ELECTRIC PARAMETERS FOR AN EFFICIENT SMELTING PERFORMANCE OF HCFeMn ALLOY

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ABSTRACT

The experiment of weight loss in CO atmosphere shows that particle mixtures of Groote Eylandt ore, coke, and fluxing agent undergo the process of sintering and softening to form a molten slag zone and indirect reduction of iron oxides and of Mn oxides to MnO at temperatures less than 1335°C and that a coke bed forms as an aggregated mass of Mn oxides melt with coke particles, in which the reduction of MnO takes place at temperatures higher than 1335°C. An efficient reducing reaction of MnO requires the temperature of coke bed to be high and its volume to be large. A pilot scale smelting experiment shows that the required energy for smelting reaction is provided by resistive heating with electric current flowing through molten slag and coke bed zones in smelting area and that furnace power maintains an inverse relationship with operating resistance, indicating that the electric current is the active parameter for increasing power. The distribution of power between molten slag and coke bed zones defines the characteristics of smelting performance, and it is controlled by the electrode position. The best smelting performance characterized by high temperature and increased volume of coke bed is attained at optimum electrode positions.

1 INTRODUCTION

At present, the majority of high carbon ferromanganese alloy is smelted in submerged arc furnaces. This process is popular over the blast furnace route because it is flexible and saves in consumption of expensive coke. Its commercial practice has been successful owing to the hard works by many process designers and operators. Now, the ferroalloy industry is challenged to develop industrial practices for a sustainable growth through conservation of resources, and such demands from society dictates for our knowledge and skill to be improved further. The improvement should come from a development of sound fundamental knowledge base on mechanisms of smelting reactions and from understanding the roles of operating parameters affecting the smelting performance. The attained skill would evolve into practices for stable and efficient operations with raw materials of deteriorating quality.

Tangstad[1] experimentally examined the transforming phenomena of Mn ores into the aggregation of Mn oxides melt with coke particles and the electro-thermal conditions affecting the smelting performances in smelting area. This report analyzes the experimental evidences and discusses the working relationship of operating parameters with physico-chemical reactions taking place in smelting area and metallurgical performances for an efficient operation of submerged arc furnaces producing high carbon ferromanganese alloy.

2 EXPERIMENT AND RESULT

Tangstad[1] designed the experiment to examine the physico-chemical transformation of raw materials taking place at various temperatures and the effect of electrical conditions on smelting performance for high carbon ferromanganese alloy in a 150 KVA pilot scale furnace. The pertinent features of the experiment and result are reviewed in the followings.

2.1 Transformation of Mn Ores at Various Temperatures

The raw materials used in the experiments were provided by a producer of ferromanganese alloys in Norway. Mn ores were sourced from lots of Groote Eylandt Mn ore, Comilog ore, and Assmang ore. Reducing agent was from that of Polish metallurgical coke, and fluxes were industrial grade dolomite, limestone, and magnesite. Most experimental runs discussed in this report were made with Groote Eylandt ore, Polish metallurgical coke, and dolomite. They were prepared as particles in the size range of 1.63 to 3.34 mm diameter. Their chemical analyses are listed in Table 1.

Table 1: Chemical analyses of raw materials in wt%

raw materials	**MnO_2**	**MnO**	**Fe_2O_3**	**CaO**	**MgO**	**SiO_2**	**Al_2O_3**	**K_2O**	**P_2O_5**
Groote Eylandt ore	76.3	4.2	3.95	0.2	0.4	4.8	3.2	1.8	0.16
dolomite				34.2	16.8	1.7			
	fixed C	volatile	ash						
coke	86.9	2	11.1						
	MnO	**FeO**	**CaO**	**MgO**	**SiO_2**	**Al_2O_3**	**K_2O**	**P_2O_5**	
ash	5.9	6.2	2.6	2.2	43.9	27.9	3.8	1.3	

The sized Groote Eylandt ore was taken, with or without dolomite and coke particles, to have a weight of about 15 grams, and charged into a graphite crucible. A graphite crucible with raw materials was attached to a thermo-balance, heated at a predetermined rate to various temperatures less than 1500°C under a CO atmosphere, and held at an aimed temperature for a predetermined time. During this heating cycle, the weight loss of samples was monitored continuously. At the end of each experimental run, the heat was stopped by turning off power to the furnace. At a room temperature, the sample was retrieved from the graphite crucible and analyzed by an optical microscope and SEM examination. This information together with the observed weight loss was used to characterize chemical reactions that had taken place.

2.1.1 Transformation at less than 1030°C

The morphology of raw materials maintained their angular features. The particles were not connected physically, and they were remained in crucibles with a high void fraction. The information of weight change and SEM examination indicates that higher Mn oxides (MnO_2, Mn_2O_3, and Mn_3O_4) than MnO were reduced to MnO and that Fe_2O_3 to FeO. Indications are that they were reduced indirectly, but these reactions did not change the morphology of raw materials. This loss of oxygen raised the contents of MnO and FeO in the pre-reduced ore to about 80 and 3.5%, respectively, and this overall MnO content placed the composition of the pre-reduced Mn ore in the manganosite (MnO) primary-phase field in multi-component oxides system.

