COMPARING MANGANESE FERROALLOY SMELTING IN PILOT-SCALE AC AND DC SUBMERGED-ARC FURNACES

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ABSTRACT

The scale-up of conventional manganese ferroalloy three-phase electric furnaces is characterized by low resistance and hence the requirement for high currents. These conditions negatively affect operational stability and have been the major limiting factor that has prevented scaling these furnaces to more than 40 or 50 MW, and thereby benefiting from the advantages of economies of scale. A DC furnace could in principle overcome this electrical constraint. The metallurgical performance of a DC submerged-arc furnace for the production of manganese ferroalloys has however not been tested.

The smelting of both high-carbon ferromanganese [HCFeMn] and standard silico-manganese [SiMn] was tested and compared using a pilot-scale furnace that was operated firstly by using a three-phase AC power supply, to set a benchmark, and then with a DC power supply for comparison, under submerged-arc operational conditions in all instances.

The pilot-furnace consisted of a steel shell lined with a sidewall refractory lining thickness of approximately 120 mm to give a working diameter of about 0.7 m. The AC setup comprised three 100 mm diameter graphite electrodes whereas the DC arrangement utilized graphite electrodes with the same diameter in a twin-cathode electrode and bath/hearth anode arrangement. A blend of the two typical South African manganese ores was utilized together with metallurgical coke and anthracite. Also in line with the local HCFeMn industry where predominantly relatively low-grade manganese ores are used, smelting was conducted to render a discard slag.

The baseline pilot test for the manufacture of HCFeMn using a three-phase AC power supply was conducted over 4 days, followed by 5 days of smelting using a DC power supply. The smelting recipes and power levels (about 120 kW) were kept similar as far as possible within operational constraints. A total of just over 8 tons of manganese ore was processed. A similar comparison was conducted where about 5 ½ tons of manganese ores together with reductants and quartzite were processed to produce SiMn.

In terms of alloy grade, manganese deportment to the different phases, as well as electrode and energy consumption, the DC submerged-arc operations of both HCFeMn and SiMn proved to be technically feasible alternatives to conventional operations.

1   INTRODUCTION

Over the past 50 years, submerged arc furnaces have been widely used for the production of ferroalloys such as ferrochromium, (standard) ferromanganese [HCFeMn], silico-manganese [SiMn] and ferrosilicon. This type of furnace typically makes use of secondary-circuit three-phase alternating current applied to three electrodes that are arranged in a triangular configuration with a common hearth. According to de Waal et al [1], the furnace electrical circuit can be described as a star, each phase of which represents an electrode. The circuit of each phase can be further summarised as a fixed inductance, as determined by the electrode and busbar arrangement, and a variable power-dissipating element in series. The heating from the latter is most commonly resistive in nature, but almost always also contains some arcing and thereby exhibits some non-linear inductive characteristics. The relative proportion of arcing is process dependent, for example the slagless

smelting of metallurgical silicon would have a larger arcing power-dissipating component than the smelting of HCFeMn.

Since their inception, these submerged-arc furnaces have been gradually increased in size to take advantage of economies of scale. However, whereas the size of a single HCFeMn furnace has been increased to approximately 140 000 to 160 000 metric tons of hot metal per annum, it remains an order of magnitude smaller than the capacity of a single blast furnace, reported as typically between 2 and 3 million metric tons of pig iron per annum [2].

Similar to the industrial use of an AC electric furnace in open-arc mode to smelt fine materials (as with ilmenite smelting [3]), a DC current ferroalloy furnace, which had initially been developed for smelting ferrochromium from fine chromite ores [4], can in principle be used to smelt ferroalloys from lumpy ore in a submerged-arc mode. This concept was initially proposed by Barcza et al in 2002 [2], and was later embodied in a SA patent [5].

