ENERGY CONSIDERATIONS FOR THE MELTING OF DRI AS A FUNCTION OF THE DEGREE OF PRE-REDUCTION

R.J. DIPPENAAR*, N.A. BARCZA**, R.T. JONES***

* Professor, University of Pretoria, Pretoria, 0002, Republic of South Africa
** Director, Pyrometallurgy Division, Council for Mineral Technology, Private Bag X3015, Randburg, 2125, Republic of South Africa.
*** Engineer, Council for Mineral Technology, Randburg, Republic of South Africa.

SYNOPSIS

The Process route in which direct-reduced iron (DRI) is pre-reduced in a rotary kiln and subsequently melted in an electric-arc furnace is similar to that used by one producer for ferro-alloy production in South Africa, and the economic evaluation of this process is consequently of great importance to both steelmaking and ferro-alloy production. This paper describes the relevant reduction kinetics of the hematite used in a rotary kiln, together with an experimental technique for the simulation of the energy requirements of an electric-arc furnace. The interrelationship of the energy requirements in the electric-arc furnace and the degree of pre-reduction of the DRI feed, as predicted by mass and energy balances, are analysed. It is shown that the production capacity of this type of plant can be increased by about 56 per cent if the degree of metallization of the product DRI is decreased by some 15 per cent and the specific power requirement of the electric-arc furnace is increased by about 12 per cent.

INTRODUCTION

Various direct reduction processes have been introduced by the South African metallurgical industry in recent years. A Krupp rotary kiln for the production of directly reduced iron (DRI) was installed in 1974 at Dunswart Iron and Steel Works Ltd and this kiln is still producing highly reduced DRI as feedstock for electric-arc furnaces. The Highveld Steel and Vanadium Corporation Ltd utilizes a modified Lurgi rotary kiln for the pre-reduction of vanadium-bearing titaniferous magnetite. That application of a rotary kiln is of special interest in the present context, because the iron ore is only partially reduced, and the degree of reduction, expressed as the percentage removal of moles of oxygen, is typically less than 60 per cent. Pre-reduction of the ore is carried out mainly so that less electrical energy will be needed in a subsequent step of the process, namely the seperation of in which titanium oxide into a slag phase, from the vanadium bearing molten iron in a submerged-arc furnace.

In 1985, the Iron and Steel Corporation of South Africa (Iscor) installed rotary kilns that were to be used in combination with ultra-high-power electric-arc furnaces at their Vanderbijlpark works. At the time of its installation, this rotary kiln plant was reported to be the largest coal-based DRI plant in operation in the world and the first installation of its kind in a fully integrated steelworks using blast furnaces and the Linz-Donawitz (LD) process for steelmaking(1). The rotary kiln plant is based on the Lurgi rotary kiln process, and the reduction unit consists of four rotary kilns of 4,8 m diameter and 80 m length, which together can produce 720 kt of DRI annually. The iron ore is supplied by Iscor's mine at Sishen and is normally reduced to more than 90 per cent metallic iron. The product DRI is fed to electric-arc furnaces as a supplement to the scrap charge. Interest in the energy consumption in this particular process route revived mainly because it was necessary to optimize the operation of this large reduction plant. However, there is yet another interesting process route that warrants an analysis of this kind. Iscor is currently commissioning a new COREX plant at its Pretoria works. This production plant, which is the first of its kind in the world, will produce liquid iron for further refining in electric-arc furnaces. The charge to the latter will consist of steel scrap and liquid crude iron. The possibility that DRI together with crude iron from the COREX-process can replace, either in part or in full, the scrap in the charge, offers an exiting prospect.

The combination of a rotary kiln and an electric-arc furnace (EAF) is not limited to steelmaking processes; very important applications of this process route are found in the ferro-alloys industry. For example, at Consolidated Metallurgical Industries Ltd (CMI), carbon containing chromite-ore pellets are reduced in a coal fired rotary kiln prior to final reduction and smelting in a submerged-arc furnace. This pre-reduction step was introduced mainly to reduce the consumption of electrical energy during final reduction.

