The Reduction of Mamatwan Manganese Ore in a Submerged-arc Furnace*

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Synopsis

The examination of samples of burden taken from a 75 MVA submerged-arc ferromanganese furnace showed that reduction of the ore takes place by different mechanisms, depending on the conditions prevailing in different localities in the furnace. In the higher regions of the furnace, reduction occurs mainly through carbon monoxide. Near the electrode tip, reduction takes place by dissolution of the oxide into the slag and by reduction at the interface between the slag and the reducing agent. In the molten pool underneath the electrode, reduction takes place mainly from the slag, which is in direct and intimate contact with the solid reducing agent. Similar reduction mechanisms were encountered during laboratory tests.

I. Introduction

Between 1975 and 1980, the total installed furnace capacity for the production of ferromanganese in South Africa has more than doubled,¹⁾ finally reaching 300 MVA. The furnaces installed during that period had transformers rated at either 48 or 75 MVA, which was in keeping with world trends towards bigger furnaces.

The activities in South African ferromanganese production are largely centred on the Mamatwan manganese ore-body, which has reserves²⁾ of about 3 000 million metric tons. The Hotazel and Wessels ore-bodies are of a much higher grade³⁾ but are less important because reserves are limited. Mamatwan ore, which is generally blended with other ores to give the desired furnace characteristics, constitutes about 70 % of the total ore charged to electric furnaces in South Africa.

The significance of Mamatwan ore is underlined by the numerous recent studies carried out on various aspects of the metallurgical importance of this ore.

The geology and mineralogy of the ore were investigated by De Villiers,⁴⁾ Pentz,⁵⁾ Kleyenstüber,⁶⁾ Koursaris and See,⁷⁾ and Koursaris *et al.*⁸⁾ investigated the mineralogy of the ore after heat treatment at various temperatures in oxidizing and reducing atmospheres. The mechanisms of reduction of the ore, its reducibility, and the influence of the reducing agent on the reduction process were investigated by Pentz,⁵⁾ Kleyenstüber,⁶⁾ Grimsley,⁹⁾ Koursaris and See.⁷⁾ The reduction tests involved samples ranging in mass from a few grams to a few kilograms and particle sizes ranging from finely pulverized materials to particles up to 13 mm in size.

Those laboratory studies gave valuable information concerning the various aspects that had been investigated. Also, a fairly complete picture emerged of

the probable processes that take place at different localities in a submerged-arc furnace for ferromanganese. It was believed that the ideal method for one to investigate the processes that take place in a furnace was to excavate the furnace and to sample its contents for further analysis.

The furnace M10 at the Meyerton plant of Metalloys Ltd., Transvaal was excavated in October 1977 after 10 days of erratic operation that had lead to its shut-down in September 1977. During those 10 days, the load was at a reduced level. The total energy input for the 2 days prior to shut-down was 494 and 422 MW h, respectively. The total energy consumption per day under good operating conditions was then about 850 MW h. The types and amounts of materials charged to the furnace during the 10 days prior to shut-down are shown in Table 1. The composition of Mamatwan ore is shown in Table 2.

The furnace M10, which had been commissioned in 1973 had been used for the production of high-carbon ferromanganese. The values of its more important parameters were as follows:

Inside diameter of hearth at floor level	9.9 m
Inside depth	5.3 m
Electrode diameter	1.9 m
Transformer rating	75 MVA
Power factor	0.5
Typical load	30 MW

The details of the excavation procedure and some preliminary results are given elsewhere¹⁰⁾ and will not be discussed at length here. It should be borne in mind that the furnace was allowed to cool down naturally and therefore the burden cooled down extremely slowly. The burden was largely removed by excavator and the sample localities given are estimated to be accurate to within 0.25 m of the

Table 1. Types and amounts of materials charged to furnace M10 during the 10 days prior to shut-down.

Material type	Amount (t)	Proportion (%)
Hotazel manganese ore	287	9.2
Mamatwan manganese ore	2 099	67.3
Return slag	136	4.4
Quartz	62	2.0
Coke	272	8.7
Coal	262	8.4

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Table 2. The chemical composition of Mamatwan manganese ore.

