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## **Developments in Plasma Furnace Technology**

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# Developments in Plasma Furnace Technology

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**Synopsis:** Plasma furnaces have been successfully applied to the production of a variety of materials, particularly ferro-alloys. They have the advantage of allowing the direct use of fine feed materials. Furthermore, because the power input is not limited by the electrical conductivity of the materials being processed, feed rate and power can be controlled independently. High power-fluxes lead to the use of smaller reaction vessels. Pilot-scale DC open-bath transferred-arc plasma furnaces of up to 1 MW in power, using single hollow graphite electrodes, are in use at Mintek. These furnaces have been used to achieve power fluxes of over 2 MW/m<sup>2</sup> of hearth area. When coupled with a fluidized-bed preheating unit, the consumption of electrical energy per ton of product decreases markedly, allowing an increase in throughput of almost 40 per cent at constant electrical power input.

Ferrochromium is produced on an industrial scale in a 40 MVA plasma furnace at Palmiet Ferrochrome in Krugersdorp, with an increase of about 20 per cent in chromium recovery relative to conventional submerged-arc furnace production. Plasma furnaces are also well suited to the treatment of electric-arc-furnace dusts. High-temperature treatment of this hazardous waste material allows the recovery of zinc and recyclable alloys, and the production of an innocuous slag. Plasma technology is also being applied to ilmenite smelting, and a process (developed in partnership between Anglo American and Mintek) based on single hollow-electrode plasma technology will be implemented on the Namakwa Sands project on the Cape west coast.

Computer programs have been developed at Mintek for the simulation of processes using plasma-furnace technology.

## INTRODUCTION

Intensive smelting operations are based either on combustion or electrical energy (or, in some instances, a combination of the two). Energy is supplied electrically when very high temperatures or highly reducing conditions are required for a process. Combustion-based processes are applicable to the treatment of materials that are easily reducible or smeltable, and those having a relatively low melting point. These materials include most base metals. The more refractory (difficult to reduce) materials, and those with high melting points, invariably require electric smelting technology. Most ferro-alloys fall into this category. Iron- and steel-making technology is intermediate between these categories, and both methods of heating are widely employed. Plasma-arc heating is a particularly effective means of supplying electrical energy to a process, and is discussed in detail in this paper.

The term 'plasma' is used to describe the fourth state of matter in the sequence (corresponding to an increase in temperature) solid-liquid-gas-plasma. A plasma may be generated by passing an electric current through a gas. A thermal plasma is essentially a gas phase with an energy content high enough to ionize a portion of the matter present. The degree of ionization depends on the temperature. A plasma comprises molecules, atoms, ions (in their ground or in various excited states), electrons, and photons; overall it is electrically neutral. The free electric charges give rise to high electrical conductivities in the gas, which may even surpass those of metals. A high-temperature plasma arc is generated between at least two electrodes: a cathode from which electrons are emitted, and an anode at which electrons are absorbed. The mean temperature of the ions lies between 5000 and 25 000 K.

A transferred-arc plasma arises from a direct-current (DC) arc being transferred from the cathode (which is commonly graphite or thoriated tungsten) to the anode (normally the surface of a molten bath of process material). In the non-transferred-arc (DC or AC) plasma, the arc is struck between two counter electrodes (commonly made of copper), normally two water-cooled annular rings. A 'tail-flame' of plasma projects beyond the downstream electrode, and impinges on the material being processed.

The practical use of plasma arcs for the bulk melting of metals dates back more than 100 years to the work of Sir W. Siemens<sup>1</sup> in 1878 in Europe. The DC furnace developed by Siemens used a vertical graphite cathode, with the arc transferred to the melt in contact with a water-cooled bottom anode. Siemens also invented an 'independent' (non-transferred) arc furnace, in which the arc was struck between two horizontal electrodes above the melt, thereby heating the melt solely by radiation.

Plasma-arc furnace technology has a number of unique advantages for industrial use. Plasma furnaces allow the direct use of fine feed materials. Furthermore, because the input of power is not limited by the electrical conductivity of the materials being processed, feed rate and power can be controlled independently. Very high temperatures can be attained, and the gas composition can be varied independently, from oxidizing to reducing in nature. High power-fluxes, and the higher reaction rates attained by the use of finer feed particles, lead to the use of smaller reaction vessels. The furnace can also respond to process changes in a relatively short period.