2.1.2 Sintering and reduction of iron oxide at 1030 to 1200°C

Sintering had taken place among oxide particles connecting by necking formation. Still, the consolidating activity was limited, and particles maintained their original mineral morphology. This limited consolidation provided some degree of structural integrity, but the aggregated structure had a significantly high void fraction and did have some rigidity to maintain the connection among particles. Iron oxide (FeO) in Mn ores was reduced to metallic iron, but MnO was not.

2.1.3 Softening at 1200 to 1300°C

MnO was not reduced yet. A liquid slag began to form and softened oxide particles locally. The information of the phase diagram for $MnO-Al_2O_3-SiO_2$ system[2] indicates that a liquid slag would form with eutectic compositions between the MnO primary phase and spessartine ($3MnO.Al_2O_3.3SiO_2$) at about 1200°C, and the formation of such liquid slag in a limited quantity appears to be responsible for the observed softening in Groote Eylandt ore. This softening activity increased the connectivity among particles and decreased the structural rigidity as well as the void fraction of aggregated body. However, particles still preserved their respective original mineral phases because of limited liquid slag volume.

2.1.4 MnO saturated oxides melt at 1300 to 1335°C

CaO was dissolved in the liquid slag preferentially over MgO. This fluxing behavior extended the liquid slag field and conditioned it such a way that the overall composition of Mn oxides melt (i.e. MnO containing oxides melt) is maintained in the manganosite (MnO) primary-phase field. This transformation erased the original identity of mineral phases. The liquid slag, which is in saturation with MnO(s), was observed to have an averaged composition of 42.2%MnO, 14.7%Al_2O_3, 25.8%SiO_2, and 17.3%CaO, neglecting other oxides. It provided some degree of mixing between Mn oxides melt and coke particles, but the Mn oxides melt did not attain a sufficient fluidity yet to flow through coke particles. MnO was not reduced.

2.1.5 Incipient reduction of MnO at 1335 to 1350°C

The reduction of MnO began significantly as temperature increased higher than 1335°C, and the fluxing reaction of CaO was continued. These phenomena appear to have increased the volume of liquid slag and the fluidity of Mn oxides melt. Consequently, Mn oxides melt was able to penetrate and to flow through coke particles to form an aggregated body. This aggregation established a good contact of Mn oxides melt with coke particles. Also, the condition of liquid slag in saturation with MnO(s) allowed Mn oxides melt to maintain MnO reducing reaction at a high rate because of its high activity of MnO (a_{MnO}=1). Metal particles were observed to form in MnO(s) phase as well as liquid slag. Their size was smaller when they were with $MnO_{(s)}$ (~10μm) than with liquid slag (~100-1000μm). It appears that metal particles were produced by reduction of manganosite and coalesced to grow in size in liquid slag.

2.1.6 Reduction of MnO at 1350°C and higher temperatures

A kinetic consideration indicates that the reducing reaction of MnO in the present study should maintain the interfacial area between Mn oxides melt and coke particles at high levels. This requirement is met by a formation of aggregates in which coke particles are well dispersed in Mn oxides melt and establish an intimate contact with it. However, their prior mixing history will affect mixing dynamics of coke particles in Mn oxides melt during the initial period of smelting reactions.

The sized raw materials, 10 grams of Groote Eylandt ore particles, 1.38 grams of dolomite, and 4.51 grams of coke, were charged into graphite crucibles with two different prior mixing conditions: (1) pre-mixed raw materials of Groote Eylandt ore and flux with coke and (2) a segregated coke layer on top of mixed Groote Eylandt ore with dolomite particles. The assembly of raw materials and graphite crucible was attached to a thermo-balance and heated to a desired experimental temperature as fast as possible (usually 12 minutes) in a flowing CO gas atmosphere. The reducing reaction of MnO was examined by monitoring weight changes at 1350, 1400, 1450, and 1500°C.

It was noted that the MnO reducing reaction proceeded at a fast rate when Mn oxides melt was saturated with the manganosite ($MnO_{(s)}$) and at a slower rate when it was exhausted. The argument presented in this section discusses the reducing reaction taken place under the condition of saturation with manganosite. Figure 1 compares the variation of MnO content with time for two different prior mixing conditions of raw materials. The results with pre-mixed raw materials are shown by open circles and those with the segregated coke layer on top of ore particles by closed ones in Figure 1.