Constituent	MgO	Al ₂ O ₃	SiO ₂	CaO	Mn ₂ O ₃	Fe ₂ O ₃	Cr ₂ O ₃	P ₂ O ₅	K ₂ O	CO ₂	H ₂ O
Mass %	3.1	0.10	4.27	12.96	55.90*	5.99**	0.36	0.17	0.21	14.91	0.54

* Total manganese expressed as Mn₂O₃

** Total iron expressed as Fe₂O₃

Fig. 1. Section of furnace M10 showing position of electrodes, furnace diameter at roof and hearth levels and planned sampling localities.

planned localities. Not all of the planned samples were taken because the burden collapsed from the side walls and there was contamination of the sample areas.

II. Sampling Procedure and Sample Identification

Samples were taken mainly from the three planes indicated in Fig. 1. The plan for sampling in each of the three planes is shown in the vertical section of Fig. 2. The location of a sample was established by measurement, the furnace roof, the shell, and the electrodes of the furnace being used as reference points.

The samples were identified with reference to electrode number, level and position. Electrode number refers to the proximity of a sample to a particular electrode. Sample level refers to the vertical distance between the sample locality and the highest point of the furnace shell, and sample position refers to the horizontal distance between the electrode and the locality of a sample. Position 0 refers to samples taken at any level directly underneath the centre of an electrode. For example, sample 1/E/2 (Fig. 2) was taken in the plane CE₁W₁ (Fig. 1) at level E and in position 2, whereas sample 1/E/0 was taken in the same plane at level E but in position 0, which is directly underneath the electrode (Fig. 2). The identifying code of samples taken from the central region (Fig. 1) starts with C. For example, sample C/1/E/2 (Fig. 2) was taken from the central region in

plane CE₁W₁ at level E and position 2.

Because the furnace burden was unhomogeneous, large samples had to be taken. The samples from face CE₁W₁ varied in mass between 2 kg and 10 kg, the mean being 4.6 kg. Processing of the samples involved screening for separation of the fine material (smaller than 3.3 mm), sorting of the reducing agent from the ore and slag, crushing, sampling at different stages, microscopic and visual examination, X-ray-diffraction analysis, and X-ray microanalysis by use of a scanning-electron microscope and an energy-dispersive system (EDS).

III. Results

1. The Visual Examination of Samples from Planes CE₁W₁ and CE₂W₂

Examination of the internal structure of furnace M10 showed that the interior of the furnace can be separated into some 10 different zones.¹⁾ Of these, only three or four appear to be of direct metallurgical significance, for example, the cone of fast-descending burden round the electrodes, the coke bed or the mixed coke-slag layer underneath the electrode tips, and the layer of alloy at the bottom.

The visual examination of the samples gave a good indication of the processes that take place in an industrial furnace during its operation.

As the charge descends through the cone of fast-moving material, the ore is reduced progressively and

Fig. 2. Vertical section through the furnace along radius CE_1W_1 (Fig. 1) showing the planned positions for sampling.

significant amounts of slag form near the electrode tip, which leads to sintering. Metallic particles begin to appear on the surfaces of lumps of ore about 2 m below the stockline. Decrepitation of the ore in the cone of fast-moving burden is very limited. Extensive decrepitation and segregation of the reducing agents occurs in the partially stagnant zone next to the furnace wall. The material immediately underneath the electrode tip is powdery, whereas the material adjacent to the alloy layer is hard and crystalline in appearance.

Significant differences were found in the appearance and composition of samples from planes CE_1W_1 and CE_2W_2 . The stage of reduction was much more advanced in samples from plane CE_1W_1 than it was in similar samples from plane CE_2W_2 . Also, the segregation of reducing agents in samples from plane CE_2W_2 was much more pronounced than it was in those from plane CE_1W_1 . The number of samples retrieved successfully from plane CE_3W_3 was limited due to the collapsing of burden and contamination of the sample areas. Samples from this plane are therefore not discussed. However, the processes taking place in plane CE_3W_3 may be expected to be similar to those taking place in plane CE_2W_2 .

