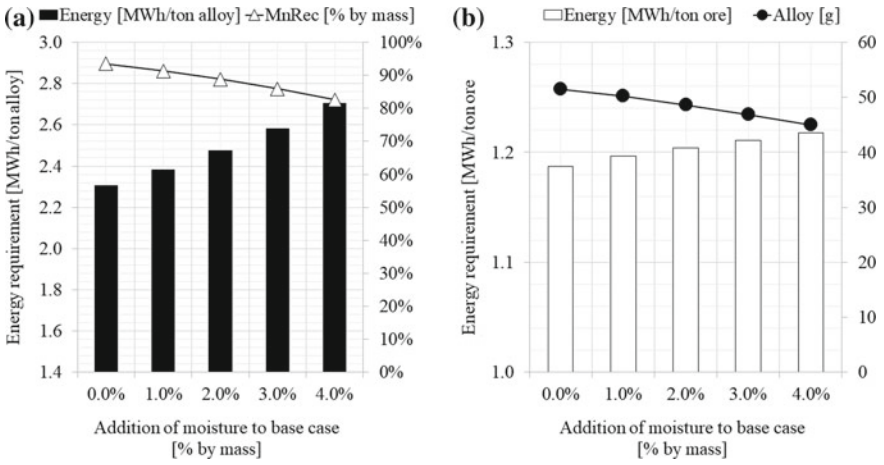

Fig. 3 Effect of moisture addition on **a** energy requirement and manganese recovery and **b** energy requirement and alloy produced, where the baseline was 0% moisture/100 g ore, i.e., at increments of 1 g moisture/100 g ore (Case #7)

manganese recovery. The increase in process energy requirement was partially due to an actual increase in process energy required as well as a reduction in the amount of alloy produced, as indicated in Fig. 3b.

The assumptions made about the product temperatures have a significant influence on the calculated process energy requirement. The effects of the reduction in product temperature and reduction in offgas temperature on the process energy requirement and manganese recovery are presented in Fig. 4. As expected, the reduction in tem-

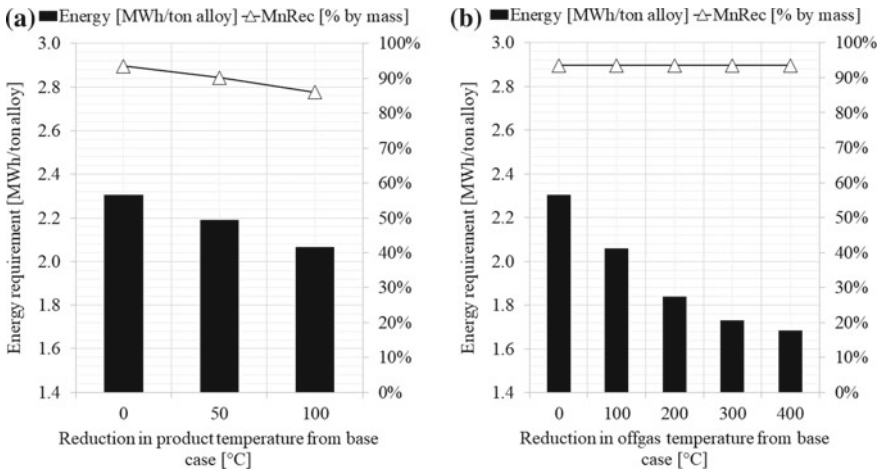

Fig. 4 Effect of reduction in temperature of **a** slag, alloy, and offgas, and **b** offgas only on energy requirement and manganese recovery where the baseline was 1500 °C for slag, 1400 °C for alloy, and 800 °C for offgas (Case #7)

perature of all products will have a significant influence on both the process energy requirement as well as the manganese recovery, at reduction of 10.4% and 8.0%, respectively, for a reduction of 100 °C (Fig. 4a). Simultaneously, the solids content of the slag increases to 4.1%. The reduction in offgas temperature will have a significant influence on the process energy requirement (27% for a reduction of 400 °C) but none on the manganese recovery (Fig. 4b).