When an AC submerged-arc furnace is to be scaled up, the electrodes need to be made bigger as Søderberg electrodes have a limit on current-carrying capacity and the risk of electrode breakages is increased significantly when this current-carrying capacity is exceeded. Also, with scale-up, the furnace resistance decreases with increasing electrode diameter. In addition, the magnetic inductance or reactance of a furnace typically increases with electrode size. Larger electrodes therefore have a compounding effect on the furnace power factor (cosø), which is the ratio between the resistance and the reactance of the furnace electrical circuit. With cosø > 0.8, there are no major operational difficulties, but with cosø between 0.65 and 0.8, a phenomenon called the "interaction effect" becomes significant and creates continual operational control problems. In short, the problem of the "interaction effect' in a three-phase AC current electric arc furnace relates to the phenomenon that a control change made to one electrode also affects the electrical parameters in the other two electrodes to a certain degree, as described by Barker et al [6]. Such a control change may include slipping an electrode, raising or lowering of the electrode, or changing the control setpoint for current (should this be the control philosophy being followed), or tapping the furnace load up or down.
In effect, this phenomenon may result in an almost unmanageable furnace from a control perspective when the power factor drops below 0.5 [2].

The patent by Barcza et al claims that a DC submerged arc furnace could be scaled up without being limited by the control problems associated with the "interaction" effect, as the current would flow through the hearth and then there would be no current "interaction". [It is further believed that even with a graphite electrode as anode, the control in a multi-electrode scaled-up DC furnace need not necessarily be a problem, regardless of the current "interaction" between cathodes and anode(s)]. Since electromagnetic inductance creates reactance only with alternating current, a further benefit of a multi-cathode large-scale DC furnace would be the fact that there would be no reactance in the electric circuit(s), with associated benefits in terms of greater power generating capacity.

This paper summarizes the results from a metallurgical comparison done on the submerged-arc smelting of HCFeMn in an AC and DC pilot-scale furnace as well as a similar comparison for the submerged-arc smelting of SiMn. A secondary objective of the testwork was to closely simulate the industrial smelting operations in terms of process metallurgy, implying the production of HCFeMn with more than 76% of manganese, and SiMn with 14-16% silicon and 65-68% manganese [7].

2   PILOT-PLANT DESCRIPTION

The submerged-arc smelting campaigns for HCFeMn and SiMn were each conducted on the '1 ton per day' electric arc furnace facility at Mintek in Randburg, and were each divided into a '300-kVA' AC campaign and a '200-kW' DC campaign. The ancillaries included a portable feeder, water cooling circuits, a gas cleaning system and a control system.

The AC power supply consisted of a 300kVA three-phase transformer with an on-load tap changer. The energy input was accumulated on a kWh counter and the hydraulic electrode hoists were controlled manually to achieve a current in each electrode of about 2 kA. The AC operation electrical data, i.e. power, currents, operating voltages, etc. were recorded on an electronic data logging

system. The feedrate and batch mass values were all controlled manually. Energy was logged every 30 minutes from the panel.

The DC operation employed a "200 kW" power supply and the twin electrode mode furnace parameters were controlled by the 'Delta V' control system. The total integrated energy input was accumulated on the control system. The two furnace transformers were each connected to one of two DC rectifiers with a voltage and current capable of achieving a power level of about 100 to 200 kW subject to operating conditions.

3   RAW MATERIALS

Typical South African Mamatwan and Wessels manganese ores types were used in the testwork. These two ore types are both mined in the Northern Cape region but differ in their mineralogy. Mamatwan type ore is rich in carbonates and has a high Mn/Fe ratio [8]. This is partly because Braunite I, the major component of Mamatwan type ore has considerably less iron as opposed to the higher iron content in the predominant Braunite II mineral in the Wessels type ore. Consequently, Wessels type ore has a lower Mn/Fe ratio. Gloria ore, being of Mamatwan type and Nchwaning, a Wessels type both originate from the same region [9, 10]. The chemical analyses of the raw materials used in the smelting testwork are given in Table 1. Table 1 also includes the reductant ash analyses. The proximate analyses and particle sizes of the reductants are given in Table 2.

Table 1:   Particle size of the charge and chemical composition of the raw materials

Description	Particle size (mm)	Al_2O_3	CaO	FeO	Fe	MgO	MnO	Mn	SiO_2	CO_2
Gloria	10-40	0.1	12.6	-	4.8	3.9	-	37.6	6.2	-
Nchwaning	10-40	0.3	6.0	-	11.1	0.3	-	48.2	2.5	-
Limestone	±50	0.7	50	0.6	-	1.6	0.7	-	6	40
Quartzite	±50	0.6	0.1	0.2	-	<0.1	<0.1	-	96	-
Anthracite ash	-	35	4	7	-	2	-	-	50	-
Coke ash	-	31	5	9	-	3	-	-	52	-

Table 2:   Particle size and proximate composition of the reductants

Description	Particle size (mm)	Fixed Carbon	Ash	Volatiles	Moisture	Total%
Anthracite	-12+10	75.8	13.1	9.9	1.2	100
Coke	±10	89.1	9.1	1.2	0.6	100

A mixture of coke and anthracite was used as the carbonaceous reductants for both campaigns. Quartzite of 96 % SiO_2 purity was used as a flux in the HCFeMn tests and as source of silicon in the SiMn smelting campaigns. Limestone was added to the SiMn charge to increase the amount of slag as this was reported to stabilize the control of SiMn operation in industry [11].