PREVIOUS INVESTIGATIONS

In view of the extensive use made of the rotary kiln - electric-arc furnace process route for steelmaking and ferro-alloy production, it is of great importance to devise some means whereby the economics of DRI usage can be evaluated. The use of fundamental process analysis would allow parameters such as process variables and materials chemistry, to be incorporated. The energy consumption and the complex interplay of the operating parameters in rotary kilns and electric-arc furnaces have been the subject of various stu-

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dies. Venkateswaran and Brimacombe[2] developed a mathematical model, based on the conservation of heat and mass, which they used to predict the operating behaviour of an SL/RN direct-reduction kiln from the main process variables. Although the rotary kiln process could be simulated by that model, the approach to the analysis of heat transfer by radiation was not entirely satisfactory. Gorog et. al.[3-5] and Barr[6] subsequently analysed the heat transfer by radiation that occurs in the rotary kiln, and applied their results to the construction of a heat-transfer model for the coal- fired rotary kiln[7].

D'Entremont and Englebrecht[8] developed a computer model that enabled them to determine the optimal operating practices for electric-arc furnaces in which scrap is partially replaced by DRI. This generalized mathematical model, which was based on mass and energy balances, combined with measured energy losses from the furnace, could be used to evaluate the effects of changes in the chemical composition of the DRI. Consequently, it was possible not only to pre-evaluate the economics of the use of DRI in an electric arc furnace, but also to determine the implications of a lowering in the degree of pre-reduction.

Strohmeier and Peters[1], in a very practical approach to a similar problem, determined the effect of an increase in the ratio of DRI to scrap in the charge, on the operation of an electric-arc furnace. These authors clearly indicated that an increase in the amount of DRI fed to the furnace results in the generation of excessive volumes of slag and that the consumption of lime increases significantly owing to its reaction with the acidic gangue present in the DRI.

Because a large fraction of heavy scrap is normally used in operations at Iscor's Vanderbijlpark works, the DRI tends to float during the melting of the scrap, and unstable melting conditions result. If the proportion of DRI in the furnace charge is increased, the consumption of electrical energy as well as the total conversion time increase, and these detrimental effects will be even more pronounced if the degree of metallization of the DRI is decreased. However in that instance, the increased amount of DRI in the feed also had some beneficial effects. An excellent foaming slag was formed[1], the heat transfer was improved, the rate of reaction between the constituents of the slag and metal phases increased as a result of the continuous carbon boil, and a product with a lower nitrogen content was obtained, while the removal of sulphur and phosphorus did not present any insurmountable problems. These results indicate that a slight lowering in the degree of metallization at a constant ratio of DRI to scrap ratio, might not seriously impair electric-arc furnace operations, since an even better carbon boil would be obtained at the expense of an increased retention time. Additional carbon would be required to completely reduce the DRI, but the use of the high-carbon liquid metal product from the COREX process, as a source of extra carbon, as was invisaged at Iscor's Pretoria works, is an interesting possibility.

PRESENT INVESTIGATION

Although satisfactory models relating to the complex transfer of energy in a rotary kiln have been reported[2,7], and computer simulations of electric-arc furnace operations have been described[8], no model that covers the combination of the pre-reduction and smelting-melting step, particularly with regard to the optimization of the two unit operations, has yet been developed.

It was against this background that the present investigation was initiated. The main purpose was the systematic development of experimental techniques and simplified models that could be used as building blocks for a more complete process model. The initial work reported in this paper was limited to an investigation of the effects of a decrease in the degree of metallization of DRI (which could, for example, result from a higher throughput of iron ore through the rotary kiln), on the energy consumption and performance of the electric-arc furnace.

In the following sections, some relevant aspects of the reduction kinetics of the iron ore of interest are discussed, and the experimental techniques by which the electrical energy requirements of the electric-arc furnace was estimated, are described. Finally, the interrelation between the energy requirements of the electric-arc furnace and the degree of pre-reduction of the DRI, as predicted by mass and energy balances, is addressed.