Conclusion

Based on the work presented here, the answers to the questions raised in the introduction are summarised. The answers form the basis of the process flowsheet and equipment design during the basic engineering study:

1. The target alloy composition will be 78% Mn, 12% Fe, 7.5 % C, 1.2% Si, and a Mn/Fe ratio of 6.5.
2. Four types of raw materials will be utilised, two manganese ores, one reductant, and one flux. The manganese ores will be Ore #A and Ore #B. Ore #A ore will consist of 37.78% Mn. 4.94% Fe, 0.13% Al_2O_3, 13.21% CaO, 3.30% MgO, and 5.6% SiO_2. Ore #B will consist of 34.29% Mn. 3.86% Fe, 0.09% Al_2O_3, 15.33% CaO, 4.21% MgO, and 4.72% SiO_2. The flux will be quartz and will consist of 1.2% Al_2O_3 and 98.8% SiO_2. The reductant will be coke and will consist of 2.62% volatile matter, 10.03% ash, and 87.33% fixed carbon—all determined on a dry

basis—and 3.96% moisture. The ash will consist of 17.01% Al_2O_3, 20.52% CaO, 33.04% Fe_2O_3, 2.25% MgO, and 27.17% SiO_2.
3. The two ores will be fed at a ratio of 61.38 to 38.62, Ore #A to Ore #B.
4. The reductant requirement will be 19.601 g/100 g ore.
5. The flux requirement will be 23.06 g/100 g ore.
6. The process energy requirement under equilibrium conditions will be 1.187 MWh/ton ore or 2.304 MWh/ton alloy for cold feed, and 1.062 MWh/ton ore or 2.061 MWh/ton alloy for hot feed.

During the pilot-scale campaign, the values obtained for the predictive mass and energy balance will be confirmed through accounting mass and energy balances.

Acknowledgements The PreMa project is funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 820561 and industry partners: Transalloys, Eramet, Ferroglobe, OFZ, and Outotec.

References

1. ASTM-A99 (2009) Standard specification for ferromanganese. West Conshohocken, PA, 2003. ASTM International
2. Ahmed A, Halfa H, El-Fawakhry M, El-Faramawy H, Eissa M (2014) Parameters affecting energy consumption for producing high carbon ferromanganese in a closed submerged arc furnace. Int J Iron Steel Res 21(7):666–672
3. Olsen S, Tangstad M, Lindstad T (2007) Production of manganese ferroalloys. Tapir Academic Press, Trondheim, Norway
4. Swamy K, Robertson D, Calvert P, Kozak D (2001) Factors affecting carbon consumption in the production of high carbon ferromanganese, Quebec City, Canada, pp 293–301
5. Healy G (1990) Ferromanganese material and energy balances calculation of electrical resistance mix. In: Proceedings of the international symposium on ferrous and non-ferrous alloy processes, Hamilton, Canada, pp 85–96
6. Corathers L (2017) Mineral commodity summaries 2017. Technical report, U.S. Geological Survey
7. Van Averbeke N (2005) SAMI—South Africa's minerals industry 2004–2005. Technical report, Directorate, Mineral Economics
8. Cairncross B, Beukes N, Gutzmer J (1997) The manganese adventure—The South African manganese fields. Associated Ore & Metal Corporation
9. Chetty D, Gutzmer J (2018) Quantitative mineralogy to address energy consumption in smelting of ores from the Kalahari Manganese Field, South Africa. In:INFACON XV, Cape Town, South Africa
10. Steenkamp J, Maphutha P, Makwarela O, Banda W, Thobadi I, Sitefane M, Gous J, Sutherland J (2018) Silicomanganese production at transalloys in the twenty-tens. J South Afr Inst Min Metall 118:309–320
11. Tangstad M, Olsen S (1995) The ferromanganese process-material and energy balance, Trondheim, Norway, pp 621–630
12. Tangstad M, Ichihara K, Ringdalen E (2015) Pretreatment unit in ferromanganese production. In: Energy efficiency and environmental friendliness are the future of the global Ferroalloy industry, Kiev, Ukraine, pp 99–106
13. Lagendijk H, Xakalashe B, Ligege T, Ntikang P, Bisaka K (2010) Comparing manganese ferroalloy smelting in pilot-scale AC and DC submerged-arc furnaces. In: Infacon XII: sustainable future, Helsinki, Finland, pp 497–508

14. Eissa M, Ghali S, Ahmed A, El-Faramawy H (2011) Optimum condition for smelting high carbon ferromanganese. Ironmak Steelmak
15. Kalenga M, Xiaowei P, Tangstad M (2013) Manganese alloys production: impact of chemical compositions of raw materials on the energy and materials balance. In: Efficient technologies in ferroalloy industry, Almaty, Kazakhstan, pp 647–654
16. Bale C, Belisle E, Chartrand P, Decterov S (2016) FactSage thermochemical software and database, 2010–2016. Elsevier 54:35–53
17. Tang K, Olsen S (2006) Computer simulation of equilibrium relations in manganese ferroalloy production. Metall Mater Trans B 37:599–606
18. Steenkamp J, Hockaday C, Gous J, Nzima T (2017) Dissipation of electrical energy in submerged arc furnaces producing silicomanganese and high-carbon ferromanganese. JOM 69(9):1712–1716