Chapter 2
Plasma Melting Studies on Static Bed Reactor

This chapter describes the thermal plasma processing in static bed reactor. The static bed is a plasma reactor in which plasma melt separation of metallized ilmenite takes place to produce titania-rich slag. Here the effects of various experimental parameters were studied on the slag quality as well as EC.

2.1 Introduction

Large-scale open-bath systems can be based on water-cooled metallic devices or on solid graphite electrodes. The water-cooled devices produce very stable, well-directed plasma-arc columns that can be readily transferred to an open bath. However, multiple water-cooled devices might be required to achieve the desired level of power and the use of a single graphite electrode operating at higher currents should be favored. A simple graphite electrode will suffice, although improved arc stability can be realized by the introduction of some plasma supporting gas down a small hole in the solid electrode to improve the directional stability of the arc to the bath. Direct current operation and a high-temperature environment improve arc stability even further [1–3].

These processes include smelting of ilmenite; Richards Bay Minerals (RBM) and Qubec Fer et Titanae (QIT) employ 6-in-line graphite electrode furnaces for the smelting of ilmenite. The furnaces are 19 m long and 8 m wide and are supplied with three transformers rated at a total of 105 MVA per furnaces. The process originally developed by QIT has been adapted at RBM to smelt fine ilmenite obtained from a beach sand deposit on the northeastern coast of South Africa [4]. The process employs a relatively open-bath approach for which careful control is required to avoid refractory erosion of side and walls. The plasma source is assumed to be a well-directed stabled electric arc that can be approximated by the model of Szekely. The reaction sequence would be as follows [5]:

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1. Dissolution of the metal oxide into the slag phase at the slag surface and within the bulk.
2. The reaction of the dissolved metal oxide with the slag surface.
3. The descent of the metal droplets formed through the bulk slag phase.
4. Find equilibrium at the interface between the bulk slag and the metal.

The extent to which these various reactions take place clearly depends very strongly on the local temperature and given the high-temperature, high power-density nature of the plasma arcs [6–8].

The open-bath process arc has the following advantages [9–15]:

1. The use of an open bath consisting of metal and some slag, and being flushed with an inert gas, permits a higher degree of control of the process metallurgy that can be obtained in a choke-fed furnace. Materials of high bulk density such as metal fines and powder materials can be fed directly into the hot metal bath, where good heat transfer takes place between the liquids and the solids, leading to rapid melting.
2. The reaction rate is faster if smaller particles are used and therefore the degree of conversion is higher for the same residence time.
3. The vapor loss from the hot zone of the furnace is higher because of the rapid and direct evolution of gases from the surface reaction layer, and there is a little possibility, and vapor will condense on the cooler, incoming solid material.
4. There is direct control over the feed rate, which is normally continuous, and over the input of electrical energy. This permits good process control and allows the temperature of the bath to be maintained at the desired level.
5. The electrical supply characteristics and geometrical arrangement of the transferred-arc furnace are similar to the conventional submerged-arc furnace, and the change to direct current is relatively straightforward.
6. Scale-up to the industrial operation is now feasible when a graphite electrode is used.
7. Transferred-arc devices have low cooling-water losses (usually less than 10%).
8. The operation of a transferred-arc plasma furnace is not normally affected by the electrical properties of the feed material and the products.
9. The transfer of energy is more effective from a d.c. transferred-arc device than from the conventional a.c. system.
10. Water-cooled non-consumable electrodes have a considerable life expectancy (up to 1000 h, depending on the current being drawn), and usually have a thermal efficiency of over 90% owing to the relatively small size of the water-cooled protection jackets.
11. Hollow graphite electrodes, alternative, but their cost can constitute an important item in the economics of the process. They have the advantage that they can carry higher currents, and at present, they are the only alternative if currents higher than 15 kA are envisaged. They also have the advantage that they can be lowered into the bath restrike the arc, which cannot be done readily with water-cooled devices. The high-voltage operation is also possible since stray arcing will not destroy the electrode although other problems may occur.

12. Problems relating to roof refractories are a feature of any closed-bath furnace. It is not the radiation from the arc column itself that causes the problem, but rather the radiation and the reflections of the arc from the hot surface of the bath since these can cause the roof refractories to fail. The height from the batch to the roof must be designed in such a way as to reduce the heat flux on the roof, but arc length is to be constraints. This concept can place a limit on the advantages to be gained from an open-bath furnace operation.