4   TESTWORK DESCRIPTION

4.1   Operating Details

4.1.1   General

Feeding was done on the basis of dumping rounds of 30 to 40 kg of premixed feed at intervals of approximately half an hour using a single feed port. Frequent observations of the condition of the furnace burden were made using a special viewport. This port also enabled some access for "rabbling" of the furnace burden after each burden observation. Tapping operations were attempted after a specified quantity of energy input to the furnace. During tapping, alloy and slag spoon samples were taken from a molten stream and submitted for assaying.

4.2   Testwork at a Glance

Table 3:   Summary of FeMn and SiMn submerged arc smelting campaigns

Parameter	Unit	Details						
Manganese ferroalloy type		HC FeMn			SiMn			
Power supply type		AC	DC		AC		DC	
Number of graphite electrodes		three	two		three		two	
Test dates [week № in 2007]		18	19		39		45	
Total duration	hours	72.7	53.7	38.5	134.3		138.2	
Downtime/"power off" time	hours	4.2	2.1	1.9	22.6		20.9	
Roof refractory type		High-alumina castable						
Batch/heat/tapping numbers		4 - 22	25-40	41-54	0 - 11	12-28	1 - 26	27-48
Warm-up tap number		4	25		0		1	
Burden melt-down numbers		23			-	29	-	49
Furnace clean-out numbers		3, 24			-	30	-	-
Furnace dig-out number		-	55		-	-	-	49
High - [Mn/Fe ratio] Mn ore : Low - [Mn/Fe ratio] Mn ore ratio	mass ratio	50:50	50:50		50:50	70:30	70:30	50:50
Coke : Anthracite ratio, mass ratio		30:70	29:71	30:70	1:2			
Total manganese ore smelted	ton	3.55	2.65	2.02	2.75		2.81	
Total reductant, kg per 100 kg Mn ore		26.9	23.8	26.9	45			
Quartzite quantity	ton	0.11	0.08	0.06	1.1		1.1	
Limestone flux quantity	kg	-	-	-	275		282	
Total energy input	MWh	8.94	11.69		13.63		16.56	
Total alloy produced #	ton	1.30	1.85		1.16		1.22	
Total slag	ton	1.07	1.52		1.95		1.94	
# Silico-manganese alloy masses corrected for dilution with iron from the tapping lance								

4.2.1   Summary of the HCFeMn campaign using a three-phase AC power supply

A typical recipe was chosen for the smelting of HCFeMn according to the discard-slag practice as performed by South African industrial manganese ferroalloy producers, using typical South African manganese ores, but no sinter. Initially a small amount of limestone flux was employed in the smelting recipe, but was changed to 5 kg of quartzite per 200 kg ore + reductant [from Tap 4] to obtain a slag basicity ratio $[(CaO + MgO)/SiO_2]$ close to the target value of 1.3 ± 0.1.

The hydraulic electrode hoists of the pilot-plant furnace were manually adjusted to maintain electrode currents in the range of approximately 2 kA, with a transformer tap selection such that the average total instantaneous power input to the furnace after the warm-up tap [i.e. from Tap 5 onwards] was about 120 kW. A statistical summary of the electrical operating data is given in Table 5.

Tapping operations were attempted after an average of 394 kWh of energy input ["power on" tap-to-tap time of 3.3 hours], or effectively approximately 192 kWh of energy when lost energy is subtracted based on average heat losses (based on conduction through refractory lining only) of about 55 kW and a total average tap-to-tap time of 3.5 hours. The quantity of alloy tapped was on average about 64 kg per tapping operation. The measured heat losses were calculated from sidewall film cooling water flowrate and its temperature increase, whereas an estimated "unmeasured" value of 25 kW was added (from previous experience on this furnace) to obtain a value for the total average heat losses per tap.