Some interesting phenomena were observed in samples of sintered charge taken from different levels in the furnace. Photograph 1 shows a lump of sinter from sample 1/C/1. The partially reduced ore is covered with a layer of slag about 2 mm in thickness, and a lump of coke is cemented in the centre. Metallic particles appear as fissures on the surface of the sintered ore. The chemical composition of the metal-

Photo. 1. Lump of sinter from sample 1/C/1 showing the distribution of metallic particles. The sinter is covered with a thin layer of slag. Actual size ($\times 7/10$)

lic particles depends mainly on their size. Initially the metallic particles consist entirely of iron since wustite is reduced preferentially.⁷⁾ Growth of the iron particles takes place by the incorporation of manganese and carbon during further reduction. Metallic particles picked from the surfaces of sinter and ore particles contained about 54 % manganese, 37 % iron and 5.2 % carbon.

The appearance of the sinter in Photo. 1 shows clearly that for reduction to metal, it is not necessary for the coke and the ore or slag to be in direct contact. This is evident by the fact that there is no more alloy adjacent to the coke lump than there is elsewhere.

Photo. 2. Sinter from sample 1/D/1 showing partially reduced ore, slag, alloy (outlined) and the previous positions of particles of reducing agent (C).
Polished section
Magnification ($\times 7/10$)

Photograph 2 shows a section through a lump of sinter from sample 1/D/1, in which partially reduced lumps of ore are surrounded by a thick layer of slag. It is evident from this sample that, after a certain stage, reduction occurs mainly from the surface layers of the ore lumps. The positions of the lumps of reducing agent relative to the unreduced ore indicate that reduction can proceed without direct contact between the reducing agent and the ore.

In laboratory experiments¹⁾ it was found that the alloy adheres preferentially to the unreduced oxide and not to the reducing agent, as shown in Photo. 2. The examination of samples from the lower levels of the central region showed that this need not be so. In this area, a viscous mixture of slag, partially reduced ore, and reducing agent formed (Photo. 3). In some cases the lumps of reducing agent were totally encapsulated by a layer of alloy, sometimes about 10 mm thick.

2. Physical and Chemical Changes in the Ore during Reduction

The mineralogical composition of Mamatwan ore is well known from previous studies.^{4,5,8)} The ore consists of a very fine aggregate of manganese and gangue minerals with local concentration of gangue in the form of veins and oolites. Manganese in the ore occurs mainly as the silicate braunite, whereas the main gangue minerals are hematite, calcite and dolomite. The microstructure of the ore undergoes drastic changes⁸⁾ when heated to temperatures greater than 1 000 °C in oxidizing or reducing atmospheres.

Microscopic examination of ore samples from face CE_1W_1 showed that the mineralogical changes in ore that has been reacted in a furnace are similar to those that occur under laboratory conditions.⁸⁾

The reduction process starts with the dissociation of calcite, dolomite and braunite, and the reduction of the higher manganese oxides to manganous oxide. These processes, which result in the formation of

Photo. 3. Lumps of reducing agent embedded in a mixture of slag and partially reduced ore. Some of the lumps of reducing agent are surrounded by a layer of alloy.

Photo. 4. The porous structure of partially reduced ore from sample 1/B/1.
Polished section
Magnification $\times 120$, enlarged 45 % ($\times 2/3$)

sponge-like lumps of ore (Photo. 4), take place between the stockline level and level *B* in plane CE_1W_1 . Traces of metal were observed in some samples from this level, indicating that wustite was being reduced to metallic iron.

Between levels *B* and *C* further reactions take place to form a significant number of iron particles in the lumps of ore. Reaction between the gangue oxides and the silica released from the braunite led to the formation of a matrix of viscous slag that surrounds grains of impure manganous oxide. The lumps of ore soften and the porosity is reduced, the pores becoming more rounded in shape (Photo. 5).