However, it should be pointed out that, at the same throughput rate and power flux, the thermal efficiency of the plasma-arc furnace is lower than that of a submerged-arc furnace. Three factors are responsible for this:

- i) more energy is lost, by radiation from the open arc and molten bath, to the walls and roof of the furnace,
- ii) some vaporized material is lost to the off-gas stream from the arc-attachment zone, and

iii) little of the sensible energy of the gases evolved is utilized in preheating the feed materials.

The open-bath system provides opportunities for excellent process and product control, but is limited by the loss of volatile materials to the off-gases, and by the relatively high losses of power to the roof (50 to 150 kW/m<sup>2</sup>). High throughput rates are therefore necessary to offset the various mechanisms of energy loss.

DC transferred-arc plasma technology is widely preferred for metallurgical processing. The use of an open bath of liquid slag and metal (the anode) permits greater control of the process metallurgy than in a choke-fed furnace. The electrical supply characteristics and geometric arrangement of the transferred-arc furnace are similar to those of conventional submerged-arc furnaces, and the change to DC operation is relatively straightforward. The use of a graphite electrode, which can tolerate high currents, allows processes to be scaled up to industrial operation. Transferred-arc devices (with graphite electrodes) lose far less energy to cooling water than metallic transferred-arc torches. An additional important feature of DC operation is the ability to sustain longer, more stable arcs than AC operation, with independent current and voltage control. As a result, a significant reduction of electrode consumption, electrical disturbances, and noise can be obtained.

In a comparison<sup>2</sup> between DC arc, AC arc, and DC plasma-gun arc, the graphite-cathode DC arc provides the most efficient energy transfer, with the largest portion of the arc power being transferred directly to the melt. This high efficiency is due to the fact that a strong, electromagnetically pumped plasma jet convects most of the power toward the anode. The DC arc, with stable unidirectional convection, is superior to the AC arc in transferring its energy directly to the anode in a metallurgical process. The consumable graphite electrode is able to operate without water cooling at far higher current and power levels than a plasma torch with water-cooled metal electrodes. Thus the combination of DC power and graphite electrode provides greater and more flexible opportunities for commercial metallurgical processes. The disadvantages of DC, compared to AC, involve the necessity for an electrical connection to the liquid metal anode (not necessary in the conventional three-phase AC system), and the extra cost and space required for rectification equipment.

Plasma-furnace technology is now well proven in industry. For example, high-carbon ferrochromium is produced on an industrial scale, from Transvaal chromite fines and fine, low-cost carbonaceous reducing agents, in a DC transferred-arc plasma furnace at Palmiet Ferrochrome in Krugersdorp, South Africa. This 40 MVA (32 MW) furnace,<sup>3</sup> which has been running since 1988, has significantly increased the recovery of chromium compared to that obtained with the use of conventional submerged-arc furnaces.

## RESEARCH AND DEVELOPMENT FACILITIES AT MINTEK

Research facilities up to 1 MW (from a 3.2 MVA power supply) are available at Mintek to study the application of plasma-furnace technology to a wide range of metallurgical processes. Mintek's 3.2 MVA DC transferred-arc plasma furnace is depicted in Fig. 1. This furnace is equipped with a six-component feed system with improved sealing and gas tightness, capable of handling dry materials ranging from 100  $\mu\text{m}$  to 12 mm. Finer feed materials (down to 1  $\mu\text{m}$ ) have been successfully fed through the screw feeder and down the hollow electrode, but cannot at present be fed continuously from the main storage bins. The versatile feed system, using vibratory feeders, can also distribute the feed either around the 125 mm graphite cathode or through a 75 mm hole down its centre (to introduce the feed directly into the high-temperature bath area). A typical feed rate is 1 t of total feed per hour, but up to 2 t/h can be used. The pilot-plant bay at Mintek has well-developed capabilities for gas handling.