Mintek has had in a 100 kVA experimental, as well as a 1.4 MVA semi-industrial, transferred-arc, molten-anode, furnace. This work is currently being extended to 3.2 MVA-scale at Mintek. High-quality metal was produced in a lumpy form, and good recoveries were achieved [6–11] plasma devices have greatly increased the stability of high-intensity arc discharges, and operatives at a much larger range of currents and voltages have been made possible. The disadvantages are as follows [12–15]:

1. High rate of electrode erosion.
2. High energy/gas consumption.

2.2 Experimental

A number of experiments were carried out in the static bed plasma reactor to study the influence of process parameters such as plasma power, time of melting, and degree of metallization on energy consumption and slag quality. Following are the parameters for assessing the experimental aberrations [16–21].

(i) Degree of metallization (%) = weight of elemental iron in PRI/weight of total iron present as elemental and oxides in the PRI × 100.

(ii) Iron Recovery: Amount of metallic iron obtained from the lump containing both iron and slag.

$$\text{Metal recovery}(\%) = \text{weight of iron extracted}/\text{weight of iron in PRI} \times 100.$$

(iii) Slag: Amount of plasma product produced without the iron, i.e., weight of lump weight of iron.

$$\text{Slag Recovery}(\%) = \text{weight of slag}/\text{weight of lump} \times 100.$$

(iv) Production Rate: Weight of the products produced by thermal plasma per unit time.

$$\text{Production Rate of slag}\left(\text{kg h}^{-1}\right) = \text{weight of slag in kg/duration of an experiment in min} \times 60.$$

(v) Energy Consumption: Amount of electrical energy required for producing slag from the PRI.

$$\text{Energy consumption}\left(\text{kWh kg}^{-1}\right) = \text{input power}/\text{production rate of slag.}$$

Experiments were planned to generate data for optimizing process parameters with a view to minimizing energy consumption and production of high-quality slag.

2.2.1 Effect of Variation of Experimental Conditions

Melting experiments were carried out with the pre-reduced ilmenite with varying degree of metallization, duration of plasma melting, and power input. The results are tabulated in Tables 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 2.10, and 2.11.

Table 2.1 Effect of hole diameter of the graphite electrode

Hole diameter (mm)	Energy consumption (kWh/kg)
4	3.2
6	2.6
8	2.9
10	3.0
12	3.5

Table 2.2 Effect of gas flow rate

Gas flow rate (lt/min)	Energy consumption (kWh/kg)
0	2.4
0.5	2.5
1	2.8
2	3.0

Table 2.3 Effect of temperature on reduction

Reduction temperature (°C)	Metallic iron (%)	Total iron (%)	Metallization (%)
800	3.57	41.64	8.57
850	6.53	42.57	15.34
900	18.01	43.16	41.72
950	36.42	45.16	80.64
1000	39.98	45.08	88.68
1050	39.99	45.70	87.50
1100	40.70	45.72	89.04

Table 2.4 Effect of residence time on reduction

Residence time (min)	Metallic iron (%)	Total Iron (%)	Metallization (%)
30	24.98	43.30	57.69
60	32.90	44.00	74.77
90	36.32	44.73	81.19
120	37.16	44.84	82.87
150	37.59	45.01	83.52
180	39.37	45.23	87.04
210	39.59	45.50	87.01
240	39.98	45.08	88.68

Table 2.5 Effect of reductant on reduction

Leco char content (%)	Metallic iron (%)	Total iron (%)	Metallization (%)
15	15.67	42.06	37.25
20	16.53	42.09	39.27
30	26.79	41.53	64.50
40	30.06	44.09	68.18
50	37.03	44.69	82.86
60	38.60	45.12	85.56
100	39.37	45.23	87.04

Table 2.6 Effect of reductant on metallized ilmenite in plasma melt separation

Coke (%)	Lump weight (g)	Iron separated (%)	Production rate (kg/h)	Energy consumption (kWh/kg)
0	320	40	9.6	1.04
0.25	232	38	7	1.43
0.5	240	35	7	1.43
2.0	198	33	6	1.67

Table 2.7 Effect of time on plasma melting

Time of melting (min)	Lump weight (g)	% Weight of iron in the lump	Production rate (kg/h)	Energy consumption (kWh/kg)
1	138	33	8.28	1.2
1.5	208	35	8.33	1.2
2	320	40	9.61	1.04
5	670	38	8.04	1.24

Table 2.8 Effect of input power on plasma melting

Power used (kW)	Lump weight (g)	Iron separated (%)	Production rate (kg/h)	Energy consumption (kWh/kg)
5	152	32	4.56	1.10
10	320	40	9.60	1.04
15	407	39	10.70	1.22
20	510	38	15.30	1.30

