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Electric Arc Furnace Production of Standard-Grade Ferromanganese

Curtis Bates

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ELECTRIC ARC FURNACE PRODUCTION OF STANDARD-GR ADE FERROMANGANESE

by Curtis Bates

A Thesis Submitted to the Department of Metallurgy

In Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Metallurgical Engineering

MONTANA SCHOOL OF MINES
Butte, Montana
May 18, 1959
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OF
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ELECTRIC ARC FURNACE PRODUCTION
OF
STANDARD-GRADE FERROMANGANESE

INTRODUCTION

Steel—the backbone of America's industrial might—cannot be made without manganese. Manganese is added to the steel in the form of ferromanganese.

Slag and flue losses in ferromanganese furnaces in the U. S. A. alone amount annually to 120,000 tons of manganese. It was with this thought in mind that this thesis was undertaken.

Definition of Ferro-alloy

Howe's classical definition of a ferro-alloy as "iron so rich in some element other than carbon that it is used as a vehicle for introducing that element in the manufacture of iron or steel" is about the best short definition that has been devised. Common usage, however, has made the term "ferro-alloy" mean somewhat more than this; it now includes a number of alloys so low in iron that they cannot properly be called "iron". For example, calcium-silicon, generally containing a maximum of 6% iron, is usually classified as a ferro-alloy.10
Standard Ferromanganese

Standard (high-carbon) grade ferromanganese has the following range of composition:

Manganese .................. 78 to 82%
Iron .......................... 12 to 16%
Carbon ...................... 6 to 8%
Silicon ....................... 1.00% max
Phosphorus ................... 0.30% max
Sulfur ......................... 0.05% max

This alloy is furnished in various crushed and ground sizes. A common form ranges in sizes from lumps weighing 75 pounds each to pieces about 2 inches in diameter. When made under favorable and closely controlled conditions, standard ferromanganese will not disintegrate or crumble.

The melting point range of standard ferromanganese is between 1960° and 2318° F.

Furnaces for Ferromanganese Production

Ferromanganese can be produced either in a blast furnace or an electric arc furnace. In blast furnace smelting, the same type furnace as that used in the production of pig iron, only smaller, is used.
In electric furnace smelting an open top furnace is used. The general practice is to use 3-phase current with 3 electrodes. Single phase is sometimes used. The furnace is lined with carbon or magnesite and operates at 2,500 kilowatts. Current flows from each electrode into the mixed charge at 75 delta volts or 35 ground volts and 20,000 amperes. The temperature of the electric arc thus produced approaches 6,600° F.

As the charge is reduced and the melt builds up an automatic hoist raises the electrodes and keeps the resistance the same throughout the reduction cycle.

Power consumption is 3,000 KW hours per long ton of ferromanganese produced and carbon electrode consumption is 30 pounds per long ton of ferromanganese.7

Production of Ferromanganese at Anaconda

At Anaconda, ore from the mine, containing about 16% manganese, as MnCO₃, is first treated in the concentrator. Sulphide impurities are removed by flotation, after which a soap flotation is used for rhodochrosite. The rhodochrosite product is thickened and calcined in a kiln to produce small, round, hard, black nodules of MnO.

The furnace charge consists of these nodules, iron in the form of scrap or ore, limestone and coke.
This charge is smelted until the alloy is formed and separates from the slag. The furnace is then tapped from the bottom and the molten mass runs into trays, the slag running off the top of the alloy and into another ladle. After cooling, the ferromanganese is broken up to the desired size and put into railroad cars for shipment to a steel plant.  

Ferromanganese in Steel Production

Among all the alloying elements employed in the manufacture of steel, manganese occupies a unique position. It is an indispensable ingredient in all commercial steels, and all efforts to make manganese-free steels have been in the nature of laboratory experiments.

Ferromanganese is used as a scavenger in open hearth and Bessemer furnaces in the course of converting iron ore to steel. It is added to take up S and O₂ and each ton of steel produced requires from 15 to 20 pounds of manganese to cleanse the molten iron of deleterious elements.

