PROPERTIES OF NCHWANING AND GLORIA ORE IN THE PRODUCTION OF Mn FERRO-ALLOYS

[1]Marius Visser, [2]Herman Smith, [3]Eli Ringdalen, [4]Merete Tangstad

[1]African Rainbow Minerals Limited, Johannesburg, South Africa
[2]Assore Limited, Johannesburg, South Africa
[3]SINTEF Materials and Chemistry, Trondheim, N-7465, Norway
[4]Norwegian University of Science and Technology, Trondheim, NO-7491, Norway

ABSTRACT

South African manganese ores, such as the ores mined at the Nchwaning- and Gloria- mines are used by various producers of Mn alloys around the world. These ores are often mixed with acid ores from e.g. Gabon and Groote Eylandt. The South African ores are known for their content of basic oxides like CaO and MgO and for their advantageous low P content. In addition to the chemical composition, other features are also of importance. The CO reactivity of the South African ores is lower than their acid counterparts but their strength is higher. This is as a result of the low porosity associated with these ores. The last property to be discussed is the high melting temperature of these ores, which will be advantageous where a higher smelting temperature is required during for example the production of SiMn.

KEYWORDS: *Carbothermic reduction, manganese ores, CO-reactivity, process temperature.*

1. INTRODUCTION

The major part of high grade manganese ores today are used to produce manganese ferroalloys for steel production. Most of it is produced in Submerged Arc Furnaces (SAF), while a decreasingly lower proportion is produced in blast furnaces. In the SAF, as well as the blast furnace, the quality of the manganese sources will affect the *product quality, the energy consumption and the stability of the operation.* In addition, it will also affect environmental emissions, like mercury and arsenic emission.

The Mn ores contain Mn-oxides, like MnO_2 and Mn_2O_3, and Fe_2O_3. Heat treated ores, like sinter or pellets are usually in the form of Mn_3O_4 and Fe_3O_4. The ores typically also contain other oxides like CaO, MgO, SiO_2 and Al_2O_3, in addition to minor elements like K_2O, BaO, TiO_2 and so forth. Carbonates may also be present in the ore, either as $CaCO_3$, $MgCO_3$ or $MnCO_3$. The reductant added is metallurgical coke, char, charcoal, coal and/or anthracite. Most carbon sources that have sufficient strength to survive up to the high temperature zone may be used. The choice of reductant is thus usually more dependent on price and availability, than quality.

The product quality is defined by the chemical analyses and strength of product. Close to all of the Fe and P in the ore will end up in the metal as shown in figure 1 where ΔG is negative at temperatures well below the operating temperature. Hence the Mn and P content in the alloy are determined by the Mn/Fe ratio and Mn/P ratio in the ore in addition to the slag strategy. The silicon in the metal is, as seen in figure 1, produced at higher temperature compared to Mn. Hence the silicon content in the metal is determined by the temperature in the high temperature zone as well as the slag chemistry given by $\%SiO_2$ and basicity.

The energy consumption for the product is usually given in kWh per ton of metal. In the high temperature zone the reactions are given by the following reactions:

$$[MnO] + C = \underline{Mn} + CO(g) \quad (1)$$

$$[SiO_2] + 2C = \underline{Si} + 2CO(g) \quad (2)$$

$$C = \underline{C} \quad (3)$$

where brackets show that the oxides are in a liquid slag phase and underscored show the alloy consisting of Mn, Fe, Si and dissolved C. For a given product, e.g. 78% Mn, 14% Fe, 7% C, the energy used in the high temperature zone producing 1 ton of alloy is constant. Because of this, the variances in energy consumption are mainly due to exothermic- and endothermic- reactions in the low temperature zone. Hence, the ore properties will affect the energy consumption per ton of alloy produced. The most important properties are total oxygen content in ore and CO reactivity, as will be discussed later.

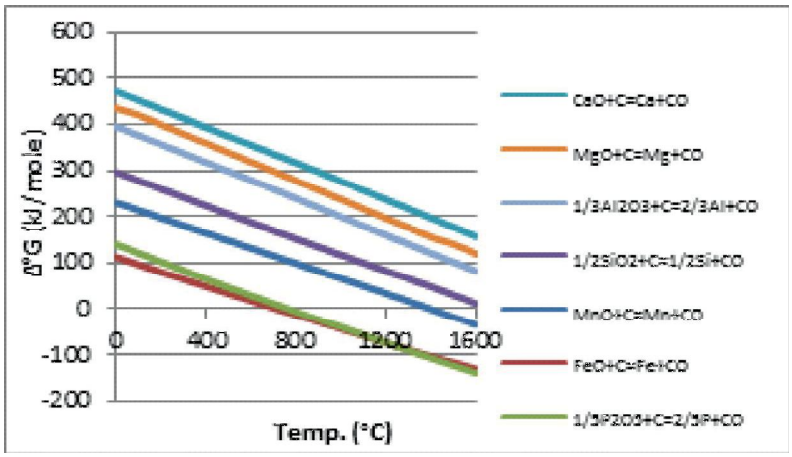


Figure 1: Gibbs free energy versus temperature for the most common oxides in the Mn-ores (HSC Outukumpu v.5)

Maintaining a stable and high load is one of the main goals when operating a furnace. The stability of the operation is important, as this will affect both the total tonnage as well Mn-loss to slag and off gas and energy consumption. As seen in table 1, Pochard et al.[1] reported that limits was set on average oxygen content in the ores, amount of fines and average Zn content in closed FeMn furnaces, due to furnace stability. In addition the strength of the ore may also affect the stability, as a lower strength ore will result in more fines in the furnace burden.