REDUCTION KINETICS

The rate of reduction of the hematite ores that are used in the South African metallurgical industry has been the subject of a number of investigations. Beeton[9] concentrated on ores from Iscor's Thabazimbe mine while Theron[10], more recently, studied the reduction of hematite from Iscor's Sishen mine using thermogravimetric analysis (TGA). Four spherical ore particles, each weighing approximately 5 g and from 10 to 12,5 mm in diameter, were supported on a pedestal in a perforated crucible, where they were reduced in a stream of hydrogen or carbon monoxide, the decrease in mass during the reduction being recorded as a function of time. Care was taken to ensure that the supply of reducing gas was not rate limiting, and a gas flowrate of 5,5 l/min was found to be adequate.

The progress of reduction can be presented by the fraction transformed, **F**, or by the relative depth of penetration, **f**. These parameters are defined[11] as follows:

$$F = (V_o - V_i) / V_o$$

and

$$f = (R_o - R_i) / R_o$$

where V_o and R_o refer to the original volume and radius of a particle respectively, while V_i and R_i denote the volume and radius of the unaffected material at time i.

The progress of the reduction, by hydrogen gas, of hematite ore from Iscor's Sishen mine (Figure 1), expressed as the change in the fraction transformed, F, is in good agreement with the results obtained in previous studies[9,12]. The linear relationship between the relative penetration, f, and the reaction time indicates that the progress of transformation can be expressed by a shrinking-core model, and that the reduction reaction is topochemically controlled. Similar results were obtained when carbon monoxide gas was used as the reducing agent, except that the rate of reduction was considerably lower, as expected. The first derivative of the fractional transformation with respect to time, dF/dt, is linear during the later stages of the reaction. The reduction of Sishen ore by carbon monoxide gas yielded similar results. The implications of these important observations will be considered in more detail in a later section.

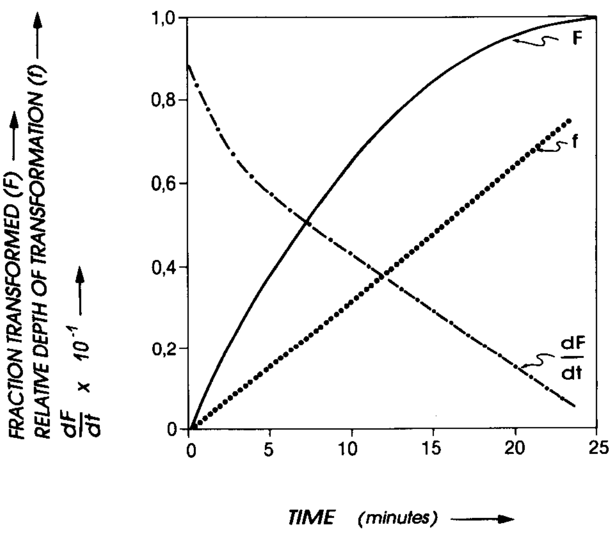

FIGURE 1

HYDROGEN REDUCTION OF SISHEN HEMATITE. FRACTION TRANSFORMED (F), RELATIVE DEPTH OF PENETRATION (f) AND THE FIRST DERIVATIVE OF THE FRACTION TRANSFORMED WITH RESPECT TO TIME, AS A FUNCTION OF TIME.

The reduction of hematite from Sishen, which is accomplished in three steps, was recently re-examined by thermogravimetric analysis[10]. An example of the reaction is shown in Figure 2. Carbon monoxide was used as the reductant, and the ratio of carbon monoxide to carbon dioxide was controlled so that only the oxide product of interest was stable. Hematite was completely reduced to magnetite before the composition of the gas was changed so that the newly formed magnetite could be further reduced to wüstite and then to iron. It was confirmed that the wüstite-to-iron reduction step, which is rate-limiting, conforms to the predictions of the shrinking-core model[11] and, like the overall reduction reaction, is topo-chemically controlled. There is also virtually a constant change in the rate of reduction in the later stages of the reduction cycle.