In the production of most steels, ferromanganese is added while the blown metal is being poured into the ladle. This brings about deoxidation and adds the amounts of carbon and manganese required to give good rolling and working properties, and to meet the physical
Fundamentals of Arc Furnace Smelting

In arc furnace smelting operations carbon is added to the charge only to reduce the oxides to metal. The degree of reduction is dependent on the quantity of reductant in the charge. The heat for the reduction reaction is generated either by arcing on the molten bath, or by passage of the current through the molten slag, or by a combination of both. When an arc is maintained between the molten bath and the electrodes the operation is usually referred to as arc-resistance smelting; when the electrodes contact the slag the operation is referred to as slag-resistance smelting. Both roofed furnaces and open-top furnaces are used.

In dry-top, arc-resistance smelting operations, reductants and usually fluxes are mixed with the ore and charged to the furnace. The reductant may be coke, charcoal, sawdust, hagged fuel (green wood chips), metallic reductants such as ferrosilicon; or mixtures of any of these materials. When fluxes are used, fluxing reagents such as limestone or quartz are mixed with the charge so that the resulting slag will be fluid enough to tap from the furnace. When the furnace is operating normally, the charge is kept at a uniform thickness. The electrodes extend through the charge, and the useful heat for the smelting is generated by
the arcing from the electrode tips to the molten bath. The heat is the result of the resistance of the slag or bath to the passage of electric current. Gas produced by the reaction escapes through the porous charge. Metal and slag are tapped from the furnace at regular intervals.

When analysis of the charge materials is known, flux, carbon, and the electric energy requirements for conducting any electric smelting operation can be calculated. Carbon is calculated as percentage over theoretical needed to produce maximum reduction. This is normally based on experience. Fluxes are used to control slag melting temperature and to improve recovery of the metallic constituents. They are also proportioned to minimize corrosion of furnace refractories. The melting temperature and corrosion characteristics of the slag can be determined from phase diagrams of slag constituents.

Slag-to-metal ratio, carbon content of the metal, slag conductivity, and the desired temperature necessary for satisfactory smelting conditions are the factors that determine the proper voltage-current relationship in any particular electric smelting operation. A comparatively high voltage-current relationship is employed where there is a high slag-to-metal ratio. This is especially true when it is desired to produce
a low-carbon alloy such as ferronickel from siliceous nickel ores. Slags produced when smelting these ores have comparatively high resistances. Contamination of the alloy with carbon and high electrode consumption is prevented by using a voltage-current relationship high enough so that the electrodes don't contact the slag.

In operations where no slag is produced, such as the production of aluminum-silicon alloys, a low voltage-current relationship is employed. In this case, it is also important to use a charge having a low electrical conductivity. If either the ratio of the voltage to the current or the conductivity of the charge is too high, current flows without producing enough heat. The voltage rises, sparks develop, and the arc is broken. As a result, the smelting zone is cooled. A continuation of these conditions usually results in an inoperable furnace. Generally these conditions can be corrected by increasing the current to the furnace. However, the current at which the maximum heating occurs is not necessarily the maximum current at which the furnace will operate. The current at which the maximum heating occurs may be called the optimum current. Optimum current differs for each ore being smelted, and is adjusted to the optimum value by line voltage.²
Comparison of Methods

Since the blast furnace and the electric arc furnace can both produce ferromanganese, the method that was used was determined by comparing the two processes.

Both furnaces are capable of supplying the necessary temperature to produce ferromanganese. However, the blast furnace requires about three times as much solid fuel as the electric arc furnace.\(^8\) Also, the loss of manganese in flue dust is much greater in the blast furnace.\(^8\)

Some of the outstanding advantages of the electric arc furnace are as follows:

1. Positive temperature control, as well as any desired temperature.
2. Freedom from contamination of the bath by the fuel, the electric current.
3. Choice of conditions in the furnace; oxidizing, reducing, or neutral.
4. The highly effective reduction zone obtained around the carbon electrode.
5. In the electric arc furnace, deoxidation and desulphurization are simultaneously accomplished.

Since there are many advantages to the electric arc furnace, this method was used to obtain the data for this paper.
Purpose of Investigation

The purpose of this investigation is to determine an operating procedure for electric arc furnace production of standard ferromanganese. An attempt was made to determine a charge which would give steady power consumption in the furnace and at the same time keep the manganese content in the slag to a minimum.