Ore samples from level *D* showed coarse oxide grains in the slag matrix, an increased amount of metal in the interior and on the surface of ore lumps, and little porosity. The size of the metallic particles inside ore particles remained basically unaltered whereas the size of metallic particles on the surface of ore particles increased drastically (Photo. 6).

The metallic particles inside ore particles consisted in general of a single phase, whereas those on the surfaces consisted of at least two phases. The microstructure of the metallic phase may be explained adequately by reference to existing sections of the Fe-Mn-C ternary phase diagram. At 600 °C a

Photo. 5. An ore particle from sample 1/C/1 showing MnO particles (light grey) and metallic particles (bright) in a matrix of slag. Pores appear black.
Polished section
Magnification $\times 120$, enlarged 45 % ($\times 2/3$)

Photo. 6. Metallic particles and grains of MnO in a matrix of slag. An alloy globule of eutectic composition adheres to the surface of the ore particle from sample 1/D/1.
Etched with 2 % nitric acid in alcohol
Magnification $\times 120$, enlarged 45 % ($\times 2/3$)

small single-phase field (alpha) exists at the Fe-rich corner of the system. This explains the appearance of small metallic particles in the interior of ore particles and confirms the finding that wustite is reduced to metallic iron before significant reduction of manganous oxide takes place. With significant increases in manganese and carbon contents the alloy composition is placed in one of the two-phase fields of the 600 °C isotherm of the Fe-Mn-C system. The alloy therefore exhibits a microstructure consisting of carbide and austenite. It should be pointed out that knowledge of the Fe-Mn-C system is incomplete and in some instances it appears to be inaccurate. The above arguments therefore should not be taken too far.

The structures observed in lumps of material from samples 1/E/1 and 1/F/1 were drastically different from those discussed above. In these localities the temperature was much higher, and the burden cooled and solidified extremely slowly. The structure of this material consisted of extremely coarse grains of manganous oxide surrounded by a narrow network of slag (Photo. 7). Metallic particles occurred interstitially between the oxide grains and, on occasion

Photo. 7. Coarse grains of MnO surrounded by a film of slag in sample 1/E/1.
Polished section
Magnification $\times 60$, enlarged 33 % ($\times 2/3$)

they appeared to occur inside oxide grains.

3. Phases in Samples from Planes CE_1W_1 and CE_2W_2

The phases in the lumps of partially reacted ore from planes CE_1W_1 and CE_2W_2 were determined by X-ray-diffraction analysis. The phases identified in the coarse fraction of samples from plane CE_1W_1 are shown in Table 3.

It is of interest that metallic manganese is present in some samples, and that the degree of reduction is higher, for comparable levels, in samples near the electrode.

The phases in partially reacted ore or slag in samples from plane CE_2W_2 are shown in Table 4. A comparison of the phases in Tables 3 and 4 will show that, for similar sample level and position, the degree of reduction was higher in plane CE_1W_1 .

4. X-ray Microanalysis of Slag, Oxide and Alloy

The three constituents in samples of partially reacted ore were slag, oxide grains and metallic particles. These constituents were analysed by use of an EDS system coupled to a scanning-electron microscope. Standard samples were not used and the analyses obtained were qualitative.

Comparison showed that the composition of the different phases was similar in the two planes.

The oxide grains consisted mainly of manganous oxide with varying proportions of magnesium oxide as the main impurity. Very low concentrations of calcium oxide and silica were also detected.

The main constituents of the slag were calcium oxide, silica and manganous oxide. The proportion of manganous oxide varied widely between samples.

Variations in the cation concentration in the oxide grains and the slag in sample 1/E/2 are shown qualitatively in Fig. 3.

The metallic nuclei consisted mostly of iron with low proportions of manganese. The proportion of manganese increased with globule size.

The variation in composition of alloy globules as a function of globule diameter is shown in Fig. 4. It should be noted that the iron and manganese contents were complementary for globules as small as

Table 3. Phases in the non-metallic constituents of samples from plane CE_1W_1 .