It shows that the aggregation dynamics during the initial period of reaction are different depending on the prior mixing conditions of raw materials. When coke particles were pre-mixed with Groote Eylandt ore and dolomite particles, the content of MnO was observed to decrease gradually with time during the initial period of about 5 minutes. Thereafter, it decreased at a steady rate. It indicates that the aggregated mass requires a finite time of about 5 minutes to establish an intimate contact between Mn oxides melt and coke particles. The rate of MnO reduction during a steady period increased with temperature from 1350 to 1500°C. With the segregated coke layer, the content of MnO decreased also in a similar manner observed with the pre-mixed raw materials. However, the initial ramping-up period of the reducing reaction was about four times longer, and a steady rate of MnO reduction was attained after about 20 minutes. It is apparent that the segregated coke particles on top of Groote Eylandt ore and dolomite particles had required about 20 minutes to disperse themselves into Mn oxides melt to establish an intimate contact in the aggregated mass. The rates of MnO reduction at the steady period were similar with those observed with premixed raw materials and increased with temperature in the same manner. When they are correlated with the inverse of temperature, all results are reasonably represented by a line with the activation energy of 207 KJ/mol MnO. The observed high activation energy suggests that the rate of MnO reduction is controlled by the chemical reaction at the interface. Under the conditions of saturation with $MnO_{(s)}$ and of an ample supply of carbon, a reduction of MnO at higher rates requires a larger volume of coke bed by virtue of an increased interfacial area between Mn oxdes melt and coke particles.

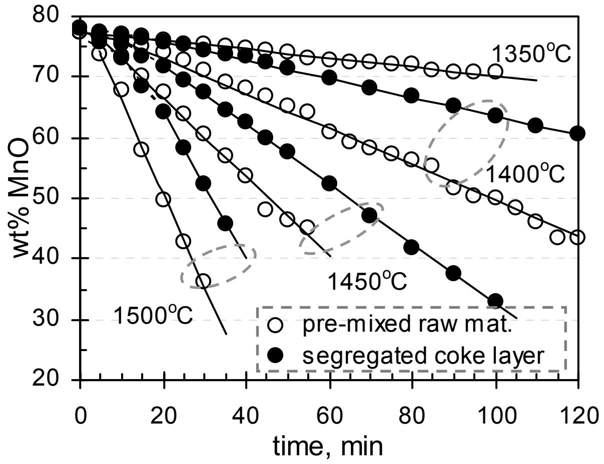


Figure 1: Variation of %MnO in slag with time for two different prior mixing conditions

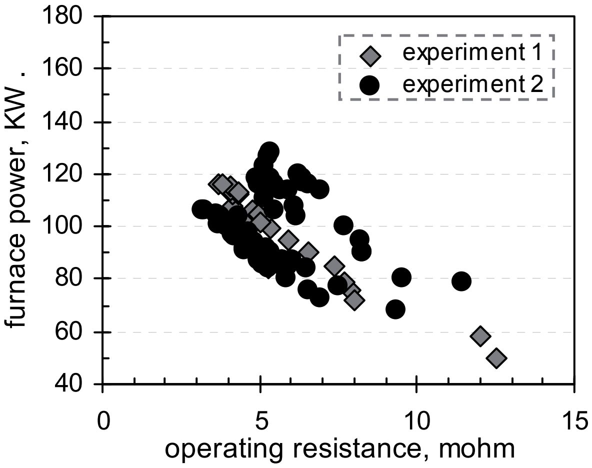


Figure 2: Relationship of furnace power with operating resistance

2.2 A Pilot Scale Smelting Test For Producing High Carbon Ferromanganese

Smelting tests of Groote Eylandt ore were made with a pilot scale furnace to produce high carbon ferromanganese. The tests consisted of two smelting campaigns. Each campaign lasted long enough to produce 6 to 8 taps of alloy and slag. At the end of each campaign, the furnace was cooled and excavated for its content. The operating parameters were correlated with the smelting performance, and the analysis of excavation was interpreted to further our understanding of metallurgical phenomena taking place in the smelting area.

2.2.1 150KVA pilot scale furnace

The smelting experiments were carried out with a 150 KVA pilot scale furnace at the Department of Materials Science and Engineering, NTNU, Trondheim, Norway. The furnace was constructed with the inner dimension of 0.63 m diameter and 0.6 m height. It was installed with a pre-baked electrode of 0.15 m diameter by a suspending mechanism from a ceiling and with a return-electrode in the hearth. The electrode position, a distance between the tip of electrode to the hearth level, was adjusted manually. The electric current and furnace power were controlled by the transformer tap voltage and monitored throughout the campaign, and the operating resistance was calculated from them.

2.2.2 Raw materials and mix order

The campaigns were made with Groote Eylandt ore, iron ore pellets, dolomite, and cokes. Their analyses are shown in Table 2. The raw materials were crushed and prepared into particles to have sizes in the range of 2 to 25 mm diameter.

The raw materials were prepared and charged to the furnace in batches. Two campaigns (experiments 1 and 2) were made with the identical mix order except a slight difference in coke ratio as shown in Table 3. However, It was found that the slight difference in coke ratio did not affect the smelting results.