Experimental Work

Work on slag composition has shown that manganese recovery increases as the basicity of the slag increases (Fig. 1). A basic slag with the lowest melting point was used in the beginning. The choice of a suitable slag, as determined by the CaO-SiO₂ phase diagram was 70% CaO - 30% SiO₂ (Fig. 2). As the work progressed the ratio of CaO to SiO₂ was altered in an attempt to produce slags lower in manganese. Other slag constituents were also introduced.

Preliminary Work

The preliminary work consisted in relining an available gas and air furnace. It was found after a few trial runs that the required temperature could not be attained in this furnace. The special silicon carbide crucibles used for these test runs partially fused to the bottom of the furnace and the charge still was not melted. The original plan was to make some test runs in this gas furnace to get an idea of
Relationship between slag basicity and manganese recovery during smelting

Figure 1
CaO-SiO$_2$ Phase Diagram

Figure 2
the procedure to be followed when using the electric arc furnace but this idea was abandoned. Figure 3 shows the furnace and crucible which were used in this part of the testing.

**Electromelt Arc Furnace**

The furnace (Fig. 4) which was used to make the tests belonged to the Research Department of the Anaconda Company. It is a Lectromelt, size W, 50 kva, double electrode, single phase, electric arc furnace.

The furnace bottom is a ladle which can be lifted from the frame by means of two handles to permit the smelted charge to be poured. It was insulated with a refractory material, but since this refractory burned out in a short time, a large carbon crucible was put in the furnace. This arrangement worked quite well.

The electrodes entered the furnace through the top of the roof and are held in place by means of clamps on handles. They can be raised or lowered, and tilted in or out by means of these handles. The electrodes and the roof are kept cool by means of water circulating through pipes. The flow of water through the pipes can be adjusted to protect the roof refractories.

The electric power used by the furnace is 110 volts which is converted from 220 volts by the furnace
Fig. 3 Gas and Air Furnace

Fig. 4 Lectromelt, Size W, Electric Arc Furnace
transformer. The power from the transformer enters one of the electrodes and leaves through the other. The impedance for the circuit (Fig. 5) was not great enough and this had a detrimental effect on the electrical operation of the furnace. This is the most important single factor in the operation of a furnace of this type, according to the operators manual which came with the furnace. An ammeter and wattmeter are mounted on a panel in front of the furnace so the operator can watch them and adjust the electrodes accordingly.
1. Supply - 220 V, 1 Ph, 60 Cycle
2. Line Switch - 2 pole single throw, 250 V, 400A Fused
3. Oil Circuit Breaker
4. Current Trip Coil - 5 Amp (Time Delay)
5. Shunt Trip Coil 40-110V - 60 cycle
6. Power Transformer - 50 KVA and Reactor
7. Manual Tap Changer - 3 Position
8. Interlock Switch - Tap Change and O.C.B. ( Normally Open)
9. Current Transformer - Ratio 800/5 Amps
10. Ammeter 5 Amp. Scale - 200% (100% = 400 Amps)
11. Heatmeter, (Wattmeter) 500 Watt, Scale 0 - 200% 80 KW (100% = 40 KW)
<table>
<thead>
<tr>
<th>Test</th>
<th>Charge Materials</th>
<th>Products</th>
<th>Manganese Recovery</th>
<th>Slag Assays</th>
<th>Metal Assays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Manganese</td>
<td>% Manganese</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Iron</td>
<td>% Iron</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% CaO</td>
<td>% SiO2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>% Al2O3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>21.6</td>
<td>45.10</td>
</tr>
<tr>
<td>2</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>21.4</td>
<td>45.10</td>
</tr>
<tr>
<td>3</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>21.2</td>
<td>45.10</td>
</tr>
<tr>
<td>4</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>21.0</td>
<td>45.10</td>
</tr>
<tr>
<td>5</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>19.0</td>
<td>45.10</td>
</tr>
<tr>
<td>6</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>17.0</td>
<td>45.10</td>
</tr>
<tr>
<td>7</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>15.0</td>
<td>45.10</td>
</tr>
<tr>
<td>8</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>13.0</td>
<td>45.10</td>
</tr>
<tr>
<td>9</td>
<td>6.80</td>
<td>33.75</td>
<td>33.75</td>
<td>11.0</td>
<td>45.10</td>
</tr>
</tbody>
</table>

**Figure 6 Test Results**
Tests

The first test was conducted using the calculated charge weights of each material. The materials were in lump form.