Sample level	Sample position							
	3	2	1	0	1	2	3	4
B	X	X	BR CaCO ₃ MnO Mn ₃ O ₄	Electrode No. 1	MnO CS-trace	Mn ₃ O ₄ MnO BR	X	X
C	X	X	X		MnO Fe CMS	X	MnO Mn ₃ O ₄ BR	X
D	X	X	X	X	MnO CMS Fe	X	X	CMS C x
E	MnO CMS Fe	MnO CMS Fe	MnO CMS Fe	CMS MnO-trace	MnO Mn	MnO Mn Fe CS-trace	A	MnO Fe x
F	X	X	X	MnO CMS Fe	MnO Mn Fe CMS CS } trace		MnO Mn Fe } trace CS }	MnOA Mn Fe

Key: BR : Braunite
CS : Calcium silicate (Ca₂SiO₄)
CMS : Calcium manganese silicate (Ca, Mn)₂SiO₄

A : Samples consisting of alloy only
X : Samples not taken from these localities
x : An unidentified phase present in appreciable amounts

Table 4. Phases in the non-metallic constituents of samples from plane CE_2W_2 .

Sample level	Sample position							
	3	2	1	0	1	2	3	4
B	X	X	X	Electrode No. 2	X	X	X	X
C	X	X	X		BR Mn ₃ O ₄ CaMg(CO ₃) ₂ CaCO ₃ Fe ₂ O ₃	MnO C x*	R	R
D	X	X	X	MnO CS x	MnO CS x	MnO CS x	C† MnO CMS	R
E	MnO CMS Fe	MnO CMS	MnO CMS	MnO Fe	MnO CMS	R	MnO CMS C	R
F	X	MnO CMS	CMS	A	C† CMS MnO	C† CMS	X	X

Key: * One or more unidentified phases present in appreciable amounts
† For samples 2/F/1, 2/F/2, and 2/D/3, the phases reported are those observed in material smaller than 3 mm;
The coarse fraction from the samples consisted entirely of reducing agent

BR : Braunite
CS : Calcium silicate (Ca₂SiO₄)
CMS : Calcium manganese silicate (Ca, Mn)₂SiO₄

X : Samples not taken from these localities
A : Sample consisting only of alloy
R : Samples consisting only of reducing agent
x : An unidentified phase present in appreciable amounts

Fig. 3. A microanalysis traverse from the centre of a grain of MnO across the slag to a neighbouring oxide grain.

Fig. 4. Variation in the composition of alloy globules of increasing size.

or less than $1\text{ }\mu\text{m}$ in diameter, indicating that the beam penetration was about $0.5\text{ }\mu\text{m}$ or less. Figure 4 also indicates that the manganese content of metallic particles inside ore particles tended to reach a maximum. Microhardness and etching tests showed that the globules in the interior of ore lumps generally contained little or no carbide.

IV. Discussion

As might be expected, the metallurgical structure of the furnace M10 showed significant similarities to the structures observed in other types of electric smelting furnaces.¹¹⁻¹⁴⁾ The molten zones directly underneath the electrodes and the partially molten material around the edge of the electrode tip show

that most of the current is conducted downwards from the electrode tip to the hearth. This is in accord with the findings¹⁴⁾ or postulations^{13,16)} of other investigators. During operation therefore little or no current is conducted between the electrodes and the furnace walls.

The reduction of the ore in the cone of fast-descending material occurs mainly through heating by the stream of gaseous reduction products that are generated in the molten regions. At the periphery of the electrode tip, reduction can take place by heat conducted from the electrode tip or radiated from the molten bath.

The processes that take place during the descent of the burden can be examined with reference to the

samples taken from position 1 in plane CE_1W_1 where it appeared that, at the time of the shut-down, the burden was descending in a steady manner. The examination of the corresponding samples from face CE_2W_2 would be more difficult, since not all of the planned samples were taken from this position.

The main reactions that occurred between the different levels in the furnace are summarized in Table 5.

Braunite and the gangue minerals dissociated between levels *A* and *B*, and the higher oxides of manganese and iron were reduced to their lowest oxidation state by carbon monoxide. Some of the iron oxide was reduced to metallic iron and there was a limited reaction between lime and silica to form slag. The ore became very porous owing to losses of carbon dioxide. The magnesium oxide from the dissociated dolomite formed a solid solution with the manganous oxide.