Hematite ore from the Sishen mine approaches complete reduction asymptotically, Figure 1, whether it is reduced by hydrogen or carbon monoxide[10,12]. Also, the rate of reduction decreases at a constant rate towards the end of the reaction, implying that the throughput of the rotary kiln could be increased significantly if a lower degree of metallization of the product DRI were acceptable. Since the consumption of energy per unit mass of ore in the rotary kiln is an approximately linear function of the retention time over the range of interest, it is possible, in principle at least, to achieve an increase in throughput of approximately 50 per cent if the degree of metallization of the DRI is decreased

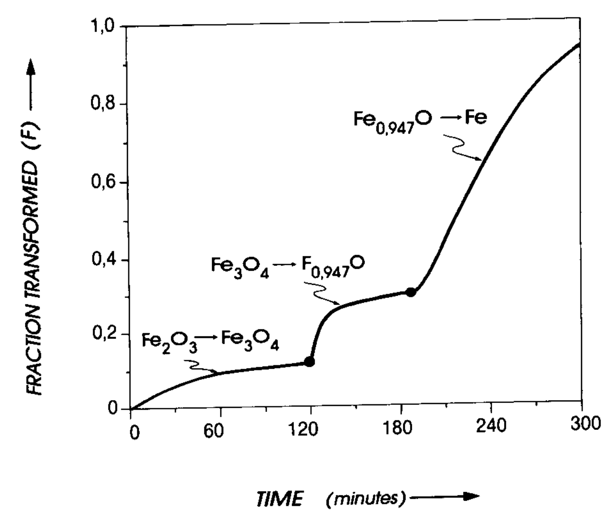

FIGURE 2

STEPWISE REDUCTION OF SISHEN HEMATITE IN CO/CO_2 MIXTURES. FRACTION TRANSFORMED AS A FUNCTION OF TIME.

from 95 to 80 per cent. However it should be emphasized that this argument holds good only if reduction kinetics, and not heat transfer, is the rate limiting factor in the rotary kiln.

In the mathematical model developed by Venkateswaran and Brimacombe(2), an empirical term proposed by Von Bogdandy(13) is used to describe the rate of reduction of hematite in a rotary kiln. An analysis of heat transfer is incorporated in this model and the rate of reduction as a function of the length of the kiln can be predicted from a combined analysis of the reduction kinetics and heat transfer. The retention time in the kiln, which is related to the transformation time in the TGA experiments, is directly proportional to the length of the kiln. The rate of reduction predicted by the model of Venkateswaran and Brimacombe(2) can therefore be directly compared to the results of the TGA tests. The trends of the results, when re-plotted, are similar to those in Figure 1. The shape of the curve of fractional transformation versus time is the same as that of the curve in Figure 1. Furthermore, the relative penetration is directly proportional to the time of transformation, and the rate of reduction also decreases at a constant rate towards the end of the reduction cycle. The model therefore confirms the conclusions from the TGA work, that the furnace throughput could be increased at the expense of a small decrease in the degree of reduction of the product.

As indicated earlier, the optimal operation of an electric-arc furnace is not limited by energy considerations alone(1). For example, the production of somewhat larger volumes of slag as a result of the ash in the coal used for the reduction of the insufficiently reduced DRI, may seriously impair the efficiency of the operation. A balance has therefore to be struck between the higher throughput attainable in the rotary kiln when only partially reduced DRI is produced, and the additional electrical energy required for the smelting-melting of partially reduced DRI in an electric-arc furnace. It is consequently of the utmost importance to devise means by which the electrical energy required for the smelting-melting of DRI can be measured, and it would be very convenient if these measurements could be carried out in the laboratory rather than on an industrial scale.

EXPERIMENTAL ASSESSMENT OF THE ENERGY REQUIREMENTS FOR THE SMELTING-MELTING OF DRI IN AN ELECTRIC-ARC FURNACE

A small, well-instrumented, direct-current transferred plasma-arc furnace, rated at 100 kVA, with a capacity of approximately 50 kg of molten metal, was utilized for the measurement of the relative energy required to smelt-melt pre-reduced DRI of varying degrees of metallization(14). In the first experiments, the electrical energy required to melt highly reduced DRI (more than 93 per cent iron), was determined. In subsequent experiments, lower degrees of metallization were simulated by the use of mixtures of iron ore and highly metallized DRI in suitable proportions. The DRI and the mixtures of DRI and ore were melted-smelted in semi-continuous campaigns, and the average energy requirement per unit mass was determined . Mixtures of DRI and ore were fully reduced by coal within the plasma-arc furnace, while the consumption of electrical energy was measured. The average tap-to-tap time was approximately 2 hours, and the duration of each campaign was at least 10 heats.