Test #1

Weight of charge materials:

Nodules ......... 6.80 lbs.
Iron Ore ........... 0.61 lbs.
Limestone ........ 2.73 lbs.
Coke .............. 1.92 lbs.
Wood Chips

Products  lbs.  %Mn  %Fe  %CaO  %SiO₂  Mn recovery
Ferromanganese  2.60   65.2  21.0  42.5%
Slag  6.45  21.1  1.8  27.0  13.8  34.0%
Fumes

The power consumption was very irregular and the charge was hard to melt. No visible brown fumes.

The relative amount of limestone was increased in the second test. The weights of the other materials was kept the same as in test #1.

Test #2

Weight of charge materials:

Nodules ......... 6.80 lbs.
Iron Ore ........... 0.61 lbs.
Limestone ........ 3.00 lbs.
Coke .............. 1.92 lbs.

Comments

This charge produced a darker slag and the power consumption was fairly even. There was some unsmelted charge left in the furnace.
Products | lbs. | %Mn | %Fe | %CaO | %SiO₂ | Mn recovery
---|---|---|---|---|---|---
Ferromanganese | 3.00 | 45.1 | 24.5 |  |  | 33.75%
Slag | 7.00 | 16.4 | 2.0 | 21.0 | 32.6 | 38.75%
Fumes |  |  |  |  |  | 27.50%

In test #3 the relative amount of limestone was reduced from the calculated amount. This gave a neutral slag instead of a basic slag as was used in the two previous runs.

Test #3

Weight of charge materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.80 lbs.</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>0.61 lbs.</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.00 lbs.</td>
</tr>
<tr>
<td>Coke</td>
<td>1.92 lbs.</td>
</tr>
</tbody>
</table>

Comments

This charge produced a black slag, indicating presence of manganese. Power consumption most irregular yet.

Products | lbs. | %Mn | %Fe | %CaO | %SiO₂ | Mn recovery
---|---|---|---|---|---|---
Ferromanganese | 0.70 |  |  |  |  | 
Slag | 6.25 |  |  |  |  | No assays were taken because the amount of ferromanganese was small and it crumbled in your fingers. 
Fumes |  |  |  |  |  | 

The charge used in test #4 was the same charge as was used in the second test, except 1.5 times the weight of each material was used. The materials were still in lump form.
Test #4

Weight of charge materials:

Nodules ............ 10.20 lbs.
Iron Ore ............ 0.92 lbs.
Limestone ........... 4.50 lbs.
Coke ................. 2.88 lbs.

Products  
Ferromanganese  3.20
Slag  8.75
Fumes

<table>
<thead>
<tr>
<th>Products</th>
<th>lbs.</th>
<th>Mn</th>
<th>Fe</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>3.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>8.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comments

This charge reduced the smelting time. Power consumption was steady after charge started to melt.

No assays were taken because the ferromanganese was crumbly.

In test #5, 1.5 times the charge weights of test #3 was used. The materials, with the exception of coke, were crushed to about \( \frac{1}{2} \) inch. The coke was pulverized to give better reduction.

Test #5

Weight of charge materials:

Nodules ............ 10.20 lbs.
Iron Ore ............ 0.92 lbs.
Limestone ........... 3.00 lbs.
Coke ................. 2.88 lbs.
Wood Chips

Comments

Power consumption was regular and there was no unsmelted charge left in the furnace.
<table>
<thead>
<tr>
<th>Products</th>
<th>1bs.</th>
<th>Mn</th>
<th>Fe</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>3.95</td>
<td>55.3</td>
<td>30.0</td>
<td></td>
<td>36.40%</td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>9.72</td>
<td>11.4</td>
<td>4.9</td>
<td>23.0</td>
<td>26.4</td>
<td>18.50%</td>
</tr>
<tr>
<td>Fumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45.10%</td>
</tr>
</tbody>
</table>

The charge for test #6 was 1.5 times the charge used in test #2. The materials were crushed to the same size as in test #5. This size was used for the rest of the tests.