Further reduction of iron oxide to metallic iron occurred between levels *B* and *C*. The amount of slag increased and formed a continuous network throughout the lumps of ore, as well as a film on the surface, which resulted in appreciable sintering of the burden. The higher temperatures between levels *B* and *C* caused the slag to soften, which resulted in a decrease in porosity and rounding of the pores. It has been shown¹⁾ that the ore softens at a temperature of about 1 000 °C. The formation of slag reduced the permeability of the ore to carbon monoxide and there was no carburization of the metallic particles inside ore particles. The metallic particles on

the surfaces of lumps of ore or sinter were readily carburized and further reduction of manganous oxide appeared to take place at the alloy-oxide interface probably by carbon dissolved in the alloy. This led to a substantial increase in the size of these alloy particles. The manganous oxide could be in the form of solid grains or of oxide dissolved in the slag. The fact that the amount of alloy in the immediate vicinity of lumps of reducing agent embedded in lumps of sinter was not greater than it was elsewhere indicates that down to level *C*, reduction occurred mainly by carbon monoxide as an intermediate product.

Between levels *C* and *D*, the proportion of slag increased drastically, and the partially reduced lumps of ore became completely covered by a thick layer of slag. This facilitated the draining of the larger metallic particles to the furnace hearth while smaller particles adhered to the partially reduced lumps of ore. The formation of a substantial volume of slag reduced the amount of contact between lumps of partially reduced ore and reducing agent, and improved the contact between the slag and the reducing agent. Under these conditions, the reduction of manganous oxide appeared to occur by dissolution of the oxide into the slag and transfer to the slag-reducing agent interface. Carbon monoxide passing through the charge could also reduce manganous oxide from the slag. However, when reactions 11 and 12 in Table 5 are considered, it becomes apparent that reduction by solid carbon is more favourable thermodynamically. The equilibrium constant for these two reactions was calculated at the arbitrary temperature of 1 600 °C. Reaction 11, however, would remain more favourable, thermodynamically, for all temperatures.

As the burden descended from level *D* to *E* and *F*, it entered a region of much higher temperature and vigorous agitation owing to the rapid evolution of gaseous reaction products. These conditions caused the complete disintegration of partially reduced lumps of ore and the formation of a suspension that consisted of liquid slag, solid reducing agent, and solid grains of manganous oxide. The proportion of manganous oxide in samples from level *E* (Photo. 7) was significantly higher than that observed in partially reduced ore from other furnace regions. This indicated that the structures observed were a result of the settling and coalescence of oxide grains.

The processes that took place between levels *D* and *F* are not certain. However, it appears that reduction occurred, in the main, by reaction between the solid reducing agent and the manganous oxide dissolved in the slag, since these two constituents were permanently in contact. Reduction by carbon monoxide would be possible, although less favourable thermodynamically.

The dissolved manganous oxide, would be equally amenable to reduction by solid carbon and carbon dissolved in the layer of alloy on the bottom of the furnace. However, the area of contact between the alloy and the slag could be expected to be much

Table 5. Summary of the main reactions that occurred at different levels in the furnace.