Table 1: Safety limitations reported by Pochard et al. 2007[1]

	Sealed furnaces	**Open furnaces**
Available oxygen	max 12%	No limitations
Ore fines	max 25% -6 mm	max 25% -6 mm
Zn content	< 0.07%	<0.07%

Some of these important properties have been investigated for Nchwaning ore and Gloria ore. In the following sections, the chemical and mineralogical composition, the CO reactivity, the porosity and thermal strength, as well as the melting behavior of these ores will be reported and discussed.

2. CHEMICAL ANALYSES AND MINERALOGY

The chemical composition was analyzed by SINTEF Molab using the thermogravimetry, permanganometric titration, XRF and IR methods.

Nchwaning ore and Gloria ore analyses are shown in table 2. They are typical of South African ores in their oxygen content, their Mn/Fe ratio and their low P content. The manganese-oxide in these ores are on average $MnO_{1.4\text{-}1.5}$, which is very close to Mn_2O_3 (=$MnO_{1.5}$). In comparison, commercial acid ores are MnO_2 ores, like Comilog-ore and Groote Eylandt ore as shown in table 3. Lower oxygen content will increase the energy consumption, but it will at the same time give a more stable operation. Hence, high oxygen ores are usually mixed with low oxygen raw materials like sinter, to decrease the average oxygen content.

Table 2: Composition of Nchwaning and Gloria ores

	Nch A	Nch B	Nch C	Nch D	Glo A	Glo B
Mn_{tot}	42.70	44.30	45.50	41.30	35.20	36.20
MnO_2	29.10	31.20	32.50	28.90	24.80	17.20
Fetot	12.40	8.90	9.00	11.20	5.30	5.40
SiO_2	6.50	5.50	4.70	3.90	6.30	6.10
Al_2O_3	0.40	0.30	0.30	0.30	0.30	0.20
CaO	7.10	8.90	7.10	3.80	14.90	14.20
MgO	0.95	1.10	0.45	< 0,1	4.10	3.70
TiO_2	< 0,05	< 0,05	< 0,05	0.06	< 0,05	< 0,05
P	0.05	0.03	0.04	0.05	0.02	0.02
S	0.15	0.26	0.41	1.70	0.08	0.16
K_2O	0.02	0.01	0.01	0.01	0.02	0.01
BaO	0.75	0.78	1.70	7.30	0.34	0.67
L.O.I.	3.70	5.20	3.80	0.96	17.10	16.30
CO_2	2.70	4.30	3.10	0.82	17.80	16.90
H_2O	0.08	0.16	0.09	0.06	0.10	0.17
Mn/Fe	3.4	5.0	5.1	3.7	6.6	6.7

Table 3: Chemical composition of some commercial Mn-ores (Olsen et al 2007[2])

Manganese ore	Mn/Fe	H_2O	SiO_2	Al_2O_3	MgO	CaO	K_2O	P	CO_2
Comilog MMA	18.5	8.7	4	5.5	0.3	0.2	0.7	0.11	0.1
Comilog MMD	9.5	9	7.7	7.2	0	0.1	0.8	0.09	0.1
Comilog MMR	13.9	9	5	6.1	0.1	0.1	0.8	0.11	0.1
Comilog MMS	12	9	7.7	7.5	0	0	0.8	0.09	0.1
Comilog Sinter	16.7	1.5	7	6.5	0	0.1	0.75	0.12	0
Asman 48	5.1	0.9	5.5	0.4	0.7	4.3	0	0.04	0.8
Amapa Sinter	5.1	1	7.6	7.6	0.5	0.8	0.3	0.1	0
Amapa Miudo 40	3.3	10	5.9	8.1	0.1	0.3	0.8	0.11	3.5
Mamatwan	8.2	1	4	0.5	3.5	14.7	0	0.02	17
Gloria	7.8	0.4	5.7	0.3	3.8	12.7	0	0.02	15.4
Groote Eylandt	11.6	2.7	6.9	4.2	0.1	0.1	2	0.09	0.5
CVRD sinter	11.5	0.6	5.4	8.7	0.5	1.9	1.4	0.11	0.2
Wessel 38%	3.2	1.2	4.9	2.5	1	6	0.1	0.04	3.6
Wessel 50%	5	0.9	3.6	0.4	1	5.6	0.1	0.04	2.6

Most of the ferromanganese producers today operate with a basic slag, either in the duplex process or in the discard slag process. In both strategies, basic oxides are required. As both the Nchwaning ore and even more so, the Gloria ore, are basic ores with a basicity of 0.9-1.7 and 2.8 respectively, they both can be mixed with acid ores to obtain the desired total basicity. Due to the lower Mn/Fe ratio in the South African ores, the ores must be blended with an ore containing a higher Mn/Fe ratio. In a FeMn alloy with 77.5% Mn and 14.5% Fe, the Mn/Fe ratio in the alloy is 5. Hence, as some of the Mn also reports to the slag, a higher Mn/Fe ratio than 5 is required to obtain the given alloy composition.

The Nchwaning ore and the Gloria ore have one of the lowest P contents of the commercial ores. This will result in a low P content in the alloy, as virtually all of the P in the ore ends up in the metal.

The 6 manganese ores were also characterised using quantitative XRD analysed with Topaz and Rietveld, optical microscopy and EPMA and the results are presented in table 4. Because the main minerals in these samples are optically similar, the main results came from Quantitative Rietveld and EPMA analyses.