Table 2.9 Effect of extent of pre-reduction on plasma melting

Extent of pre-reduction (%)	Lump weight (g)	Iron separated (%)	Production rate (kg/h)	Energy consumption (kWh/kg)
60	280	24	8.4	1.19
72	275	28	8.25	1.21
75	280	35	8.40	1.19
85	320	40	9.60	1.04

Table 2.10 Effect of time of melting and metallization in static bed reactor (input power: 10 kW)

Degree of metallization (%)	Time (min)	Iron recovery (%)	Yield[a] (kg/h)	Energy consumption (kWh/kg)
60	1	57.9	9.15	1.15
	1.5	57.1	10.36	1.42
	2	56.6	8.41	1.34
75	1	67.6	9.26	1.11
	1.5	69.2	10.55	1.35
	2	69.0	8.56	1.28
85	1	79.5	9.42	1.06
	1.5	77.1	10.76	1.22
	2	76.8	8.77	1.18

[a]Represents the yield of slag and metal together

2.2.2 *Static Bed Plasma Reactor*

In course of the present investigation in the SBR, time was varied from 0 to 2 min., input plasma power from 5 to 20 kW and degree of metallization of ilmenite were varied from 62 to 85%. The following factors have been considered which can contribute to energy reduction (increase in production rate) and quality of slag (% metal extracted). Under the above conditions, experiments were carried out to find the effect of E.C and slag quality on the above processing parameters.

Table 2.11 Effect of input power and metallization in static bed reactor (melting time: 2 min)

Degree of metallization (%)	Input power (kW)	Metal recovery (%)	Yield[a] (kg/h)	Energy consumption (kWh)
60	5	59.7	4.0	1.25
	10	61.6	8.9	1.12
	15	62.4	13.9	1.07
	20	64.7	17.3	1.15
75	5	63.2	3.4	1.47
	10	72.4	7.5	1.33
	15	76.3	12.2	1.23
	20	81.6	16.0	1.25
85	5	76.3	3.5	1.42
	10	79.7	8.7	1.15
	15	86.8	12.4	1.21
	20	90.8	14.7	1.36

[a]Represents the yield of slag and metal together

1. Diameter of the hole of graphite electrode
2. Gas flow rate
3. Amount of reductant (graphite added)
4. Input power
5. Duration of melting
6. Extent of metallization

The first two instrumental parameters have been optimized first with respect to energy consumption for carrying out the various experiments.

Accordingly for all other experiments electrode with hole diameter 6 mm and gas flow rate 0.5 lt/min were optimized. Amount of pre-reduced ilmenite was also kept constant at 500 g. This melt separation was found to depend on the next four parameters which were varied during the experiment.

2.3 Pre-reduction/Metallization of Ilmenite

The reduction reaction which depends on the three parameters as mentioned earlier were optimized and the results are given below.

2.3.1 Reduction Temperature

The reduction temperature was varied from 800 to 1100 °C in steps of 50 °C. Residence time was maintained constant at 4 h for the above temperature levels. All the reduced samples after the reduction were separated from the non-magnetic part by magnetic separation and analyzed for metallic and total iron contents, and the results are shown in Table 2.3.

From Table 2.3, it is clear that up to a temperature of 900 °C, the reduction rate was very slow. After, 900 °C, there is a sudden increase in metallization level and reached a maximum at a temperature of 1000 °C. At temperatures beyond 1000 °C, there was no appreciable change in the metallization. Reduction temperature of 1000 °C was considered as optimum.

2.3.2 Residence Time

After optimizing reduction temperature, experiments were carried out at an optimized temperature (1000 °C), while the residence time at the above temperature was varied from 30 to 240 min in steps of 30 min.

In the first half an hour, more that half of the iron was metallized. The metallization reached 85% in one and half hour and afterward there was a gradual increase in metallization and reached a maximum in 4 h. The residence time of 3 h was found to be optimum.

2.3.3 Amount of Reductant

Leco char was taken as the reductant which contains about 75% of fixed carbon. The stoichiometric requirement of leco char was calculated on the basis of ferrous iron, the ferric iron of ilmenite, and fixed carbon content of leco fines. However, an excess of leco char was needed than the stoichiometric requirement in order to reduce the iron oxide and to provide a reducing cover to the metallized product, thereby preventing it from oxidation.