Table 2: Chemical analyses of raw materials in wt% for pilot scale smelting test

raw materials	**MnO_2**	**MnO**	**Fe_2O_3**	**CaO**	**MgO**	**SiO_2**	**Al_2O_3**	**K_2O**	**P_2O_5**
Groote Eylandt ore	68	7.2	4.8	0.2	0.05	6.9	4.3	2	0.16
iron ore pellets			93			7			
dolomite				34.2	16.8	1.7			
	fixed C	volatile	ash						
coke	86.9	2	11.1						
	MnO	**FeO**	**CaO**	**MgO**	**SiO_2**	**Al_2O_3**	**K_2O**	**P_2O_5**	
ash	5.9	6.2	2.6	2.2	43.9	27.9	3.8	1.3	

Table 3: Mix order per batch for pilot scale smelting test

campaigns	**Kg Groote Eylandt ore**	**Kg dolomite**	**Kg iron ore pellet**	**Kg coke**
experiment 1	30	4.8	1.1	6.6
experiment 2	30	4.8	1.1	6.9

Table 4: Smelting performance for the experiment 1

tap No.	**1**	**2**	**3**	**4**	**5**	**6**
tap to tap time,min	58	51	44	43	48	69
alloy, kg	22	29	23	20	25	26
wt%Mn	78.47	76.49	79.98	80.8	78.75	80.8
%Fe	13.8	13.8	12	12.2	13.2	11.4
%Si	0.67	0.75	0.02	0.12	0.11	0.13
%C	6.92	6.77	7.33	7.33	7.09	7.17
slag, kg	10	21	17	11	19	24
wt%MnO	28.1	37.8	32.1	33.6	33.3	30.4
%SiO_2	25.1	21.4	23.4	22.2	22.6	23.3
%Al_2O_3	16.6	13.5	14.9	14	14	14.3
%CaO	17.5	13.3	15.7	14.8	15.6	16.8
%MgO	9.3	8.9	10.1	9.8	10.1	10.5
electrode pos. cm	11.5	11.5	11.5	11.5	11.5	11.5
KWH/MT alloy	4447	2857	3256	3063	3029	3643

Table 5: Smelting performance for the experiment 2

tap No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
tap to tap time,min	50	45	39	49	41	50	45	51
alloy, kg	18	16	18	21	16	25	24	25
wt%Mn	78	79.2	80.6	81.5	80.4	81.1	81.9	81.4
%Fe	14	13.2	12.4	10.4	10.9	10.4	10.4	10.7
%Si	0.20	0.10	0.04	0.24	0.98	0.79	0.46	0.41
%C	7.0	6.9	6.8	6.9	6.9	6.8	6.0	6.9
slag, kg	10	5	10	16	12	13	15	15
wt%MnO	34.2	37.0	31.5	27.9	24.1	16.5	20.4	21.9
%SiO_2	23.0	21.4	21.7	23.7	24.3	25.7	25.1	23.1
%Al_2O_3	13.6	13.0	13.6	14.9	15.6	18.3	17.9	15.2
%CaO	15.5	16.2	16.6	16.5	18.2	21.1	19.4	17.3
%MgO	9.2	8.9	11.3	11.1	11.4	13.4	12.0	11.1
electrode pos. cm	28	27	27	25	23	20.5	21	21.5
KWH/MT alloy	5495	4097	4323	3755	4099	2909	3772	2748

2.2.3 Procedure of pilot scale smelting tests

The smelting test with the pilot scale furnace started by an initial heating of 12 cm coke layer in the bottom, and the batches of the raw materials were added at 94 KWH after power on. Since then, the alloy and slag were tapped at about 80 KWH. This makes each tapping cycle at less than about one hour. The experiment 1 and 2 made 6 and 8 taps, respectively. The experiment 1 was carried out with a low electrode position and the experiment 2 with high electrode positions. The smelting results with the pertinent operating parameters are listed in Table 4 and 5 for the experiment 1 and 2, respectively.

2.2.4 Operating resistance and furnace power

The operating resistance during tapping was observed to be unstable and to increase to a high level. After closing tap hole, it gradually decreases for about 10 minutes and stabilizes at lower values after that. The electric current was lower when the operating resistance was high, and it was higher when the resistance was low. This behavior repeated for each tapping cycle. The observed high operating resistance during tapping is attributed to interruptions in current paths during tapping, and an establishment of good conducting paths produces a low resistance and is favorable for a higher electric current with a consequence of increasing furnace power.

Figure 2 shows the relationship of the furnace power with operating resistance observed during two campaigns. In general, the furnace power is shown to increase as the operating resistance decreases. The lowering characteristic of resistance for increasing power indicates that the electric current is the active parameter for producing electro-thermal effect in smelting area. This general behavior is in agreement with the proposal by Westly[3,4], who pointed out that an efficient smelting operation should maintain this inverse relationship of furnace power with operating resistance. A closer examination of Figure 2, however, shows that each different electrode position calls for their-own respective relationships. The electrode position appears to be the controlling parameter to affect the operating resistance and to define the characteristic power distribution in smelting area.