Table 4: Mineralogy of Nchwaning ore and Gloria ore samples

Mineral	NA	NB	NC	ND	GA	GB
Braunite 1 Mn_2+Mn_3+$6O_8SiO_4$	42	50	39	22	30	32
Braunite 2- Ca(Mn, Fe)$_{143}$+SiO_{24}	24	9	22	41	0	1
Bixbyite- Mn_3+$2O_3$	6	5	11	8	1	0
Calcite- $CaCO_3$	10	10	8	3	18	20
Kutnahorite- $Ca(Mn,Mg,Fe)(CO_3)_2$	0	1	2	0	32	21
Jacobsite-$(Mn^{2+},Fe^{2+},Mg^{2+})(Fe^{3+},Mn^{+3})_2O_4$	0	0	0	0	4	4
Hausmannite-$(Mn^{2+})(Fe^{3+}, Al^{3+})O_4$	2	9	5	7	9	14
Hematite- Fe_2O_3	10	7	6	8	3	3
Barite- $BaSO_4$	1	1	4	10	0	1
Manganite- MnO(OH)	4	3	2	1	0	0
Marokite- $CaMn_3$+$2O_4$	-	5	1	1	1	2
Bementite $Mn_8Si_6O_{15}(OH)_{10}$	-	-	-	-	3	2

The Nchwaning ores contain mainly Braunite 1 and Braunite 2, while Gloria contains Braunite 1 in addition to the carbonates in the form of Calcite and Kutnahorite. The Kutnahorite contains about equal amounts of Ca and Mn, no Fe and traces of Mg. Hence, the carbonate phase is mostly calcium-carbonate and the major part of the Mn is present as Mn_2O_3. Only about 20% of the Mn is present as carbonate in the Gloria ore.

Compared to acid ores, like CVRD ore, Comilog ore and Groote Eylandt ore, none of the phases are common as shown in table 5.

3. CO REACTIVITY, POROSITY AND THERMAL STRENGTH

As the ores are heated in the Submerged Arc Furnace with solid carbon, the higher manganese- and iron- oxides will be reduced with CO gas according to the following reactions:

$$MnO_2+½CO_{(g)} \quad ½Mn_2O_3+½\ CO_{2(g)} \qquad (4)$$

$$½\ Mn_2O_3+{}^1/_6CO_{(g)} \quad {}^1/_3Mn_3O_4+{}^1/_6CO_{2(g)} \qquad (5)$$

$$^{1}/_{3}\ Mn_3O_4 + {}^{1}/_{3}CO_{(g)} \qquad MnO + {}^{1}/_{3}CO_{2(g)}, \qquad (6a)$$

$$^{1}/_{3}C + {}^{1}/_{3}CO_{2(g)} \qquad {}^{2}/_{3}CO_{(g)}, \qquad (6b)$$

$$^{1}/_{3}Mn_3O_4 + {}^{1}/_{3}\ C \qquad MnO + {}^{1}/_{3}\ CO_{(g)}, \qquad (6)$$

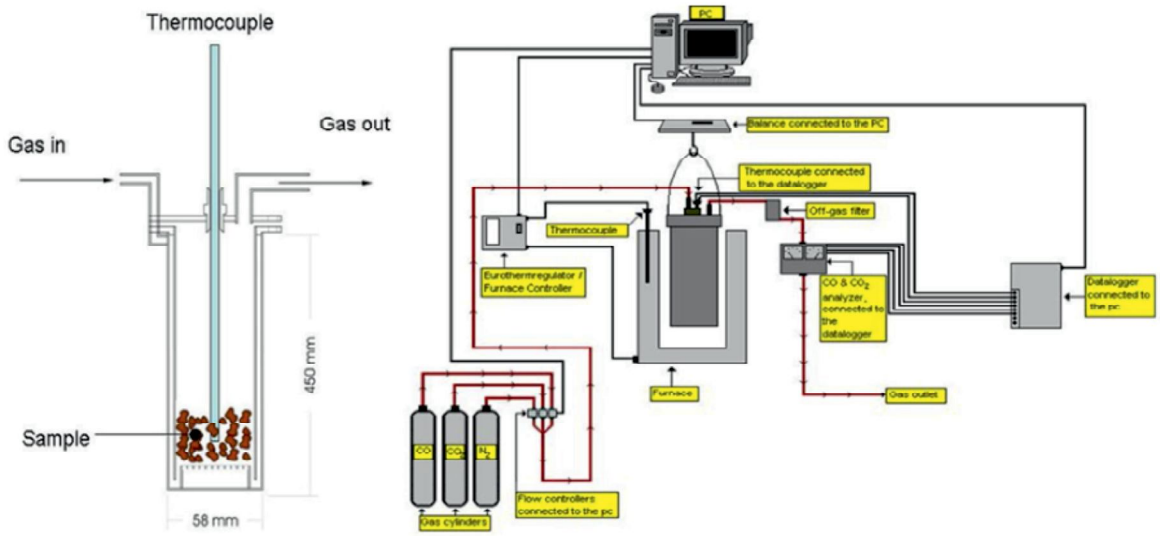
Table 5: Mineralogy of some commercial ores [3]