Measurements were done to determine the distance between electrode tips and the furnace hearth. A summary of these distances is given in Table 4.

Table 4:   Electrode-to-hearth distances measured during AC FeMn smelting

Tap/batch number	Particular parameter	Distance, mm		
	Electrode number	E 1	E 2	E 3
Tap 18	Difference in measurement markings	170	210	210
Tap 19	Difference in measurement markings	150	150	200
	Average from two measurements	160	180	205
	Standard deviation from two measurements	14	42	7
Overall average		182		

4.2.2   Summary of the SiMn campaign using a three-phase AC power supply

For the three-phase AC pilot test a typical industrial recipe for smelting SiMn from South African manganese ores was employed, but without manganese sinter. The reductant consisted of coke and anthracite in a mass ratio of 1:2 with total reductant 45 kg per 100 kg manganese ore. The campaign was conducted in two parts, the first with equal amounts of the two types of manganese ore, whereas in the second part, the manganese ore with the high Mn/Fe ratio was increased to 70% of the combined manganese ore contingent. Quartzite in the recipe was 40 kg per 100 kg manganese ore and limestone 10 kg per 100 kg ore.

Table 5 summarizes averages and standard deviations of tap/batch average electrical parameters E1, E2, E3, V1, V2, V3, P1, P2, P3 and total power.

Table 5:   Statistical summary of the electrical data for the AC FeMn and AC SiMn campaigns

Electrical parameter	Average/standard deviation for tap average							
	HCFeMn				SiMn			
Phase voltage	V1	V2	V3		V1	V2	V3	
Average phase voltage, V	39.9	41.8	39.0		39.7	42.5	39.4	
Standard deviation for average voltage, V	3.2	3.1	2.8		4.2	4.2	4.0	
Electrode current	I1	I2	I3		I1	I2	I3	
Average electrode current, A	1834	1909	1882		1815	1810	1799	
Standard deviation on average electrode current, A	178	171	192		245	255	249	
Power input	P1	P2	P3	P-total	P1	P2	P3	P-total
Average phase and total power, kW	40.6	45.3	34.3	120.3	39.2	47.9	39.5	126.6
Standard deviation on average phase and total power, kW	9.1	10.1	8.5	11.1	12.3	12.1	11.8	14.5

The target slag basicity ratio of about 0.6 was achieved. The slag MnO content varied over quite a range between 15 and 30%, with an average of 22% and a standard deviation of 4%. Huge variations in especially the Mn and Fe analysed in the alloy samples were indicative of the effect of iron dilution from the lance during extended tapping operations.
At the end of the campaign, the furnace was drained as far as possible. Hereafter, the positions of the electrode tips in relation to the furnace hearth were determined as 40 mm, 45 mm and 55 mm for electrodes 1, 2, and 3 respectively.

After the warm-up onwards, the average energy input between tapping operations was of the order of 446 kWh at an average instantaneous power level of around 124 kW, giving an average tap-to-tap "power on" duration of 3.6 hours. With an average total tap-to-tap time of 4.3 hours [average downtime of 0.7 hours per tap] the effective average energy per tapping operation was around 232 kWh, and an average total amount [slag + alloy (corrected for iron pick-up from lancing)] of 106 kg [40 kg alloy] was tapped. The average heat losses by conduction through furnace refractory totaled about 50 kW [calculated as the sum of 25 kW of measured and an estimated 25 kW of unmeasured heat losses], roughly 5 kW lower than that in the HCFeMn smelting test.

4.2.3   Summary of the HCFeMn campaign using a DC current power supply

For the HCFeMn submerged-arc smelting campaign with DC current, the necessary busbar changes were made. The furnace dome and shell after the clean-out that followed the AC FeMn test remained in the same position. Only the roof with three apertures for the graphite electrodes was replaced with one that contained only two apertures for the twin-cathode electrodes.

The DC sub-arc campaign for smelting HC FeMn started with Tap 25. The feed blend with the start-up was the same as was used in the AC FeMn test, but a change was made in the percentage reductant with the start of Tap 28 – the total reductant was reduced by approximately 10% from 26.9 kg per 100 kg manganese ore to 23.8 kg per 100 kg manganese ore. The reason for the change was that a lot of carbonaceous material had been found in the material removed during the digout after the AC FeMn test. However, to be able to compare the AC and DC submerged-arc smelting of HCFeMn on the same basis, the raw material blend was changed back to 26.9 kg total reductant per 100 kg manganese ore from Tap 41 to the end of the DC test.