2.2.5 Excavation of the pilot scale furnace

At the end of campaigns, the furnace power was off, and the furnace was let to cool for two days. An excavation was made to display the transformed features of furnace charge as they may occur during smelting operation. Figure 3 and 4 show vertical cutaway views through electrode for the experiment 1 and 2, respectively. Although details vary, the general features for both experiments are that the raw furnace charge covered the furnace top zone, and this was followed by zones of sintered, molten slag, coke bed, slag, and metal, as it descended down in furnace. These successive zones maintained a reasonable contact each other, indicating a steady movement of raw materials in furnace.

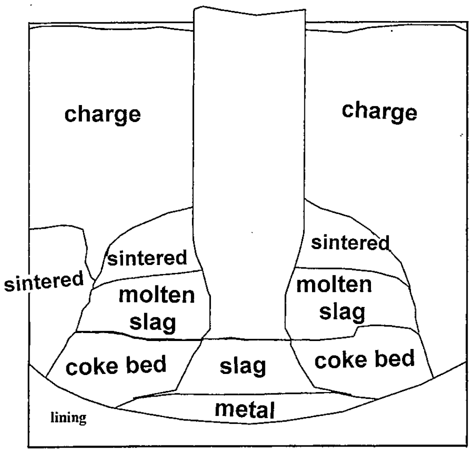


Figure 3: Furnace contents in zones after the experiment 1, low electrode position

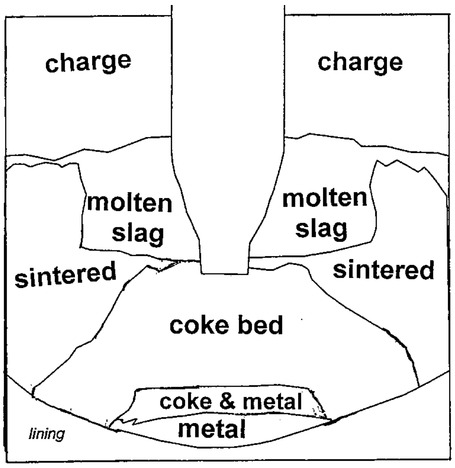


Figure 4: Furnace contents in zones after the experiment 2, higher electrode positions

Top furnace charge was a loose mixture of raw materials. Sintered zone developed some degree of connectivity among raw materials. Molten slag zone had slag melt and some metal particles. The content of MnO in slag was in the range of 60 to 75%MnO, and that of Mn in metal was 50 to 80%Mn. It indicates that some degree of MnO reduction had taken place in this zone. In general, these three zones were found in the upper space of furnace above the tip of electrode, although some sinter formed a bank along the side wall. Coke bed zone was found in the space below the tip of electrode, and coke particles were mixed well with slag and metal. The MnO content of slag in coke bed was in the range of 27 to 35%MnO for the experiment 1 and 10 to 35%MnO for the experiment 2. The content of Mn in metal was in the range of 75 to 86%Mn. It indicates that most of MnO reduction had taken place in coke bed zone.

The electrode maintained a contact with zones of top furnace charge, sintered mass, molten slag, and coke bed. Its lower portion which is in contact with molten slag and coke bed zones was eroded in a shape of tapering-down profile, but its upper part did not show any visible sign for erosion activity. This observed pattern of electrode erosion indicates that virtually no electric current flows across the top furnace charge in the upper part of furnace but that it flows through molten slag zone and, most intensively, in coke bed zone. As they are closely associated with the phenomenon of MnO reduction, the molten slag and coke bed zones are defined as the smelting area in this report.

The structure of coke bed zone was found to be different from the experiment 1 to 2. For the experiment 1, which was carried out with a low electrode position at 11.5cm average, a dense slag mass was formed in the central area of doughnut shaped coke bed zone underneath electrode. The slag mass did not have coke particles or gas pores. No such segregated slag mass was found in coke bed zone for the experiment 2. This abnormal coke bed structure at the low electrode position might have been unstable, and the smelting reaction might not be able to progress in a steady manner.

3 DISCUSSION

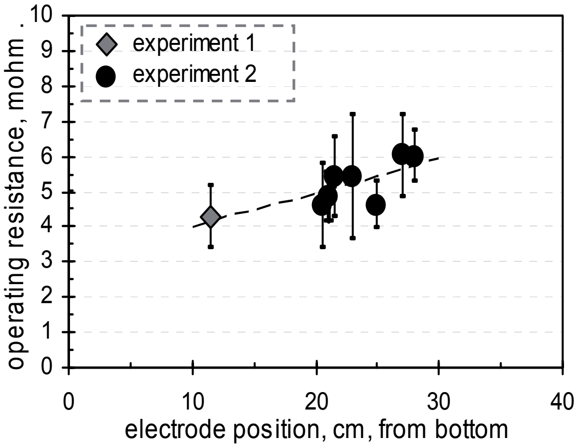
The experimental evidence shows that the principal smelting reaction in submerged arc furnaces takes place in the coke bed which is an aggregated mass of Mn oxides melt with coke particles. The operating parameters define its physico-chemical states for efficient smelting performance.