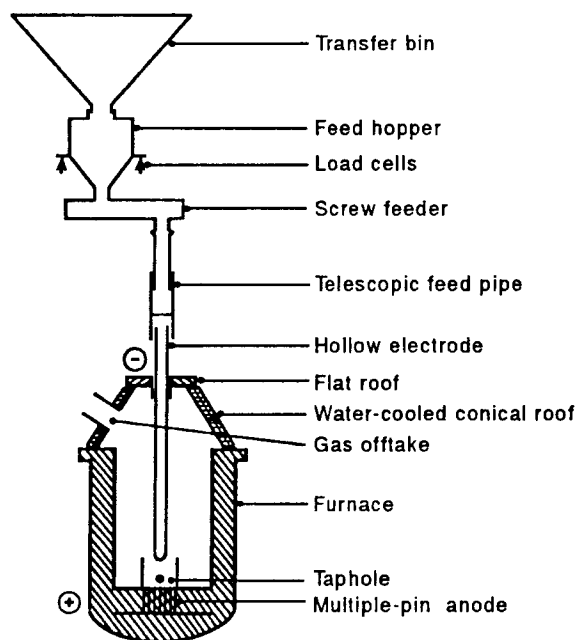


Figure 1: Mintek's 3.2 MVA plasma-arc furnace

Hollow graphite electrodes are usually used as cathodes, but water-cooled electrodes have also been used when required. Graphite electrodes are preferred for most purposes, as they impose no limits on the current (up to, say, 100 kA), are simpler (requiring less skilled maintenance), and introduce no source of water into the furnace (also saving on the costs of a water-cooling circuit).

Recent plasma-furnace work at Mintek has involved high-intensity smelting<sup>4-6</sup>, the high-temperature reactions in the arc-attachment zone<sup>7</sup>, and the application of large-scale plasma systems.<sup>8,9</sup> Apart from applications to iron and steel, ferro-alloys, and light and refractory

metals, Mintek has undertaken work on the production of other chromium-containing products such as  $\text{Cr}_7\text{C}_3$ , the production of pure chromium via the aluminothermic reduction of  $\text{Cr}_2\text{O}_3$ , and the production of zirconium compounds ( $\text{Zr}$ ,  $\text{ZrAl}_3$ , and partially-stabilized  $\text{ZrO}_2$  from  $\text{ZrSiO}_4$ ). Pilot-scale work has been done at Mintek on the recovery of copper, nickel, and cobalt from converter slags. Other applications include the production of ferroniobium, catalyst regeneration, the fuming of lead and zinc from lead blast-furnace slags, and the treatment of low-carbon ferrochromium slags.

## HIGH-INTENSITY SMELTING

Mintek has for some time been actively evaluating the application of transferred-arc open-bath plasma systems to remelting and smelting processes. The comprehensive pilot-plant facilities that have been established at Mintek permit experiments to be conducted at power levels from 30 kW up to about 1 MW, in a range of furnaces with internal diameters of 0.2 to 1.5 m. Most of the work at Mintek has been directed towards materials of relatively low value, e.g. ferro-alloys, iron, steel, and stainless steel, because of the abundance of the associated minerals in South Africa. The attainment of large-scale plasma systems capable of processing these materials at a throughput large enough to be economical is therefore of particular interest to Mintek and the relevant industries.

As an example of high-intensity processing, a pilot-scale DC plasma-arc furnace at Mintek has been shown to be very suitable for the continuous melting of DRI metallized to about 90 per cent. Power levels of close to 400 kW have been achieved in a furnace with an internal diameter of 0.44 m. A power flux of over  $2 \text{ MW/m}^2$  of hearth area has thus been achieved, with an electrical-to-thermal efficiency for melting of DRI of more than 80 per cent, even at this relatively small scale, since the energy loss of about 50 kW remained virtually constant with increasing power level. This confirmed that the energy transfer to the DRI was not rate-limiting as far as melting is concerned, even up to such high values of power flux.

Previously there were several areas of concern regarding the use of DC arcs in open-bath processes. These included stray arcing between the electrode and the water-cooled panels or refractory side-walls of the furnace, excessive radiation from the bath to the roof causing refractory damage, preservation of the anode contact with the bath, loss of fine feed material with the off-gases from smelting processes, poor distribution of thermal energy to the process itself, i.e. excessive energy loss from the bath and in the off-gases, and localised superheating of the arc-attachment zone. Many of these problems have been overcome, and developments have resulted in improved control of the feed rate and power input. Mintek has succeeded in operating its pilot-plant facility at power levels of over 1 MW, and at electrical-to-thermal energy efficiencies of over 80 per cent.