A statistical summary of the electrical operating data is given in Table 6. Subsequent to the warm-up tap [i.e. from Tap 26 onwards] the average instantaneous power input from the two drives was about 134 kW and tapping operations were attempted after an average of 361 kWh of energy input [average tap-to-tap "power on" time of 2.7 hours], giving about 204 kWh of energy when lost energy is subtracted based on average heat losses (based on conduction through refractory lining only) of about 55 kW over an average total tap-to-tap time of 2.8 hours. The net effect was that, as with the AC HCFeMn test, the average quantity of alloy per tapping operation was about 63 kg.

Several electrode-to-hearth determinations were done with the numerical average of eight measurements [4 per electrode] being 183 mm.

4.2.4   Summary of the SiMn campaign using a DC current power supply

The DC submerged-arc smelting campaign commenced using the same recipes used in the AC submerged-arc test for SiMn. The only difference was that the recipe with the larger amount of high Mn/Fe ore was used in the first part [Taps 1 to 26] and the recipe with equal amounts of the two manganese ore types in the smelting blend was used during the latter part of the test [Taps 27 to 48].

Most of the tapping operations were markedly more difficult during this test as compared to the SiMn smelting campaign using the AC setup. This is born out by an iron balance subsequent to the test that shows that on average 5.2 kg of lance rod was used per tapping operation in the DC submerged-arc SiMn test as compared to 3.5 kg in the AC submerged-arc SiMn test. The dilution effect on the alloy was compounded by the fact that the average quantity of molten material tapped in the DC test [average total amount [slag + alloy (corrected for iron pick-up from lancing)] was about 65 kg [25 kg alloy], compared to approximately106 kg [40 kg alloy] in the AC test.

The furnace control philosophy was based on current setpoint as was the case with the HCFeMn submerged arc campaign. The current setpoint was initially 2000 A per drive, up to Tap 8, after which it was changed to 2500 A per drive, in order to get better stability with respect to power input. Table 6 summarizes electrical parameters, specifically averages and standard deviations of Tap averages of the parameters E1, E2, V1, V2, P1, P2, and total power.

The average heat losses [by conduction through furnace refractory] totaled 65 kW – these losses increased during the course of the campaign with an average of 60 kW for the first part and 72 kW for the second part. After the warm-up batch [Tap 1], i.e. from Tap 2 onwards, the average energy input between tapping operations was of the order of 329 kWh at an average instantaneous power level of around 142 kW, giving an average tap-to-tap "power on" duration of 2.3 hours. With an average total tap-to-tap time of 2.7 hours [average downtime of 0.4 hours per tap] the effective average energy per tapping operation was around 152 kWh, compared to 232 kWh for the AC submerged-arc SiMn campaign. The ratio of these values for the effective average energy per tapping operation is of the same order of the ratio of average molten material tapped per tapping operation between the two campaigns.

After Tap 49 [burden meltdown and tapping], the positions of the electrode tips in relation to the furnace hearth were determined. These distances were 45 mm and 60 mm for electrodes 1 and 2 respectively.

Table 6: Statistical summary of the electrical data for the DC FeMn and DC SiMn campaigns

Electrical parameter	HCFeMn				SiMn			
	Period	Average/standard deviation for tap average			Period	Average/standard deviation for tap average		
Voltage	Taps	V1	V2		Taps	V1	V2	
Average electrode voltage, V	25 - 38	26.5	26.5		2 - 9	35.1	36.9	
	39 - 41	25.2	23.3		10 - 26	29.1	28.3	
	42 - 54	27.2	26.3		30 - 49	29.0	27.4	
Standard deviation for average voltage, V	25 - 38	5.8	6.7		2 - 9	9.1	10.0	
	39 - 41	3.1	2.1		10 - 26	6.2	6.8	
	42 - 54	7.6	7.5		30 - 49	7.9	6.3	
Current		I1	I2			I1	I2	
Average electrode current, A	25 - 38	2457	2457		2 - 9	1987	1988	
	39 - 41	2456	2497		10 - 26	2484	2496	
	42 - 54	2505	2503		30 - 49	2494	2492	
Standard deviation on average electrode current, A	25 - 38	55	55		2 - 9	94	50	
	39 - 41	212	150		10 - 26	114	33	
	42 - 54	12	23		30 - 49	44	48	
Power		P1	P2	P-total		P1	P2	P-total
Average electrode and total power, kW	25 - 38	64.6	67.9	132.5	2 - 9	69.4	75.7	145.1
	39 - 41	60.8	61.1	121.8	10 - 26	72.1	73.9	146.0
	42 - 54	69.1	69.1	138.2	30 - 49	72.3	71.6	143.9
Standard deviation on average electrode and total power, kW	25 - 38	15.5	16.9	23.6	2 - 9	19.8	21.0	29.5
	39 - 41	3.7	3.4	5.4	10 - 26	17.5	17.2	26.8
	42 - 54	20.8	19.7	29.9	30 - 49	21.1	16.9	27.0