Mineral	Formula	% *Mn*	Comilog ore %	CVRD ore %	Wessel ore	Groote Eyland ore
Hausmannite	$(Mn^{2-})(Mn^{3-})_2O_4$	*64*			X	
Pyrolusite	MnO_2	*63,2*	14,3	3,0		X
Manganite	MnO(OH)	*62,5*			X	X
Cryptomelane	$K_xMn^{4-}{}_{8-x}Mn^{2+}{}_xO_{16}$	*56*	35,3	13,7		
Bixbyite	$(Mn, Fe)_2O_3$	*55*			X	
Todorokite	$(Mn^{2-},Ca,Na,K)(Mn^{4-},Mn^{2-},Mg)_6O_{12} \cdot 3H_2O$	*49-52*		18,3		
Braunite II	$Ca(Mn)_{14}SiO_{24}$	*52*			X	
Lithiophorite	$(Al,Li)Mn^{4+}O_2(OH)_2$		7,4	5,3		
Nsutite	$(Mn^{4-})_{1-x}(Mn^{2+})_xO_{2-2x}OH_{2x}$, where x = 0.06-0.07		32,6	35,5		
Quartz	SiO_2		5,9	1,8	X	X
Kaolinite(BISH)	$Al_2Si_2O_5(OH)_4$			15,2		X(?)
Hematite	Fe_2O_3		1,5	5,8		
Calcite	$CaCO_3$				X	

The reduction of Mn_3O_4 to MnO may take place by one of two reaction paths. First, it may be reduced by $CO_{(g)}$ in an exothermic reaction (reaction 6a). Second, this reaction may take place in conjunction with the endothermic Boudouard reaction (6b). It is believed that the Boudouard reaction (6b) will occur above about 800 °C, and if all the Mn_3O_4 is reduced before this temperature, that is no oxygen left above MnO, the Boudouard reaction will not occur as no CO_2 is developed above this temperature. CO reactivity is thus measured by determining the quantity of oxygen above MnO that remains in 10-15 mm particles heated above 800°C, in the presence of a 70%CO and 30% CO_2 gas mixture.

The CO reactivity test was performed in the apparatus shown in figure 2. Approximately 200g of the fraction 10 -14.7 mm was used in each experiment. The reduction of the materials was performed in a crucible as shown in the figure. The sample thermocouple was positioned near the centre of the charge, and the gas flow was preheated by flowing down an annulus in the wall of the crucible and entered the charge from below. Controlling of the furnace temperature was performed by a thermocouple placed near the heating element. The crucible was hooked up beneath a balance and the furnace was raised to surround the crucible. During experiments the computer automatically recorded the time, furnace (controlling) temperature, and sample temperature, weight of crucible and individual gas flow rates in the crucible. While running the experiment, the material was be heated under a reducing atmosphere with a blend of CO and CO_2 gas flow. The heating rate was 10°/min up to 1100°C, and the gas flow was 70% CO + 30% CO_2 at 1 atm and 4 Nl/min. When the temperature in the crucible reached 1100°C, the sample was quenched under Ar. During the experiment the temperature of the crucible and the weight loss were measured.

The abrasion test was performed on the reduced manganese ore by analysing the size distribution of the ore before and after 30 minutes of tumbling in a Hannover drum (figure 3). The rotation speed of the drum was 40 r.p.m.



a) b)

Figure 2: Schematic drawing of a) the crucible including thermocouple, gas flow, and charge and b) the thermo balance set-up

Data from the tests includes sample temperature and weight change during the reduction, and C.I. and T.I.5 from the tumbling and sieving tests. C.I. is defined as the fraction of ore left of the original size range after reduction but before tumbling. T.I.5 is defined as the fraction of ore sample larger than 4.75 mm after reduction and tumbling.

The oxygen decrease with increasing temperature is shown in figure 4. Typically these ores are Mn_2O_3 ores, close to a molar ratio of 1.5. As the reduction occurs the Mn_2O_3 (=1.5) will be reduced to Mn_3O_4 (=1.33) and to MnO (=1). At around 800°C, the O/Mn ratio is in the area 1.2-1.4. Compared to other ores as shown in figure 5, this is a bit higher. The ores with the highest reactivity obtains an O/Mn ratio of 1.05 when it is heated to 800°C. In addition to the oxygen associated with the Mn, the figure does not include any CO_2 and oxygen associated with the iron.

The lower CO reactivity in the South African ores is believed to be due to the low porosity. Compared to Comilog ore with a porosity of about 30%, the Nchwaning ore and Gloria ore exhibit a porosity of less than 7% in average. This low porosity however results in a higher thermal strength. About 50-65% of the ore was still larger than 5 mm (TI5) after heating, pre-reduction and tumbling as shown in figure 6. This falls within the high strength area when compared to other ores as shown in figure 7.