**Test #6**

**Weight of charge materials:**

<table>
<thead>
<tr>
<th>Nodules</th>
<th>10.20 lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>0.92 lbs.</td>
</tr>
<tr>
<td>Limestone</td>
<td>4.50 lbs.</td>
</tr>
<tr>
<td>Coke</td>
<td>2.88 lbs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Products</th>
<th>1bs.</th>
<th>Mn</th>
<th>Fe</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>3.90</td>
<td>60.7</td>
<td>30.4</td>
<td></td>
<td>39.50%</td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>10.00</td>
<td>16.0</td>
<td>4.6</td>
<td>24.5</td>
<td>24.1</td>
<td>26.70%</td>
</tr>
<tr>
<td>Fumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33.80%</td>
</tr>
</tbody>
</table>

In test #7 the size of the charge was reduced because the electrodes were arcing to the roof and burning it out. Al₂O₃ was added to this charge in the expectation that it would reduce the manganese loss in the slag. The amount added was not calculated.
since it was not known if it would go to the acid or
base side in the slag.

Test #7

Weight of charge materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.80</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>0.61</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.00</td>
</tr>
<tr>
<td>Coke</td>
<td>1.92</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Products

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lbs)</th>
<th>Mn%</th>
<th>Fe%</th>
<th>CaO%</th>
<th>SiO₂%</th>
<th>Mn Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>1.35</td>
<td>53.7</td>
<td>33.8</td>
<td></td>
<td></td>
<td>12.10%</td>
</tr>
<tr>
<td>Slag</td>
<td>6.70</td>
<td>18.2</td>
<td>3.6</td>
<td>23.0</td>
<td>26.2</td>
<td>20.30%</td>
</tr>
<tr>
<td>Fumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>67.60%</td>
</tr>
</tbody>
</table>

The charge used in test #8 was the same as the
one used in test #7, except the relative amount of
coke was increased.

Test #8

Weight of charge materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.80</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>0.61</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.00</td>
</tr>
<tr>
<td>Coke</td>
<td>2.50</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Comments

The furnace ran much hotter than in the previous test.
In test #9 the relative amounts of coke and Al\textsubscript{2}O\textsubscript{3} were both increased, while the rest of the charge materials were the same as in the previous test.

**Test #9**

**Weight of charge materials:**

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.80 lbs.</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>0.61 lbs.</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.00 lbs.</td>
</tr>
<tr>
<td>Coke</td>
<td>2.75 lbs.</td>
</tr>
<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>2.00 lbs.</td>
</tr>
</tbody>
</table>

**Comments**

The metal was scattered throughout the slag in the form of small, round balls so no weight of metal and slag was obtained. Enough of each was taken for an assay.

---

**Products**

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>%Mn</th>
<th>%Fe</th>
<th>%CaO</th>
<th>%SiO\textsubscript{2}</th>
<th>Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>---</td>
<td>66.9</td>
<td>19.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slag</td>
<td>---</td>
<td>8.7</td>
<td>8.0</td>
<td>10.6</td>
<td>36.4</td>
<td></td>
</tr>
<tr>
<td>Special</td>
<td>---</td>
<td>13.0</td>
<td>7.5</td>
<td>10.3</td>
<td>39.2</td>
<td></td>
</tr>
</tbody>
</table>
Summary

Only nine tests could be made because the roof of the furnace burned out and the research department wanted to use the power source for other tests.

In tests 1, 2, and 3 the weight of limestone was varied from the calculated amount in order to determine the effect of a basic slag on manganese recovery. It was found that a basic slag was better than a neutral slag to a certain basicity. When the basicity passed a certain point the recovery decreased, which is in direct contrast to the results obtained by the Bureau of Mines (Fig. 1).

The first tests were run with the materials in lump form. This caused the power consumption to be very irregular and some unsmelted charge remained in the furnace.

In tests 4, 5, and 6 the charge used was 1.5 times the previous charge weights. This made the smelting time shorter and the power consumption steadier. Starting with test 5 the materials were crushed to about ½ inch with the exception of the coke, which was pulverized to give better reduction. This reduced the smelting time still further and the amount of unsmelted charge remaining in the ladle was small.
Starting with test 7, the size of the charge was reduced because the furnace was too full. Al₂O₃ was added to the charge materials in tests 7, 8, and 9 with the expectation that it would go to the basic side in the slag and thus force MnO out of the slag and increase the manganese recovery. It was found that as the amount of Al₂O₃ added to the charge increased, the furnace ran hotter and the electrodes had to be raised up to keep the temperature down. This ultimately burned out the roof as the electrodes arced to the roof.