3.1 Operating Resistance and Electrode Position

The electric current flowing through furnace charge which serves as a resistor is responsible for the generation of ohmic energy required for chemical reactions in smelting area. The operating resistance controls it by virtue of its electrical relationship with voltage and defines how power distributes in smelting area as discussed by Westly[3,4]. In operation of submerged arc furnaces, the operating resistance is usually calculated from the readings of ammeter and voltmeter, and the furnace operators control it by raising and lowering electrode positions. In the present analysis, the operating resistances during steady periods as mentioned in the Section 2.2.4 were averaged and correlated with electrode position. Figure 5 depicts their relationship. It shows that the operating resistance decreases with decreasing electrode position, indicating that the control of electrode position is the important operating parameter to affect furnace power for a desired smelting performance.

3.2 The Rate of Alloy Production and Size of Coke Bed

The production of alloy is an important index to evaluate the smelting performance. Figure 6 examines the rate of alloy production with the electrode position. It increases with decreasing electrode position from 30 to about 20 cm. However, data at the position of 11.5 cm show a wide variation. As mentioned above, this may be attributable to the unsteady smelting reaction caused by abnormal structure of coke bed at this low electrode position. This behavior does not allow clearly defining the rate of alloy production at electrode positions less than 20cm. In the absence of better information, the rate of alloy production at electrode positions less than 20cm may be taken as the averaged rate at the electrode position of 11.5cm as suggested in Figure 6. However, an interpretation of the results suggests that an optimum electrode position for a maximum productivity may exist at an electrode position between 11.5 and 20 cm, perhaps closer to 20 rather than to 11.5cm. A physico-chemical consideration of smelting reaction indicates that an increased rate of alloy production would come from the increased temperature and volume of coke bed zone.



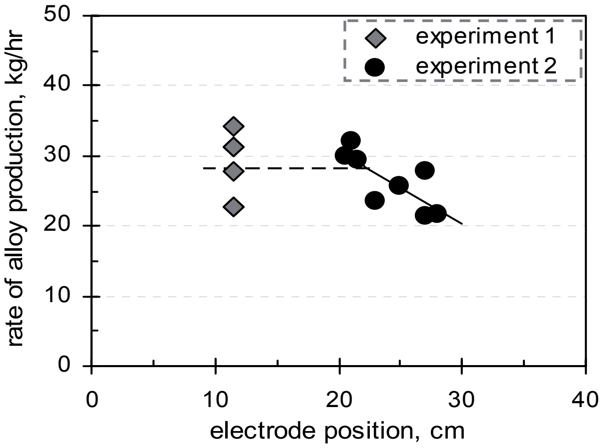


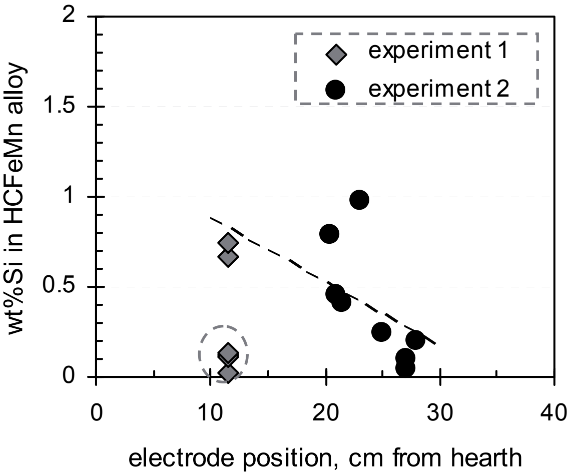
Figure 5: Operating resistance with electrode position

Figure 6: Rate of alloy production with electrode position

3.3 Temperature of Coke Bed and Electrode Position

Tangstad[1] determined the temperature profile of coke bed with embedded thermocouples for two experimental set-ups. The observed tendency of temperature distribution is that it is higher in the area underneath of electrode in coke bed and it becomes lower at locations away from it. In general, the operating condition by the experiment 1 produced a lower temperature profile than did by the experiment 2. In order to extend this finding, this study derives the temperature dependency of coke bed by examining the temperature dependency of smelted alloy and slag. This is based on an assumption that, although the temperature in coke bed is higher than that of tapped alloy and slag, they may maintain a similar temperature dependency on the electrode position because all tapping operations of this study were subjected to same heat transfer conditions.