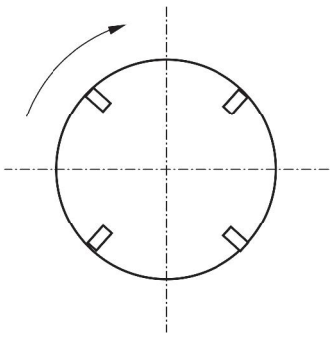


Figure 3: Schematic of a Hannover drum

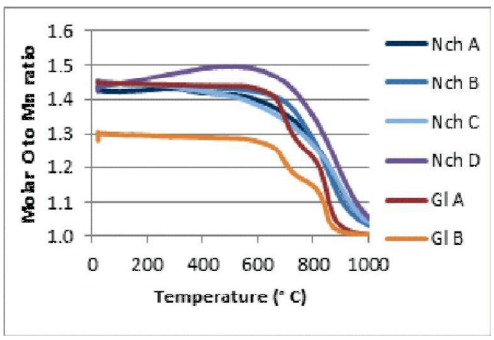


Figure 4: Molar O to Mn ratio with increasing temperature

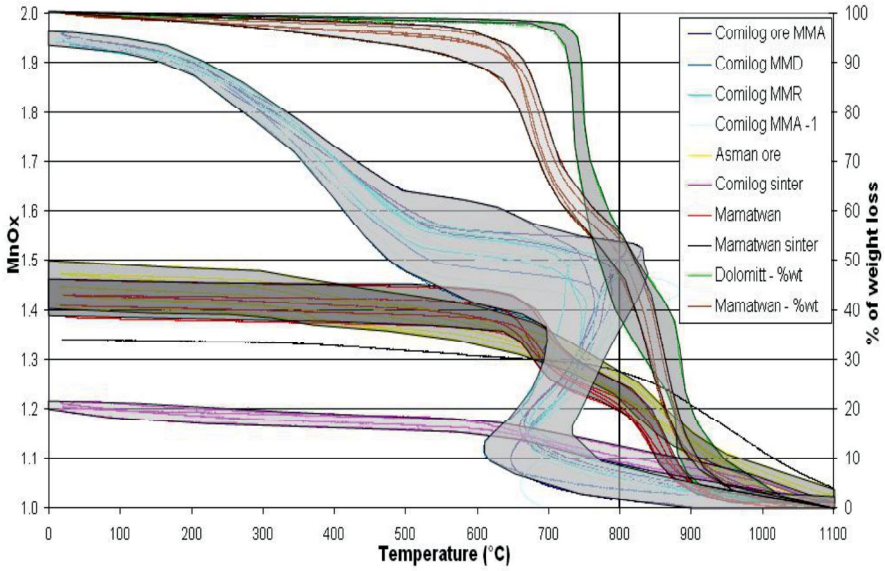


Figure 5: Oxygen content of various ores with temperature in CO/CO_2 atmosphere (Ishak and Tangstad, 2007)

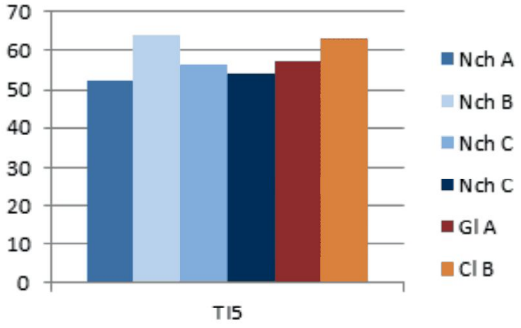


Figure 6: Tumbler index for Nchwaning- and Gloria –ores

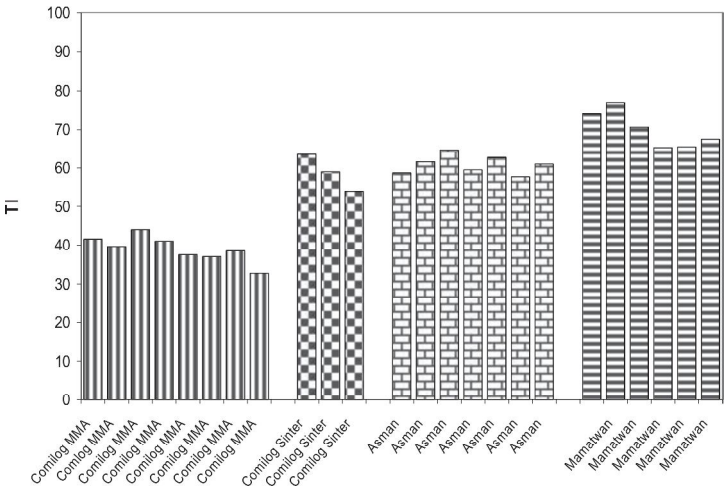


Figure 7: Tumbler index after pre-reduction and tumbling (Tangstad et al. 2004)

4. MELTING TEMPERATURE

The melting behaviour of Mn ores can be illustrated with the MnO-SiO_2 phase diagram as shown in figure 8.

When a pre-reduced ore containing a high amount of MnO is heated, it will form a solid MnO phase in co-existence with a liquid slag phase, as it reaches its solidus (arrow A). If in contact with solid carbon, the MnO in the liquid slag will be reduced, and the solid MnO phase will be dissolved in the liquid phase. Hence, the total content of solid MnO phase will decrease as the MnO is reduced (arrow B). The reduction and melting is thus occurring at the same time. When considering the melting behaviour of the ore, one is thus actually considering both the reduction and melting behaviour.

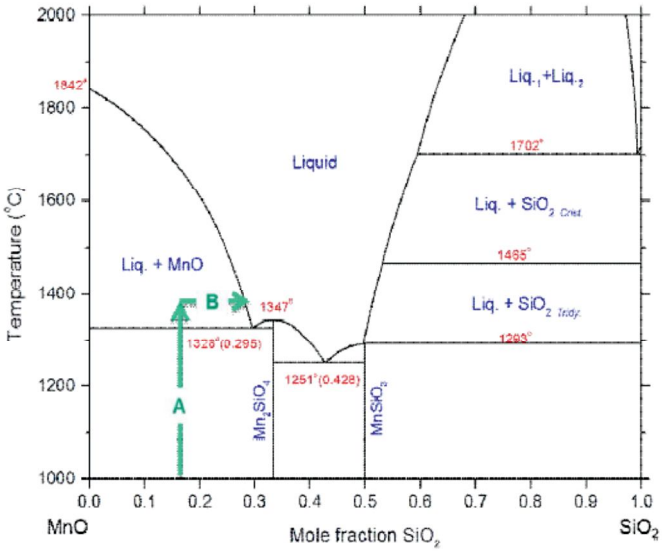


Figure 8: MnO-SiO_2 phase diagram illustrating the reduction path with arrows A and B

The melting behaviour is investigated in 3 apparatus; the sessile drop furnace, the TGA/DTA apparatus and bulk induction melting.