The production rate is determined by the commodity produced. High-value materials are produced in small quantities, and therefore require small furnaces operating at lower power levels (typically 0.5 to 2 MW). The production of materials of lower value, e.g. iron, steel, stainless steels, ferro-alloys, and titania-rich slags, must be on a very much larger scale to be economic. Typical industrial production rates are from about 10 to 60 t/h. The energy requirement (excluding losses) varies from 0.5 MWh/t for the melting of metal scrap to between 3 and 8 MWh/t for the smelting of ferro-alloys. The total power level required therefore varies between about 30 and 60 MW. Power fluxes of about 2 MW/m<sup>2</sup> (for melting) and 1.5 MW/m<sup>2</sup> (for smelting) have been attained in open-bath tests at Mintek. Successful performance at high power fluxes can be achieved, but only where the process chemistry is neither rate-limiting nor associated with the excessive generation of volatile species (e.g. SiO or Mn). This consideration can be used as a basis for the calculation of furnace diameter. Fig. 2 shows the relation between the power flux and the internal diameter of a furnace. Dimensions such as height and bath depth are related to the operating voltage, which is a function of arc length. The refractory design must ensure that the hot-face temperature does not exceed the maximum temperature specification of the material. Refractories with high thermal conductivities are frequently effective in high-intensity processes, in order to keep hot-face temperatures as low as possible. The steep temperature gradients cause high rates of loss of energy (20 to 30 kW/m<sup>2</sup>) from the furnace shell, but this decrease in thermal efficiency can be offset by the high throughput of feed materials, and the decrease in surface area because of the smaller furnace size.

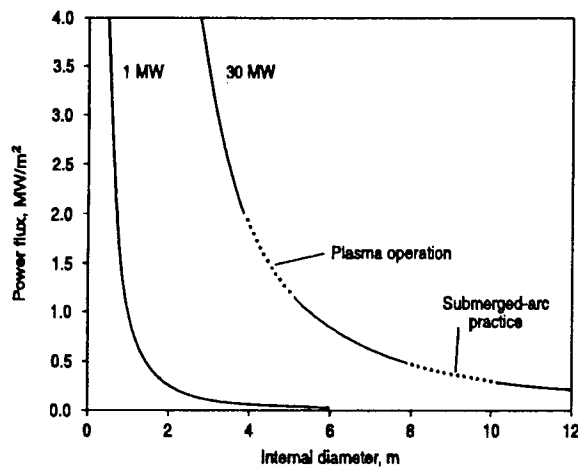
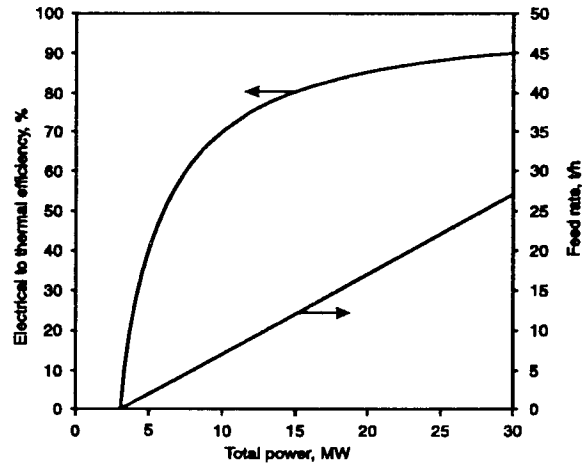


Figure 2: The relationship between power flux and the internal diameter of a furnace

A previous study<sup>4</sup> has indicated that there is considerable scope for improvement of the existing submerged-arc furnace by its conversion to a transferred-arc furnace, in which it might be possible for the overall power flux (power per unit of hearth area) to be increased from 0.5 to 1.5 MW/m<sup>2</sup>. As shown in Fig. 2, this would have the advantage that a substantial decrease in furnace diameter would be achieved.