Skilled workers had recognized that the content of Si in tapped high carbon ferromanganese increases with temperature. Figure 7 presents the analyzed Si content in tapped alloys at various electrode positions. It does not produce a clear relationship due to a wide variation in data. Especially, a wide scatter in the analysis at the electrode position of 11.5 cm appears to be responsible for the



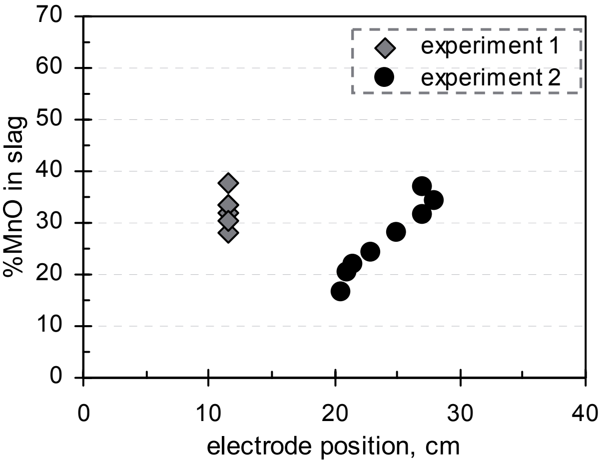


Figure 7: %Si in HCFeMn with electrode position

Figure 8: %MnO in slag with electrode position

uncertain conclusion. This may be attributable to the unstable coke bed structure. If these data are neglected, the Si content shows an increasing tendency with decreasing electrode position, i.e. an increase of temperature with decreasing electrode position. A further support to this interpretation is sought by the temperature dependency of MnO content in tapped slag as discussed in the following. The content of MnO in Mn oxides melt decreases as the reducing reaction of MnO progresses. The reducing reaction of MnO is observed to take place in two stages, the reaction at faster rates during the initial stage and the subsequent one at slower rates in the second stage. As shown in Figure 1, the rate of MnO reducing reaction during the first stage increases strongly with temperature, i.e. it has a high temperature dependency during the first stage. On the other hand, the temperature dependency of the rate appears to be low during the second stage. If the smelting time is not excessive, the residual MnO contents in slag are expected to show a similar temperature dependency to that during the first stage. This assumption appears to be reasonable when a consideration is given to the fact that tap-to-tap time is less than one hour in the present study. Figure 8 relates the analyzed MnO content in slag with electrode position. The MnO content decreases with decreasing electrode position in the range of 20 to 30 cm. A lower residual MnO content in slag means a higher temperature of tapped slag. The MnO contents at electrode position of 11.5cm shows a considerable scatter but are higher than that at 20cm. This observed higher MnO content at the lowest position may be attributed to an insufficient reducing reaction caused by the abnormal coke bed structure.

The observed behavior of analyzed alloy and slag suggests that the temperature of coke bed increases with lowering electrode position to reach a maximum at an optimum electrode position at about 20cm. A further decrease in electrode positions results in formation of abnormal coke bed and, consequently, decreases its temperature. Apparently, this temperature behavior reasonably explains the above mentioned lower temperature profile observed by the experiment 1 than 2 from the pilot scale test.

3.4 Furnace Power and Electrode Position

The distribution of furnace power between molten slag and coke bed zones affects the smelting performance in smelting area. In a similar procedure discussed in the Section 2.2.4, the furnace powers were read during the stable period of operating resistance and averaged them for a given tap to tap cycle. The averaged furnace power was related with electrode position in Figure 9. It presents a pattern of decreasing furnace power with decreasing electrode position to reach a minimum at an optimum electrode position of about 20 cm. Thereafter, it shows an increasing tendency with further decrease of electrode position. When this behavior is considered together with that of alloy production in Figure 6, the smelting performance would be most efficient at electrode positions of about 20cm because of its maximum rate of alloy production with minimum furnace power. This aspect is examined further in the followings. The specific energy consumption, KWH/MT alloy, was calculated