4.1. Sessile drop experiments

When melting properties are measured in the sessile drop apparatus, a 10-50 mg ore sample placed on a graphite substrate is heated in CO-atmosphere under increasing temperature. Changes of sample shape is recorded by video and coupled to measured temperatures. The melting properties are determined by visual analysis of the recorded data:

- Start of melting - when the shape of the particle has lost the sharp edges.
- Final melting - when the droplet is round, with no artefacts.
- Start of reduction - the first bubble is visible.

The melting properties of the investigated Mn sources are shown in table 6. The lowest melting temperatures are found for Nchwaning D that starts melting at 1450°C and are completely molten at 1560°C. Gloria 38 which has the highest melting temperatures will start to melt at 1588 °C and is completely molten at 1702°C. This means that Nchwaning D is completely molten before Gloria 38 start to melt. For all ores gas evolution commences before the ore start to melt. Gas evolution is normally taken as an indication of the start of reduction. Images of the melting experiments with these ores are shown in figure 9.

Table 6: Melting properties of Manganese sources from Assmang measured with sessile drop

	Initial melting	Complete melting	Start of reduction
Nch A	1478	1600	1469
Nch B	1519	1628	1435
Nch C	1521	1550	1314
Nch D	1450	1560	1277
Glo. A	1588	1702	1538
Glo.B	1512	1674	1489

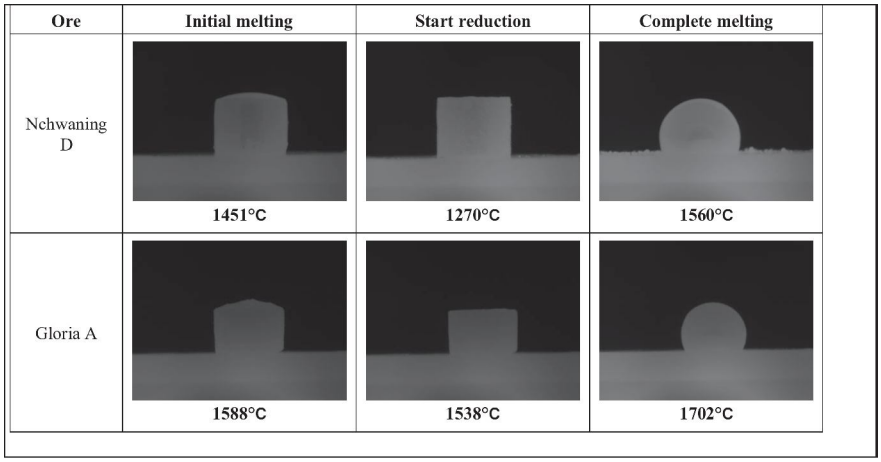


Figure 9: Images of the sessile drop experiments

4.2. TGA/DTA apparatus

When melting properties are measured by DTA/TGA (Differential thermal analysis/Thermogravimetric analysis), a 120-180 mg sample, placed in a graphite crucible is heated with increasing temperature. Weight changes and changes in consumed or evolved energy are measured. Two samples of each ore were tested. An example of DTA/TGA results is shown in figure 10.

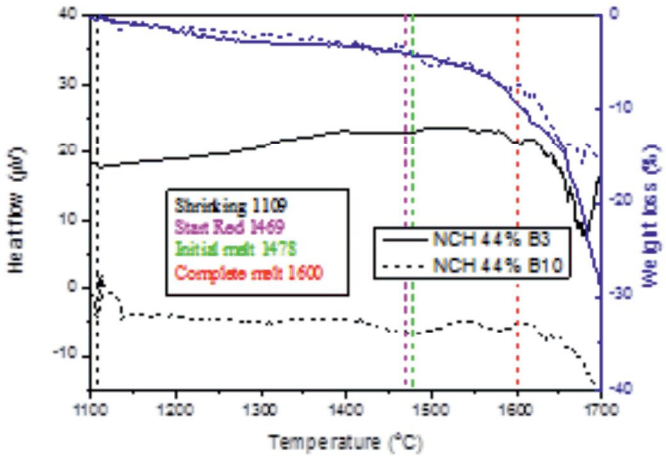


Figure 10: DTA/TGA results for NCH A

The dips in the DTA curves indicate endothermic events, such as melting, phase changes or reduction of the sample. The noisy DTA/TGA signals at high temperatures in all the trials are believed to be due to a relatively high reduction rate that is associated with the evolution of a relatively large amount of gas which results in movement of the sample. This is supported by the dancing droplet witnessed during the sessile drop tests at high temperatures. The temperatures established during the sessile drop test are also shown on this graph as a reference.

The experiments are run up to around 1700°C and provide information up to the temperature determined by the sessile drop tests for complete melting of the ores. The DTA signal provides information regarding phase's changes and can be used to determine the melting temperatures while the TGA signals that shows weight loss are mainly used to identify reduction temperatures and reduction rates.

Based on the DTA and TGA signals, temperature for initial melting and start of reduction for the ores are estimated. Temperature for initial melting is estimated based on the DTA signal. Since this includes a very small amount of melt, the temperature can be higher than measured with other methods. For Mn-ores change in weight-loss from TGA curves is believed to give the best identification of temperature for start of reduction. This is determined manually and is the temperature that is used in further discussions. The melting properties determined by DTA/TGA are shown in table 7.