**Discussion of Tests**

The two main objectives of these tests were to determine if a basic slag was better than a neutral slag and if the addition of Al₂O₃ to the charge would result in a lower manganese content in the slag.

In relation to the use of a basic slag, better recovery and smoother furnace operation were obtained as the basicity of the slag increased. A maximum value was reached after which recovery decreased.

The size of the feed materials was important, both in the amount of unsmelted charge left in the furnace and the length of time required to melt the charge. Also, the size affected the power consumption.
The larger the size of the charge materials, the more erratic the power consumption and the harder the charge was to melt.

Although no definite conclusions can be drawn regarding the use of $\text{Al}_2\text{O}_3$ in the charge, the tests indicate that it does force MnO out of the slag. The manganese recovery more than doubled in the second test with $\text{Al}_2\text{O}_3$ by increasing the coke, which seemed to indicate lack of coke for reducing power in the first test using $\text{Al}_2\text{O}_3$. The last test using $\text{Al}_2\text{O}_3$ was not fully smelted when the furnace roof burned out and stopped the testing. The metal which was recovered and assayed had the highest manganese content of all the runs, and the slag had the lowest manganese content of all the runs. Although the manganese recovery could not be calculated due to the roof burning out before the charge was smelted, the assays indicated that this test gave the best results. If a furnace were available which could operate at the increased temperatures produced by adding $\text{Al}_2\text{O}_3$ to the charge, I feel that further work of this nature would be justified, using these results as a starting point.

Conclusions

From the test results a few conclusions were drawn.
They are:

(1) The more basic the slag, the smoother the operation, the steadier the power consumption, and the better the smelting.

(2) The size of the charge materials is important from the standpoint of power consumption and smelting time; the finer the size, the better the power consumption and the shorter the smelting time with less unsmelted charge.

(3) The use of Al₂O₃ increased the temperature of the furnace.

(4) The addition of Al₂O₃ to the charge reduced the manganese content of the slag and produced a higher grade ferromanganese.

(5) The loss of manganese in the fumes was reduced when wood chips were used in the charge.

Recommendations for Future Work

The following recommendations are made for future work on this problem.

(1) Further studies of smelting efficiency with slags of increasing basicity.

(2) Further studies of the effect of the addition of varying amounts of Al₂O₃.

(3) Further studies to determine the ratio of coke to wood chips which would give the least fume loss.

(4) Construction of a single electrode furnace with a bottom return.
BIBLIOGRAPHY


10. ASM, Metals Handbook, Cleveland: American Society
for Metals, (1948).

ACKNOWLEDGMENT

I wish to express my thanks to everyone who helped in this project. In particular, special thanks to Prof. Ralph Smith and Mr. Charles Arentzen for their valuable assistance and to the Research Department of the Anaconda Company for the use of their equipment.
Appendix

Charge Calculation

Assays for Charge Materials

<table>
<thead>
<tr>
<th>Nodules</th>
<th></th>
<th>Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>59.0% (81.8% Mn(_2)O(_4))</td>
<td>CaO</td>
</tr>
<tr>
<td>Fe</td>
<td>3.8%</td>
<td>MgO</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>7.2%</td>
<td>SiO(_2)</td>
</tr>
<tr>
<td>CaO</td>
<td>5.2%</td>
<td>FeO</td>
</tr>
<tr>
<td>P</td>
<td>0.15%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Iron Ore</th>
<th></th>
<th>Coke</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>3.1%</td>
<td>C</td>
</tr>
<tr>
<td>MgO</td>
<td>2.7% (3.78% CaO)</td>
<td>CaO</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>7.4%</td>
<td>SiO(_2)</td>
</tr>
<tr>
<td>FeO</td>
<td>72.6% (80.7% Fe(_2)O(_3))</td>
<td></td>
</tr>
</tbody>
</table>

The basis of the calculations is 25 lbs. of ferromanganese which will have the following assay:

- Mn 80%
- C 6%
- Fe 12%
- P, Si 2%

Manganese Balance

Mn needed = 25 lbs. x 0.80 = 20 lbs.