5 TEST RESULTS

5.1 Comparison between Ferromanganese Smelting in AC and DC Submerged-arc Furnaces

5.1.1 Refractory temperatures

The average sidewall and hearth temperatures for the two ferromanganese smelting tests are summarized in Table 7. The hearth thermocouple temperature for the AC HCFeMn campaign increased up to a temperature of around 235ºC and decreased to about 210ºC towards the end. After warm-up of the DC FeMn test, the corresponding hearth thermocouple temperature remained steady at about 235ºC up to the end of the test.

Table 7: Sidewall and hearth temperatures for AC and DC submerged-arc smelting of HCFeMn

Campaign	Temperatures	Unit	Sidewall refractory lining			Hearth lining	
Refractory type			Al_2O_3-MgO castable			MgO/CaO dry ramming	
	Designation		T 1	T 2	T 3	T 1	T 2
AC FeMn	Numerical average	º C	304	254	262	-	197
	Standard deviation	º C	20	16	37	-	34
DC FeMn	Numerical average	º C	337	138	291	315	229
	Standard deviation	º C	42	8	34	9	12

5.1.2 Metallurgical parameters

The metallurgical comparison between the AC and DC submerged-arc smelting tests on standard ferromanganese is summarized in Table 8.

Table 8: Comparison of metallurgical parameters between AC and DC HC FeMn campaigns

Metallurgical parameter	Specifics	Units	Details/values			
	Smelting campaign		AC		DC	
Tap numbers where alloy samples were contaminated			13 to 16		25 to 28	
	Selected periods/taps		7 - 12	17 - 22	29 - 40	41 - 54
Average alloy composition		% Mn	77.2	77.1	78.0	78.7
		% Fe	15.6	15.4	15.9	15.5
		% Si	0.6	1.0	0.7	0.9
		% C	6.6	6.5	6.9	6.6
Standard deviations on alloy composition						
		% Mn	1.6	0.6	1.6	2.9
		% Fe	0.4	1.0	0.8	0.9
		% Si	0.3	0.6	0.6	0.5
		% C	0.2	0.4	0.2	0.3
Average slag composition		% MnO	27.4	25.5	25.4	23.7
Slag basicity mass ratio [(CaO + MgO)/SiO$_2$]			1.3	1.3	1.3	1.4
Standard deviations on slag composition and slag basicity mass ratio [(CaO + MgO)/SiO$_2$]		% MnO	6.3	3.6	7.4	6.8
			0.1	0.1	0.1	0.1
Slag – to – alloy mass ratio			0.82		0.82	
Average tapping temperature		° C	1490		1495	
Standard deviation on tapping temperatures		° C	50		51	
Manganese deportment	To alloy	%	82.1 ± 0.5		83.4 ± 0.5	
	To slag	%	17.9 ± 0.5		16.6 ± 0.5	
Mn – to – Fe mass ratio	Feed		5.4		5.4	
	Alloy		5.0		5.0	
Energy consumption	process	kWh/kg alloy	3.15		3.23	
	Actual #	kWh/kg alloy	6.01		5.59	
Graphite electrode consumption		kg/MWh	8.9		8.9	

5.2 Comparison between SiMn Smelting in AC and DC Submerged-arc Furnaces

5.2.1 Refractory temperatures

The average sidewall and hearth temperatures for the two SiMn smelting tests are summarized in Table 9. Towards the end of the DC SiMn campaign, the hearth temperature T 1 did not stabilize but approached 900ºC indicating that hearth erosion was extensive and failure thereof imminent.