The energy efficiency of the furnace is determined by the total loss of energy from the furnace and the throughput (production) rate. Fig. 3 illustrates these relationships for a hypothetical 30 MW DC transferred-arc furnace with a rate of loss of energy of 3 MW, operating on a process having an ideal energy requirement of 1 MWh/t.



**Figure 3:** Efficiency relationship for a hypothetical 30 MW DC transferred-arc plasma furnace

Single water-cooled plasma devices cannot attain such power levels, and the only option at present is the use of graphite electrodes. Graphite electrodes remove the restriction on current capacity, and power levels of 30 MW per electrode are readily achieved. A 30 MW DC arc furnace would require an electrode of about 500 mm in diameter to operate at 60 kA, and would have a typical voltage of 300 to 500 V.

## Reaction rates and mechanisms

The smelting processes considered are the open-bath carbothermic reduction of metal oxides in the presence of a silicate slag. The following reaction sequence is envisaged:

- i) dissolution of the metal oxide into the slag phase at the surface and within the bath,
- ii) the reaction of dissolved metal oxide with solid carbon at the slag surface,
- iii) the descent of the metal droplets formed through the bulk slag phase,
- iv) further reaction (i.e. refining) of these metal droplets with the slag while they are descending to the bulk metal phase, and
- v) the final approach to equilibrium at the interface between the bulk slag and the metal.

As the feed flux (i.e. the feed rate per unit hearth area) increases, the most probable rate-limiting step should be (i) or (ii), since they occur at the surface of the liquid slag bath. An accumulation of feed materials would be expected in either case, and undesirable side reactions might occur, leading to unsatisfactory metallurgical performance. These factors may possibly limit the throughput.



## **Limitations of high-power-flux smelting**

The losses of energy will depend upon the temperature distribution in the furnace at the higher power flux. The possible changes in this distribution will depend on the technique by which the power is increased. The exact effects cannot be predicted accurately, and pilot-plant tests are required for the determination of the most suitable refractory configuration, e.g. water-cooled roof panels. The high feed-material throughput rates that result from high power fluxes should allow selective water-cooling to be used where necessary without a significant decrease in the efficiency of the furnace.

The increased production rates of liquid furnace products (slag and metal) require a decreased tap-to-tap time and, at very high power fluxes, may involve continuous tapping. The gas volumes produced may limit the minimum particle sizes of the feed materials owing to the risk of entrainment (unless the feed is injected into the bath), since the superficial gas velocity in the furnace rises with increasing reaction rates at increased power fluxes.

## **Possible improvements**

The use of only the surface of the slag as the reaction zone in the furnace imposes a constraint on open-bath processing. The distribution of the feed particles throughout the slag volume would be expected to greatly increase the capability of the furnace to accept higher feed rates. Such distribution could be achieved in a number of ways, e.g. by stirring of the bath with inert gas, pneumatic injection of the feed materials into the bath via a vertical lance, or bottom or side tuyeres, and electro-magnetic stirring of the bath. This would mix the contents of the bath thoroughly, increase the rates of mass and energy transfer to the feed materials, trap volatile reaction products in the slag, and possibly directly utilise the carbon and hydrogen in the volatile materials in the coal. However, these conditions could give rise to refractory problems, and extensive research and development is still required.

## **FLUIDIZED-BED PRETREATMENT**

Owing to the high cost of the electrical energy supplied to a plasma furnace, the thermal efficiency of the furnace has a direct bearing on its operating costs. The reduction in energy loss that can be achieved for a given furnace is usually limited by the required operating temperature, the type and thickness of the refractories, and the external surface area and geometry of the furnace. However, an improvement can be achieved by an indirect approach in which the throughput rate is increased without a simultaneous increase in the rate of energy loss. It has previously been shown<sup>5</sup> that the rate of loss of energy from the furnace remains

essentially constant even when operated at higher power fluxes (and concomitantly increased feed fluxes).

A portion of the specific electrical energy required in the furnace can be replaced by energy from cheaper sources, such as furnace off-gas or coal, including duff coal, to preheat or prereduc the feed to the furnace. Pretreatment also permits a greater production rate to be attained without upgrading of the furnace transformer. Both of these factors contribute to a reduction in the total operating cost per ton of product. Preheating and prereduction of the fine materials fed to a plasma furnace is best accomplished in a fluidized-bed reactor. This device is complementary to the plasma furnace, in that both are well suited to the processing of fine feeds without prior agglomeration, and both are high-throughput reactors with relatively short response times.