Table 7: Melting properties determined by DTA/TGA

	Start of melting, °C	Start of reduction TGA, °C
Nchwaning A	1630*	1520*
Nchwaning B	1640*	1500*
Nchwaning C	1652	1550*
Nchwaning D	1604	1550*
Gloria A	1620	1600*
Gloria B	1721	1675*

* Estimated temperature

4.3. Bulk softening and melting

When melting properties are measured by bulk softening and melting a 500 g sample consisting of 10-15 mm ore particles is placed on the top of a coke bed in a graphite crucible. The crucible is heated slowly, and simultaneously the change in height of the charge level is measured. A 10% reduction in height of the charge is defined as the initial melting point, while the ore is regarded as fully molten at 70% slumping. When the height is reduced with 70 % relative to the original height of ore layer, the experiment is stopped. One sample of each material was tested, and the results are shown in table 8.

The sections of the crucibles after the experiments are shown in figure 11. The ore layer in experiments with Gloria contains remnants of un-molten raw material, while all Nchwaning type ores are completely molten.

The amount of metal formed in experiments with all Nchwaning ores is significantly higher than in experiments with Gloria ores. The slag and metal phases in Gloria sections had not drained to the bottom of the crucible. The molten ore had not drained to the bottom. This is most likely due to high viscosity. On the images of Nchwaning ores sections the alloy and some slag phases can be seen almost at the bottom of the crucible. This indicates lower viscosity of slag in comparison to Gloria ores. The results indicate that after 70 % slumping Nchwaning ores were reduced to a higher degree in comparison to Gloria ores. The higher viscosity of Gloria ore indicates higher melting temperatures for these ores.

Table 8: Melting temperatures determined by bulk melting and softening

Ore	Start melting, 10 %	Fully molten, 70 %
Gloria A	1235	1530
Gloria B	1190	1519
Nchwaning A	1202	1473
Nchwaning B	1291	1518
Nchwaning C	1304	1528
Nchwaning D	1284	1514

Examination of the crucibles after the experiment showed that Gloria ores were not fully molten after 70 % slumping and that the bulk melting method did not give the temperature for complete melting of Gloria. Instead of continuous measurement of slumping, it is believed that more information about melting properties could have been achieved by the alternative method with examination of the amount of un-reacted and softened ore when stopped at selected temperatures.

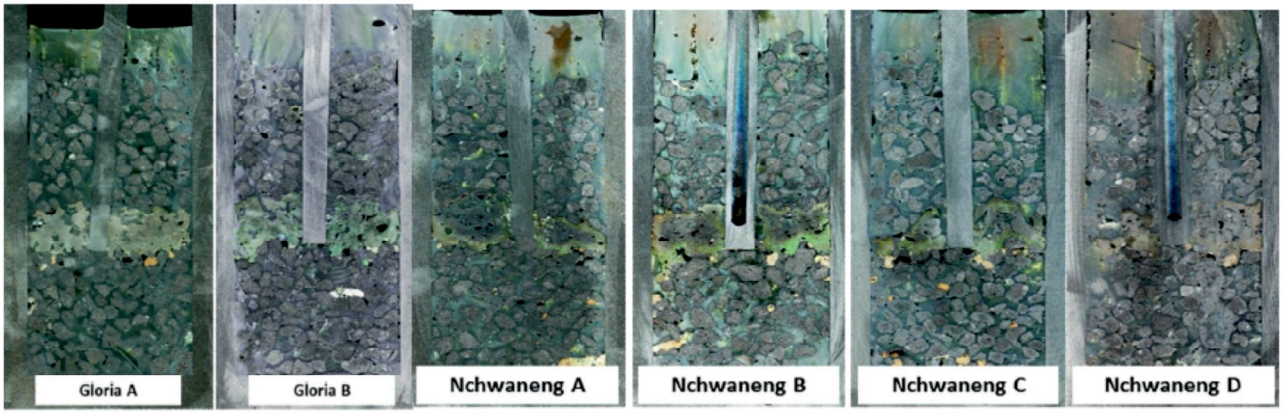


Figure 11: Cross sections of crucibles after heated to 1700°C

4.4. Summary melting behaviour

Measured melting and reduction properties for the investigated ores are shown in table 9. Comparison with other ores and previous investigations of Assmang ores indicates that Nchwaning ores start to melt at approximately or slightly higher temperature than CVRD and Comilog ore, but requires a higher temperature to be completely molten[6,7,8,9,10]. Gloria ores requires a higher temperature than the other ores before it starts to melt, nearly 1600°C for Gloria A, and these ores are not completely molten until around 1700°C. For comparison HC-slag is completely molten around 1230°C and CVRD ores around 1500°C.

Table 9: Most important melting and reduction properties for the investigated Mn-sources

	Init. Melt. sess drop,°C	Start red. TGA,°C	Comp. Melt. sessile drop,°C	TG % reduction at 1600 °C	TG Reduction rate, gram/min	Bulk Melting Ore reduction with 70 % compaction
Nch A	1480	1550	1600	91,8	0.133	High
Nch B	1520	1500	1630	79.9	0.105	High
Nch C	1520	1520	1550	71.5	0.103	High
Nch D	1450	1550	1560	81.8	0.118	High
Glo A	1590	1675	1700	38.2	0.055	Low
Glo B	1510	1600	1675	37.3	0.054	Low

The higher melting temperature of the Nchwaning ore and especially Gloria ore, may be discussed based on the ternary phase diagram shown in figure 12. When the ore reaches a basicity higher than about 1, the pre-reduced ore will be in the 3 phase area of solid MnO-solid $2CaO•SiO_2$ and liquid slag, instead of in the liquid slag+solid MnO area. As the basicity increases, the amount of liquid phase that will be present decreases. To obtain a high reduction rate, the ore requires a high

viscosity and hence a high amount of liquid phase. A higher basicity will hence result in an expected higher reduction temperature.