Table 9: Sidewall and hearth temperatures for AC and DC submerged-arc smelting of SiMn

Campaign	Temperatures	Unit	Sidewall refractory lining			Hearth lining	
Refractory type			Fused-grain MgO-Cr$_2$O$_3$ bricks			MgO/CaO dry ramming	
	Designation		T 1	T 2	T 3	T 1	T 2
AC SiMn	Numerical average	° C	61	45	41	204	167
	Standard deviation	° C	7	6	12	7	22
DC SiMn	Numerical average	° C	38	54	56	465	192
	Standard deviation	° C	4	6	7	143	28

Sidewall thermocouples used with the SiMn tests showed lower temperatures than those in the HCFeMn tests due to their position – only about 1 to 2 cm into the cold face of the bricks as opposed to being cast about halfway into the MgO-Al$_2$O$_3$ lining used in the HCFeMn tests. Further confirmation that there had not been any erosion of the MgO-Cr$_2$O$_3$ bricks during the SiMn tests was the fact that the Cr$_2$O$_3$ levels in the slag were very low.

5.2.2 Metallurgical comparison with results as received

The metallurgical comparison between the AC and DC submerged-arc smelting tests on silico-manganese is summarized in Table 10.

Table 10: Comparison results as received between AC and DC submerged-arc smelting of SiMn

Metallurgical parameter/specifics	Units	Details/values					
Campaign		AC smelting of SiMn			DC smelting of SiMn		
Gloria – to – Nchwaning ore ratio		50:50	70:30 condition		70:30 condition		50:50
Mn-to-Fe ratio in ore blend		5.42	6.11		6.11		5.42
Period number within condition			1	2	1	2	
Tap/batch numbers selected within period		0 to 12	13 to 21	22 to 29	3 to 8	9 to 24	28 to 48
Numerical average analyses of tapped alloy	% Mn	57.3	60.4	64.3	59.3	54.8	46.0
	% Fe	23.0	19.6	19.6	18.7	21.0	32.3
	% Si	13.2	14.8	13.3	15.2	14.7	11.3
	% C	1.7	1.6	2.2	1.7	1.4	1.6
Mn-to-Fe ratio in tapped alloy		2.49	3.08	3.28	3.17	2.61	1.42
Standard deviation on analyses of tapped alloys	% Mn	9.3	3.3	4.7	7.2	5.5	9.6
	% Fe	7.3	3.4	5.0	6.2	6.7	13.8
	% Si	3.5	3.0	2.1	3.1	3.2	2.8
	% C	0.7	0.4	0.3	0.8	0.5	0.8
Weighted average analyses of tapped alloys	% Mn	55.5	60.5	66.4	59.8	55.7	46.3
	% Fe	24.4	19.4	17.7	19.3	19.6	31.3
	% Si	13.7	15.3	14.3	14.7	14.8	11.5
Overall alloy mass	ton	1.27			1.47		
Assumed iron pick-up	kg	106			251		
Lance rod consumed per tapping operation	kg	3.5			5.2		
Numerical average slag composition and basicity ratio #	% MnO	21.2	21.0	23.5	21.8	9.4	19.2
	Basicity ratio	0.7	0.6	0.6	0.6	0.9	0.7
Standard deviation on slag composition and basicity ratio	% MnO	4.2	5.3	3.6	4.0	6.6	6.5
	Basicity ratio	0.1	0.1	< 0.1	0.1	0.2	0.2
Average tapping temperature	Alloy, ºC	1374	1437	1403	1373	1332	1355
	Slag, ºC	1484	1490	1486	1427	1465	1465
Standard deviation on tapping temperature	Alloy, ºC	53	50	29	17	31	24
	Slag, ºC	49	22	83	24	62	23
Graphite electrode consumption	kg/MWh	8.4			8.5		
# In the calculation of the average slag analyses for the DC test, tap numbers 15, 16, 18, and 19 were excluded due to alloy contamination as evident from iron levels in excess of 5 %. Tap numbers 17 and 18 were excluded in the AC test for the same reason.							

5.2.3 Metallurgical comparison with results corrected for SiMn alloy contamination by iron

Chemical analyses and energy consumption values were calculated based on a "corrected" mass of alloy, which excluded the iron dilution from the tapping lance, and assuming 100% accountability of the iron input from the raw materials.