The quantity of ilmenite was kept constant in each of the experiments while the percentage of leco char was varied from 15, 20, 30, 40, 50, 60 to 100% on the basis of the weight of ilmenite. All the reduction experiments were carried out at 1000 °C temperature for 3 h duration. Addition of 60% of leco char was found to be optimum.

On reduction of above factors, the pre-reduced ilmenite is obtained which is the basic raw material for plasma melt separation. The plasma melt separation experiments were carried out on the pre-reduced ilmenite (PRMI) to obtain titania-rich slag of better quality. Various input parameters were varied on PRMI in static bed reactor (SBR) with an aim to obtain less energy consumption, which is the main drawbacks in plasma processing.

2.4 Plasma Melt Separation

The plasma melt separations experiments were carried out by varying the following four parameters for optimizing conditions for minimum energy consumption.

2.4.1 Amount of Reductant in the Pre-reduced Ilmenite

Coke was used as a reductant. Amount of coke was varied from 0 to 5%, and the reaction was carried out for 2 min.

From the above results, it was evident that the addition of any amount of coke not only reduced production rate but also reduced the percentage of iron separated.

Therefore, no more reductant was added in subsequent experiments.

2.4.2 Effect of Time on Plasma Melting

Time plays a major role among all other parameters as it directly affects the production rate and energy consumption. So, careful optimization of time was highly necessary. The results are shown in Table 2.7.

Time of 2 min was found to be optimum as the lump weight; production rate and iron separated were highest with lowest energy consumption.

2.4.3 Effect of Input Power on Plasma Melting

After optimizing time and amount of reductant, it was decided to vary the plasma power input to study the effect of production rate and energy requirement. The results are shown in Table 2.8.

It can be seen from Table 2.8 that the production rate does not follow a linear pattern. As a result, energy consumption increases above 10 kW power input. Accordingly, 10 kW was taken to be the optimum.

2.4.4 Effect of Extent of Pre-reduction on Plasma Melting

Pre-reduced ilmenite of different metallization ranging from 60 to 85% was studied, and the results are shown in Table 2.9.

It can be seen that production rate, as well as power consumption, does not vary significantly up to about 75% metallization. There is a drastic increase in production rate and a decrease in power consumption with an increase in the percentage of metallization.

Thus, the following conditions were found to be optimum for maximum production rate and minimum power consumption for the said setup.

Parameters	Value
For pre-reduction	
(i) Reduction temperature	1000 °C
(ii) Residence time	3 h
(iii) Amount of reductant	60%
For plasma melt separation	
(i) Amount of reductant	Nil
(ii) Duration of melting	2 min
(iii) Input power	10 kW
(iv) Extent of metallization	85%

Effect of variation of extent of metallization with input power keeping the time of melting constantly is shown in Table 2.10.

2.5 Discussion

The results are shown in Tables 2.10 and 2.11, and Figs. 2.1 and 2.2 clearly indicate that degree of metallization plays a very important role toward higher metal recovery, lower energy consumption, and better quality of slag production. A higher iron recovery leads to a slag with higher TiO_2 content. Higher metallized ilmenite also takes less time to melt out the metal from the pre-reduced ilmenite and hence will be able to reduce the energy consumption. The results clearly indicate that for obtaining slag with higher TiO_2 content, an optimum condition of plasma power and time of melting are necessary for ilmenite having a particular degree of metallization. Table 2.10 shows that 10 kW power and time of 2 min in an optimized condition for static bed reactor with 85% metallized ilmenite.