Sample level	Depth in furnace (m)	Reaction No.	Reaction
<i>A</i> to <i>B</i>	0 to 1	1	$3(\text{MnO} \cdot 3\text{Mn}_2\text{O}_3 \cdot \text{SiO}_2) = 7\text{Mn}_3\text{O}_4 + \text{O}_2 + 3\text{SiO}_2$
		2	$\text{CaCO}_3 = \text{CaO} + \text{CO}_2$
		3	$\text{CaMg}(\text{CO}_3)_2 = \text{CaO} + \text{MgO} + 2\text{CO}_2$
		4	$\text{Mn}_3\text{O}_4 + \text{CO} = 3\text{MnO} + \text{CO}_2$
		5	$\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{FeO} + \text{CO}_2$
		6	$\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$
		7	$\text{CaO} + \text{SiO}_2 = \text{CaO} \cdot \text{SiO}_2$
<i>B</i> to <i>C</i>	1 to 2	8	$\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$
		9	$2\text{CO} = \text{C} _{(\text{a})} + \text{CO}_2$
		10	$ \text{C} _{(\text{a})} + \text{MnO} = \text{Mn} _{(\text{a})} + \text{CO}$
<i>C</i> to <i>D</i>	2 to 3	11	$(\text{MnO})_{(\text{s})} + \text{C} = \text{Mn} _{(\text{a})} + \text{CO}$ $\Delta G_{11}^\circ = 287\,441 - 170.07T \text{ J} \cdot \text{mol}^{-1}$ $K_{11(1600^\circ\text{C})} = 7.41$
		12	$(\text{MnO})_{(\text{s})} + \text{CO} = \text{Mn} _{(\text{a})} + \text{CO}_2$ $\Delta G_{12}^\circ = 16\,734 + 169.3T \text{ J} \cdot \text{mol}^{-1}$ $K_{12(1600^\circ\text{C})} = 7.94 \times 10^{-12}$
<i>D</i> to <i>F</i>	3 to 5	13	$(\text{MnO})_{(\text{s})} + \text{C} = \text{Mn} _{(\text{a})} + \text{CO}$ $(\text{MnO})_{(\text{s})} + \text{C} _{(\text{a})} = \text{Mn} _{(\text{a})} + \text{CO}$

Key: Subscript (a)=alloy; (s)=slag.

smaller than that between the slag and the solid reducing agent. Daines and Pehlke¹⁷⁾ consider that the rate of reduction of manganous oxide from a slag by carbon dissolved in the alloy is controlled by the rate of the chemical reaction. If this is so, it can be expected that the amount of reduction carried out by carbon dissolved in the alloy will be small compared with that carried out by the solid reducing agent. This is because the area of contact between the slag and the metal is relatively small.

Reduction of the manganous oxide by carbon dissolved in the alloy would reduce the carbon content of the alloy and there would be dissolution of the carbon from the furnace lining or from the reducing agent in the burden. The fact that the carbon lining at the bottom of submerged-arc furnaces can last for as long as 20 years¹⁸⁾ indicates that dissolution of the lining by the layer of alloy is normally very low. It would, therefore, appear that the alloy dissolved the carbon mainly from the stagnant zones of the furnace, which were rich in reducing agents.

The appearance of samples from the central region of the furnace indicated clearly that manganous oxide could also be reduced by a mechanism somewhat different from those proposed above. The sequence of interfaces between the carbon, the alloy and the slag plus oxide showed that, under certain conditions, the metal reduced by the solid reducing agent can remain in contact with it and eventually form an envelope round the lumps of reducing agent. Further reduction would then occur by dissolution of the carbon into the alloy and transfer to the interface between the alloy and the slag plus oxide. This reduction mechanism is not dissimilar to that proposed by Gimsley⁹⁾ for temperatures higher than 1 200 °C.

The condition that would favour this mechanism would appear to be a relatively low temperature giving a mushy charge. Under these conditions, the fluidity of the slag would be low and the alloy being formed would not drain to lower levels very easily. The appearance of the large quantity of sintered material in the central region of the furnace indicated that these were the prevailing conditions.

V. Conclusions

(1) The examination of samples from a submerged-arc furnace for ferromanganese showed that reduction of the ore can take place by different mechanisms in different furnace localities.

(2) In the cone of fast-descending material, the ore is reduced mainly by reaction with carbon monoxide.

(3) Near and underneath the electrode tip, reduction takes place by dissolution of the manganous oxide into the slag and transport to the interface between the slag and the reducing agent. Reduction does not appear to be significant at the interface between the slag and the alloy layer on the furnace hearth.

(4) Under conditions of relatively low temperature and slow movement of the burden, reduction can

take place by the diffusion of carbon from the lumps of reducing agent through an envelope of alloy and by reaction at the interface between the alloy and the slag plus oxide.

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