The relationship between the degree of pre-reduction and the energy required to smelt-melt the partially reduced DRI is given by the following equation :

$$E/E_0 = - 0.017M + 2.67 \quad ..... \quad (1)$$

where E and E_0 are the amounts of electric energy in kWh per tonne of metal, required to melt DRI and 95 per cent reduced DRI respectively, and M is the degree of metallization in per cent.

Meihack et. al.(15) continued the use of experimental plasma-melting facilities for the study of the electrical energy requirements for the melting-smelting of DRI, and also studied the effect of pre-heating the charge. Their experiments were carried out in a 200 kW plasma-arc furnace in a continuous campaign that lasted 110 hours. The procedure was similar to that used by van der Schijff(14). The feed material was continuously fed to the furnace, and after each batch the furnace was switched off and tilted to allow the slag and the metal to be tapped. The results essentially confirmed those of van der Schijff(14). These authors also reached the relevant and very important conclusion that the rate of loss of energy is independent of the operating power of the furnace and the feed flux, provided that these two dependent variables are correctly balanced according to thermodynamic requirements.

The observation that the final reduction of iron ore from Sishen in a rotary kiln is approached asymptotically, whereas the additional electrical energy required to melt partially reduced DRI in an electric-arc furnace is a linear function of the degree of metallization, stimulated further investigations. Theoretical energy balances for a conceptual rotary kiln, and an electric-arc furnace, were therefore calculated.

ENERGY BALANCE

The energy balance was calculated by the use of the PYROSIM steady-state pyrometallurgical simulation computer program. The development and applications of this program have been fully described elsewhere (16), and it is necessary to refer only to the specific application of this program to the study of the rotary kiln - electric-arc furnace route of steelmaking currently under discussion.

A simple empirical model was used in the analysis of the energy balance in the rotary kiln. The temperature in the reduction zone of the kiln was assumed to be 1100 °C and the ratios of carbon monoxide to carbon dioxide and of hydrogen to water vapour in the off-gas were specified as 0.5 and 0.1 respectively.

An attempt was made to predict the increase in throughput attainable in the kiln if the degree of metallization of the product DRI was lowered while a balance in the mass and energy requirements was maintained. It was assumed that heat transfer in the rotary kiln is not rate-limiting, and that the maximum feed rate of hematite is limited only by the applicable reduction kinetics. The flowrates of raw materials, of which air and coal are the most important, were accordingly adjusted to yield the same rate of energy loss from the kiln as that occurring when DRI of 95 per cent metallization is produced. These feed rates were taken as reference parameters and the chemical composition of the input streams were then specified for the conceptual kiln. Examples of the relative increase in the required supply of raw materials, as well as the resulting increased production rates for three different degrees of reduction of the product DRI, are shown in Table 1 .

TABLE 1

MASS BALANCE FOR A ROTARY KILN

OPERATING CONDITIONS			
Temperature	1 100 °C		
CO/CO_2 (by volume)	0.5		
H_2/H_2O (by volume)	0.1		
Metallization of DRI (%)	**95**	**80**	**65**
Feed rate (t/h)			
Hematite	32.0	50.0	66.0
Coal	20.0	25.0	27.0
Air	66.0	85.0	97.0
Dolomite	1.5	2.3	3.0
Production (t/h)			
Solids	30.0	46.0	61.0
Gas	90.0	117.0	132.0

The relationship between the rate of production and the degree of reduction of the ore in the range 65 to 95 per cent metallization is described by the following equation:

$$G/G_o = -0.034M + 4.22 \quad \ldots\ldots \quad (2)$$

where **G** is the feed rate of hematite to the kiln, in tonnes per hour, and G_o is the feed rate of hematite for the production of DRI metallized to the extent of 95 per cent, and **M** is the degree of reduction.

This model predicts that a decrease in the degree of reduction from 95 to 80 per cent will result in a 56 per cent increase in the rate of production of DRI.