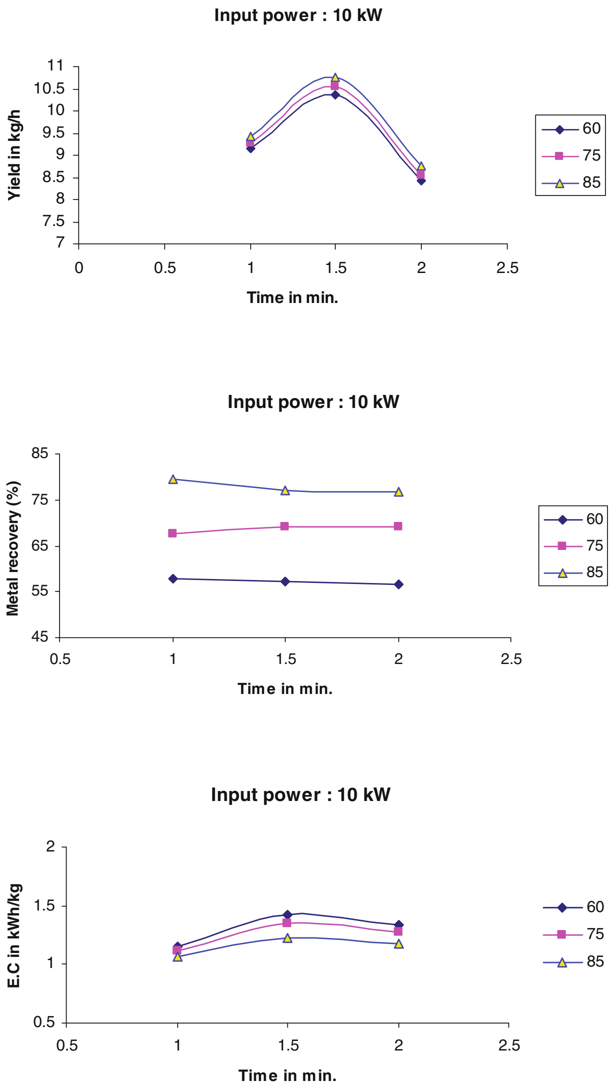

Fig. 2.1 Effect of metallization and input power on yield, metal recovery, and energy consumption in static bed reactor

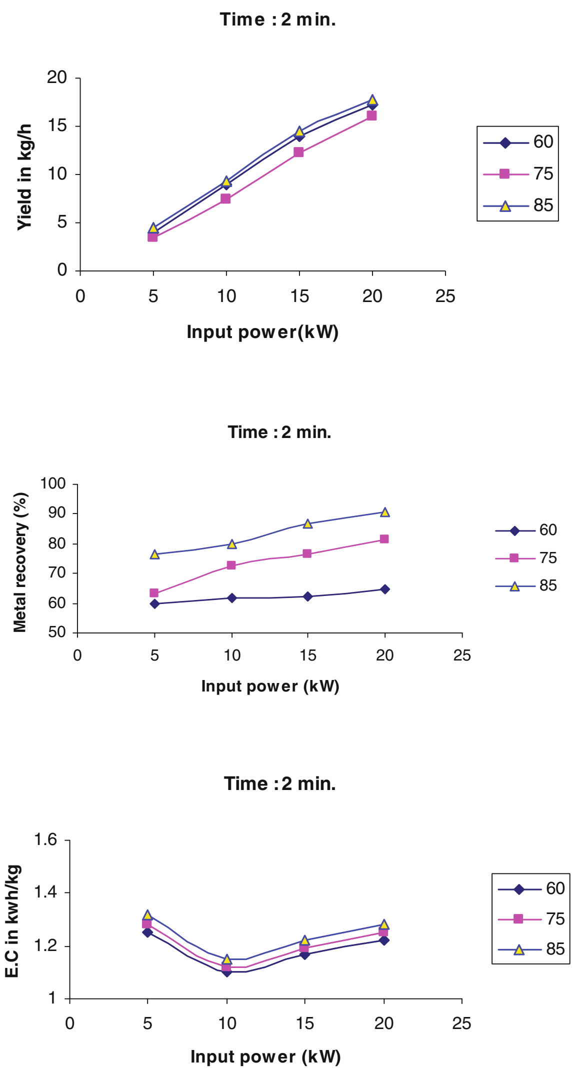

Fig. 2.2 Effect of metallization and melting time on yield, metal recovery, and energy consumption in static bed reactor

2.6 Conclusion

The result of the present study clearly indicates that by varying various plasma processing parameters, it is possible to reduce the energy consumption significantly. Further, the charge material, i.e., metallized ilmenite plays a key role in not only reducing energy consumption but also can give slag with higher TiO_2 content. However, translating observations of the static bed reactor into moving bed reactor for continuous production of TiO_2-rich slag and metal have been attempted by designing and fabricating a moving bed reactor.

The results clearly indicate that both time and power have to be optimized for metallized ilmenite having a specific degree of metallization. This is not possible in static bed reactor; hence, a concept of moving bed reactor has been developed for optimizing energy requirement in a plasma process. The following chapter gives a detailed investigation on the moving bed reactor. Its a clear indication that on increasing metallization, yield (rate) and iron recovery get increased, simultaneously E.C reduced considerably. On increasing time of melting, E.C goes on increasing as it's a batch production. Keeping in mind, modified reactor has been procured in moving bed reactor for reducing energy consumption in thermal plasma processing of ilmenite. From the experiments carried out in SBR, shows that residence time has a great impact on reducing energy consumption. To study the variation in residence time, and how it affects on quality of slag, E.C and MBR are designed with variation in speed of the reactor [22, 23].

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