In an industrial furnace the goal is usually a high and stable load. Hence, if the temperature is too low for the reduction to occur, the temperature will increase. One would thus expect that temperature in the high temperature zone will be somewhat higher, when a high melting ore is used. In the FeMn process this may not be of importance. However, in the SiMn process, a high temperature is required to obtain the desired Si content in the alloy. It is thus believed that a high melting ore will contribute to a higher Si content in the metal.

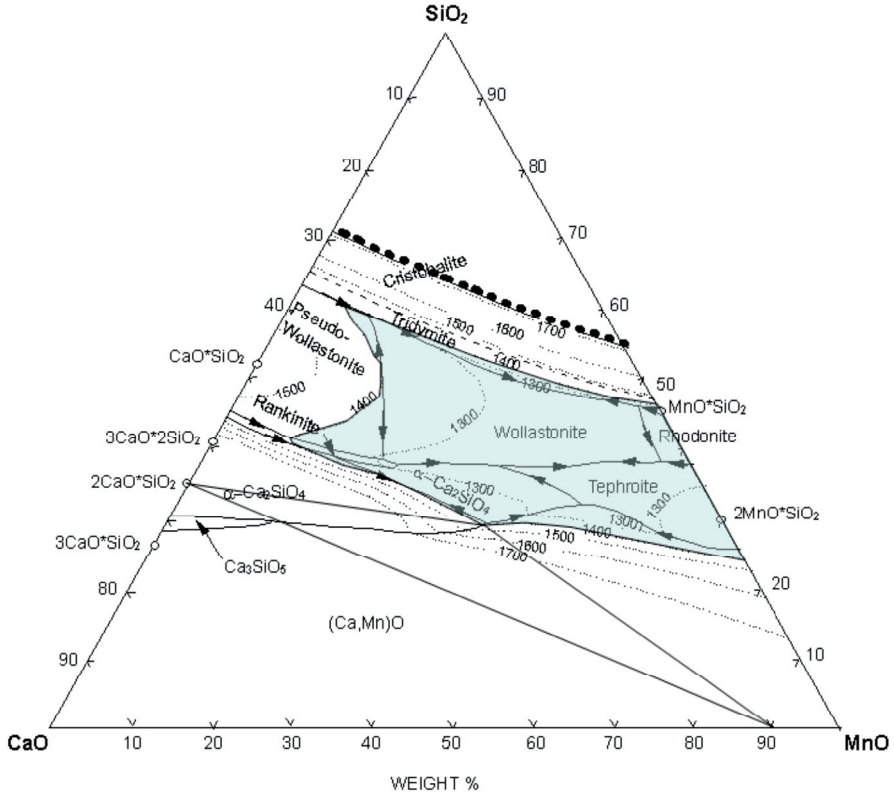


Figure 12: Ternary phase diagram where the liquid area at 1400°C is indicated

5. CONCLUSION

The properties of Nchwaning ore and Gloria ore have been experimentally investigated. The reproducibility of the properties within the ores is quite good, though the samples are taken from different seams. The differences to other ores are larger than the differences within the ores. The results show that the major advantages with these ores are a low P content and a high strength. In addition, when mixed with acid high oxygen ores, the basic features in the Nchwaning ore will decrease the energy consumption compared to mixing with a carbonate like lime or dolomite. Also the stability of the operation will increase, as the Nchwaning ore and Gloria ore contain lower oxygen content. Lastly, it is believed that the high melting temperature in these ores will be beneficial when a high process temperature is required, as would be the case in SiMn production.

6. ACKNOWLEDGEMENT

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7. REFERENCES

[1] G. Pochard, L.Joncourt, N.Touchard, C.Perdon, Metallurgical benefit of reactive high grade ore in manganese alloys manufacturing, Infacon XI, 2007, New Delhi, India.

[2] S.Olsen, M.Tangstad and T.Lindstad: Production of Manganese Ferroalloys, Tapir, Trondheim 2007, ISBN: 978-82-519-2191-6.

[3] B Sorensen, S Gaal, E Ringdalen, M Tangstad, R Kononov, O Ostrovski, Phase compositions of manganese ores and their change in the process of calcination, International Journal of Mineral Processing 94 (2010) 101–110.

[4] R. Ishak and M.Tangstad, Degree of prereduction without carbon consumption in industrial furnaces, Infacon XI, 2007, New Delhi, India.

[5] M.Tangstad, P. Calvert, H.Brun, A-G.Lindseth, Use of Comilog ore in FeMn production, Infacon X, Cape Town, 2004.

[6] E. Ringdalen, M. Tangstad, S. Gaal: Initial melting and Reduction of Ore and Fluxes at the Top of the Coke Bed during SiMn-production, Molten Slags and Fluxes, Santiago, Chile 2009.

[7] S. Gaal, E. Ringdalen, D. Vaganov and M. Tangstad, Melting phenomenon of manganese bearing ores, Infacon XII, Helsinki, 2010.

[8] E. Ringdalen, S.Gaal. O. Ostrovski, Ore properties in melting and reduction reactions in Silicomanganese production, Infacon XII, Helsinki, 2010.

[9] E.Ringdalen, S Gaal, M Tangstad, and O Ostrovski: Ore Melting and Reduction in Silicomanganese Production, Metallurgical and Materials Transactions B, Vol 41B (2010) 1220-1229.

[10] D.Slizovskiy, M.Tangstad, S.Wasbø, Melting temperature of ore for ferromanganese production, to be published in 2013.

[11] A.Muan, E.F.Osborne, Phase equilibria among oxides in steelmaking, Addison-Wesley, 1966.