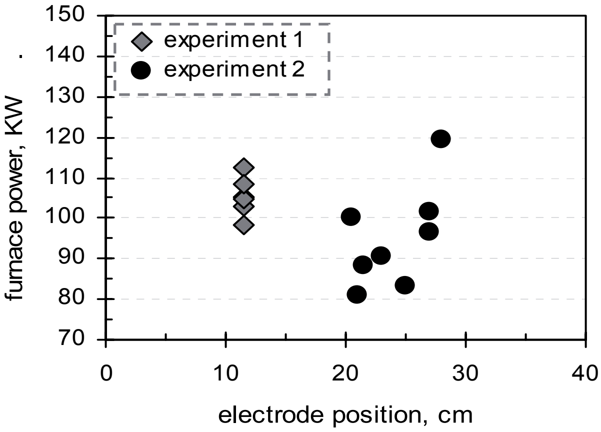


Figure 9: Furnace power with electrode position

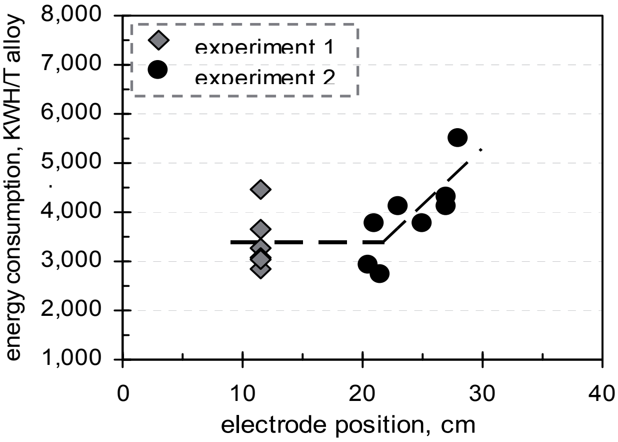


Figure 10: Specific energy consumption with electrode position

at each tap and correlated with electrode position in Figure 10. Again, the observed wide variation at electrode position of 11.5cm was attributed to the increased power due to the abnormal coke bed structure. The specific energy consumption appears to be lowest at an optimum electrode position of about 20 cm and higher as electrode position is raised above 20 cm or lowered below it. It indicates that a strategy of raising furnace power by increasing electrode position beyond the optimum one does not increase the production of alloy and, consequently, result in a poor efficiency of smelting operation. Silver[5] discussed the peril of such operating strategy.

3.5 Abnormal Coke Bed Structure

Coke bed is shown to change its structure at electrode positions lower than an optimum one. At the electrode position of 11.5cm, a dense slag mass with no coke particles and gas pores was formed in central area of the doughnut shaped coke bed underneath electrode. One possible explanation for such segregated structure is to have a non-uniform temperature distribution in coke bed zone. If a high temperature is developed in the central area underneath electrode, slag would be fluid enough to segregate out coke particles. If the space in the bottom of coke bed is limited, the dense slag could not flow away. Instead, it remains as a core in middle of coke bed doughnut as observed in this study. If slag attains a high enough fluidity and has a space to drain it away, coke bed will denude slag and enrich itself by coke. Barcza[6] observed such coke-enriched coke bed formed under electrode. The consequence of forming such abnormal coke bed structure is a poor power distribution and an unstable and reduced degree of smelting reaction of MnO in coke bed zone.

4 CONCLUSION

Mn ores charged with reducing and fluxing agents go through a series of physico-chemical transformation as they travel down in submerged arc furnaces. The experimental evidence with Groote Eylandt Mn ore shows that the carbothermic reduction of MnO at high reaction rates takes place at temperatures of 1335^{o}C and higher in the aggregation of Mn oxides melt with coke particles. Such requirement in submerged arc furnaces is provided by the formation of coke bed, and an efficient smelting operation calls for higher temperature and larger volume of coke bed.

The required energy for chemical reactions in submerged arc furnaces is provided by the resistive heating with electric current flowing through molten slag and coke bed zones, and the furnace power maintains an inverse relationship with operating resistance, indicating that the electric current is the active parameter for increasing power for efficient smelting operations. The operating resistance characterizes the distribution of power between molten slag and coke bed zones in smelting area to facilitate effects on temperature and size of coke bed zone. These effects of operating resistance are controlled by electrode position. The smelting performance improves as the electrode position is lowered. However, it suffers at its extreme low positions beyond its optimum because of developing abnormal coke bed structure. The best smelting performance for high carbon ferromanganese is attained at optimum electrode positions.

5 REFERENCES

[1] Tangstad, M., “The High Carbon Ferromanganese Process-Coke Bed Relations”, Dr..Ing. Thesis, 1996, Universitetet I Trondheim Norge Tekniske Hogskole, Norway

[2] Roghani, G., Jak, E., Hayes, P., “Phase Equilibrium Studies in the MnO-Al_2O_3-SiO_2 System”, Metal. Mater. Trans.B., vol.33B, 2002, pp.827-838

[3] Westly, J., “Resistance and Heat Distribution in a Submerged Arc Furnaces”, INFACON74, Proc. Of the First International Ferro-alloy Congress, Johannesburg, S. Africa, 1974, pp.121-127

[4] Westly, J., “Critical Parameters in Design and Operation of the Submerged Arc Furnaces”, Electric Furnace Conference, vol.33, 1975, pp.47-53

[5] Silver, R.F., “Resistance:Load Relationship Applied to Furnace Problem Solving”, Electric Furnace Conference, vol.41, 1983, pp.175-180

[6] Barcza, N.A., Koursaris, A., See, J.B., Gericke, W.A., “The Ding Out of a 75 MVA High-Carbon Ferromanganese Electric Smelting Furnace”, Electric Furnace Conf, vol.37, 1979, pp.19-33