The simulation of the electric-arc furnace is based on the assumption of multiphase chemical equilibrium, and uses the technique of free-energy minimization[16]. The requirements for the production of DRI metallized to the extent of 95 per cent were taken as reference parameters and the amounts of DRI, reductant and fluxes were adjusted for a production of 72 t of metal per hour while energy and mass balances were maintained. Examples of the feed rates of the raw materials and the rates of production of metal, slag, and off-gas for three different degrees of metallization of the product DRI are shown in Table 2.

The following linear relationship was found to exist between the degree of metallization of the

TABLE 2

MASS BALANCE FOR AN ELECTRIC-ARC FURNACE

OPERATING CONDITIONS			
Temperature	1 700 °C		
Slag basicity	3.7		
Metallization of DRI (%)	**95**	**80**	**65**
Feed rate (t/h)			
DRI	33.0	34.0	36.0
Scrap	43.0	43.0	43.0
Oxygen	2.1	2.1	2.1
Dolomite	2.6	2.6	2.6
Antrasite	0.7	0.7	0.7
Coke	1.4	3.0	4.7
Burnt lime	4.6	5.0	5.4
Production (t/h)			
Metal	72.0	72.0	72.0
Slag	9.4	10.0	11.0
Gas	5.8	9.0	12.0

DRI fed to an electric-arc furnace and the additional energy required for melting.

$$E/E_O = -0.012M + 2.14 \quad ..... \quad (3)$$

This result is in good agreement with the experimentally determined energy requirement of the plasma furnace (equation 1). However, if the DRI to scrap ratio in the electric-arc furnace is increased to make use of the higher throughputs attainable in the rotary kiln, electrical energy is utilized more efficiently. When this is taken into account, the expression for the energy requirement becomes:

$$E/E_O = -0.0091M + 1.865 \quad ..... \quad (4)$$

If the degree of reduction of the DRI supplied to the electric-arc furnace were to be decreased from 95 to 80 per cent and the more efficient use of electrical energy is taken into account, the increase in the specific energy consumed in the melting process is approximately 13 per cent.

For increased production of steel, the actual operating load of the electric-arc furnace and the throughput of the rotary kiln both need to be increased. The potential increase in the production of steel in relation to the required operating load, predicted by the model when the ratio of DRI to steel scrap in the feed to the electric-arc furnace is kept constant, is shown in Figure 3.

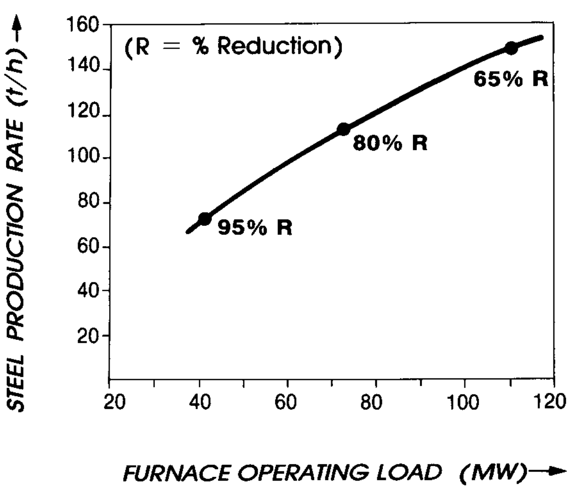

FIGURE 3

PRODUCTION RATE OF STEEL AS A FUNCTION OF MW LOAD.

It should be emphasized again that the analysis reported here is based on simplified assumptions and empirical data. However, the results obtained are encouraging, and clearly demonstrate the need for a dynamic process model. The design of this type of model, which should include an economic analysis, is envisaged as the next step in the current research programme.

CONCLUSIONS

The present investigation has shown that it should be possible to increase production by the steelmaking route employing a rotary kiln and an electric-arc furnace. Steel production can be increased by approximately 56 per cent if the degree of reduction in the rotary kiln is decreased by some 15 per cent, the specific power input to the electric-arc furnace is increased by about 12 per cent and the actual power level is increased by 75 per cent.

An overall increase in production from an existing plant might involve capital expenditure or larger transformers, but the increased output would probably offset this cost. However, these considerations could be taken into account in the design of a new plant and, if scrap were omitted from the feed, a closed-top direct current transferred plasma-arc furnace could be used instead of the conventional electric-arc furnace.

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