Corrected alloy analyses were calculated based on a methodology employing the Mn-to-Fe ratio as verifying parameter. Initially an expected Mn-to-Fe ratio for the corrected alloy product was calculated for each campaign and each period within that campaign. These target Mn-to-Fe ratios were determined from the Mn-to-Fe ratio in the manganese ore feed blend and the deportment of manganese and iron between the slag and alloy phases. Secondly, through a trial-and-error procedure, small portions of the total known masses of excess iron for each campaign were

subtracted from the original iron mass for each tapping operation until, finally, the Mn-to-Fe ratios of the corrected alloys correlated with those set as the targets.

The corrected alloy analyses and energy consumptions are summarized in Table 11 together with details of various parameters used in the calculation of the "corrected" results.

Table 11: Comparison of corrected results between AC and DC submerged-arc smelting of SiMn

Metallurgical parameter/specifics	Units	Details/values					
Campaign		AC smelting of SiMn			DC smelting of SiMn		
Ore ratio condition		50:50	70:30 condition		70:30 condition		50:50
Period number within condition			1	2	1	2	
Selected period tap/batch numbers		0 to 12	13 to 21	22 to 29	3 to 8	9 to 24	28 to 48
Corrected alloy mass	ton	1.16			1.22		
Overall slag-to-alloy mass ratio #		1.68			1.59		
Numerical average % MnO in slag		21.2	21.0	23.5	21.8	9.4	19.2
% deportment of Mn to alloy *		69	70	69	70	84	71
% deportment of Mn to slag *		31	30	31	30	16	29
Calculated target alloy Mn-to-Fe ratio	Period	4.22	4.77	4.69	4.78	5.72	4.33
	Total	4.52			4.91		
Corrected analyses of alloy	% Mn	62.8 †	64.8 †	68.4	64.2 †	62.2 †	58.7 †
	% Fe	14.8	13.7	14.6	13.3	10.8	13.5
	% Si	15.4	16.3	14.8	15.7	16.8	14.8
Mn-to-Fe ratio in corrected alloy	Period	4.24	4.74	4.68	4.81	5.78	4.34
	Total	4.48			4.92		
Process energy consumption	kWh per kg corrected alloy mass	Period	6.8	6.0	4.9	5.6	7.0	5.6
		Total	5.9			6.0		
Actual energy consumption		Period	12.1	10.1	9.2	9.4	12.7	12.6
		Total	10.4			12.1		
# The overall slag-to-alloy ratio was used in the calculations using "corrected" alloy masses							
		† Low Mn value could be due to 3 – 5 % slag in samples					
* Based on initial estimated "corrected" percentage manganese in alloy, and iteratively converged							

6   CONCLUSIONS

A total of over 8 tons of South African manganese ores have been smelted to produce HCFeMn, containing > 76% Mn in both an AC and a DC pilot-scale submerged arc operation. A comparison of metallurgical parameters including graphite electrode consumption [kg/MWh], process energy consumption [kWh/kg alloy], HCFeMn alloy grade and manganese recovery to alloy indicated that the DC submerged arc process is a viable alternative to a conventional AC submerged arc smelting process. There was no evidence of furnace hearth erosion during the DC submerged-arc HCFeMn smelting campaign.

The smelting campaigns to produce SiMn using both an AC and a DC submerged arc pilot-furnace were more difficult than the two HCFeMn test in terms of operability – the furnace operation with SiMn was prone to slag foaming and tapping difficulty at this scale. As a consequence, alloys were diluted with iron from the oxygen tapping lance, and a "corrected" alloy grade had to be calculated to negate this dilution effect. Also, manganese levels in the slag were in general somewhat higher than the 10 to 20% MnO levels obtained during commercial SiMn smelting in South Africa. In addition, shorter electrode tip to hearth distances of about 5 cm as opposed to approximately 20 cm in the HCFeMn tests, resulted in hearth erosion during the DC SiMn test, thereby changing the thermal profile and the slag basicity (and thereby the process chemistry). However, there was a short period of operation during the DC SiMn test prior to the onset of the hearth erosion, which may be compared with the AC SiMn test – notably the DC test period Taps 3 to 8 compares well with the AC test period Taps 13 to 21 in terms of the metallurgical parameters of alloy grade and manganese deportment to the alloy. The overall graphite electrode consumption and overall process energy consumption for the two SiMn

campaigns are also comparable. These results indicate that with the necessary process optimization, a DC submerged arc SiMn operation would be viable and be able to match the conventional AC submerged-arc process for the production of SiMn.

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