Mn from nodules = 59%

Weight of nodules required = 20 lbs./0.59 = 33.9 lbs.
Iron Balance

Weight of iron required = 25 lbs. x .12 = 3 lbs.

Sources of Iron

1. Fe from nodules = .038 x 33.9 = 1.29 lbs.
2. Fe from iron ore = 3 - 1.29 = 1.71 lbs.

Per cent Fe in iron ore

\[ \frac{72.6 \times \frac{\text{Fe}}{\text{FeO}}}{56} = 72.6 \times \frac{56}{72} = 56.5\% \text{ Fe} \]

Weight of iron ore required = 1.71 /.565 = 3.03 lbs.

Carbon Balance

Carbon to reduce FeO: \( \text{FeO} + \text{C} = \text{Fe} + \text{CO} \)

\[ \frac{0.038 \times 3.03}{56 \text{ lbs. Fe/mole}} \times 12 \text{ lbs.} = \text{C/mole Fe} = .0246 \text{ lbs. C} \]

Carbon to reduce \( \text{Fe}_2\text{O}_3 \): \( \text{Fe}_2\text{O}_3 + 3\text{C} = 2\text{Fe} + 3\text{CO} \)

\[ \frac{.007 \times 3.03}{160 \text{ lbs. Fe}_2\text{O}_3/mole} \times 36 \text{ lbs.} = \text{C/mole Fe}_2\text{O}_3 = .550 \text{ lbs. C} \]

Carbon for the ferromanganese

25 lbs. x .06 = 1.5 lbs. C

Carbon to reduce \( \text{Mn}_3\text{O}_4 \): \( \text{Mn}_3\text{O}_4 + 4\text{C} = 3\text{Mn} + 4\text{CO} \)

\[ \frac{.818 \times 33.9}{229 \text{ lbs. Mn}_3\text{O}_4/mole} \times 48 \text{ lbs.} = \text{C/mole Mn}_3\text{O}_4 = 5.81 \text{ lbs. C} \]

Total carbon = 5.81 + 1.5 + .55 + .0246 = 7.38 lbs.

Coke needed to supply 7.88 lbs. carbon

\[ 7.88 / .321 = 9.60 \text{ lbs. coke} \]
\[ \text{SiO}_2 \text{ and CaO Balance} \]

**Nodules**

\[ \text{SiO}_2 = 0.072 \times 33.9 = 2.44 \text{ lbs.} \]
\[ \text{CaO} = 0.052 \times 33.9 = 1.76 \text{ lbs.} \]

**Iron Ore**

\[ \text{SiO}_2 = 0.074 \times 3.03 = 0.224 \]
\[ \text{CaO} = (0.031 + 0.0378) \times 3.03 = 0.208 \]

**Coke**

\[ \text{SiO}_2 = 0.07 \times 9.6 = 0.67 \]
\[ \text{CaO} = 0.008 \times 9.6 = 0.077 \]
\[ \text{Total SiO}_2 = 3.33 \text{ lbs.} \]
\[ \text{Total CaO} = 2.05 \text{ lbs.} \]

**Ferromanganese**

\[ \text{SiO}_2 = 0.01 \times 25 = 0.25 \text{ lbs.} \]

**Limestone**

\[ \text{CaO from limestone} = (50.6 + 2.8 + 0.39) - \frac{70\% \text{CaO}}{30\% \text{SiO}_2} \]
\[ \times 7\% \text{SiO}_2 = 37.46\% \text{CaO} \]

\[ \text{SiO}_2 \text{ in slag} = 3.33 - 0.25 = 3.08 \text{ lbs.} \]
\[ \text{Weight of slag} = 3.08/0.30 = 10.25 \text{ lbs.} \]
\[ \text{CaO in slag} = 10.25 - 3.08 = 7.17 \text{ lbs.} \]
\[ \text{CaO to be added} = 7.17 - 2.05 = 5.12 \text{ lbs.} \]
\[ \text{Limestone required} = \frac{5.12}{3746} = 1.365 \text{ lbs.} \]

**Charge:**

- **Nodules** 33.9 lbs.
- **Iron Ore** 3.03 lbs.
- **Coke** 9.60 lbs.
- **Limestone** 13.65 lbs.