A 200 kW plasma furnace (with an internal diameter of 0.5 m) was operated in conjunction with a fluidized-bed reactor<sup>6</sup>, to allow the combined operation of the two units to be studied, in a continuous campaign that lasted 110 hours. The single-stage fixed fluidized-bed reactor had an internal diameter of 280 mm and a freeboard internal diameter of 450 mm. The bed depth was controlled at 350 mm by virtue of the location of the overflow pipe, leaving a 1.3 m freeboard. A pair of sealed tubular vibratory feeders delivered material onto the surface of the bed in the reactor; separate feeders delivered materials that were not to be processed in the fluidized bed direct to the furnace. The small amount of material elutriated from the bed was collected in a cyclone separator and introduced to the furnace together with the particles that overflowed from the bed. Under steady conditions, the flowrate of material to the furnace was constant, and equal to the feed rate to the bed.

The effect of feed flux on furnace efficiency was measured at constant electrical power. For this to be accomplished, it was necessary to vary the specific energy requirement of the process being conducted in the furnace, because the feed and energy inputs must be balanced at all times if the furnace is to be operated at a constant temperature. Different feed flux levels can be attained by preheating or prereduction of the feed materials. In the investigation, both cold and preheated hematite were smelted, and both cold and preheated direct reduced iron (DRI) were melted in the plasma furnace. An operating power set-point of 120 kW was selected, and the feed rate was set to correspond to this in each case. The fluidized-bed reactor was used merely as a means for preheating the feed materials, and no attempt was made to optimize its operation. Liquefied petroleum gas (LPG) was combusted in the bed to provide the required energy. When DRI was preheated, an excess of LPG was admitted to the bed to minimize the re-oxidation of the DRI.

The power flux in the furnace was held constant with a deviation of less than  $\pm 2.5$  per cent, while the feed flux was increased by a factor of greater than 3.

The thermal efficiency of the furnace is defined as the ratio of the thermodynamic energy requirement to the actual electrical energy supplied. The thermodynamic energy requirement was determined from the difference between the total enthalpy (relative to the elements in their standard states at 25°C and 1 atm.) of the streams leaving the furnace (slag, metal, and gas) and the total enthalpy of all the streams entering the furnace. This approach renders the calculation independent of assumptions regarding the actual chemical reactions and the temperatures at which they occur.

A combination of the results of the work by Curr *et al.*<sup>5</sup> and Meihack *et al.*<sup>6</sup> implies that the rate of energy loss is independent of both feed flux and power flux. The temperature of the furnace as a whole, rather than local temperatures (e.g. the arc temperature or the in-flight temperature of the feed materials), therefore appears to determine the magnitude of the losses of energy.

Although pretreatment of the feed does not improve the thermal efficiency of the furnace, it is clear that the energy loss from the furnace per unit of metal produced decreases with increasing degree of pretreatment. Provided that the energy required for pretreatment can be supplied more cheaply than the electrical energy consumed in the furnace (which is certainly the case with preheating), there is a clear economic advantage to be gained from pretreatment.

To clarify this point, a definition of the efficiency of utilization of electrical energy is convenient. In any definition of efficiency, the actual energy consumed is compared to some chosen ideal case or datum. To show the effect of preheating, a suitable choice of datum is the electrical energy that would have been required in the absence of preheating. On this basis, the efficiency of utilization of electrical energy in these experiments for the remelting of cold DRI is 44 per cent (which is the same as the thermal efficiency of the furnace), while that for the remelting of the preheated DRI is 61 per cent. Stated differently: without preheating of the feed, some 2.25 times the thermodynamic requirement of energy was supplied electrically, whereas preheating of the feed reduced this to only 1.63 times. At a constant power level in the furnace, this translates to a potential increase in throughput of 38 per cent.

Preheating of the feed to a plasma-arc furnace has a marked effect on the efficiency of utilization of electrical energy. For the remelting of DRI in a plasma-arc furnace operated at 120 kW, the delivery of the DRI to the furnace at a temperature of 700°C increased this efficiency from 44 to 61 per cent.

Preheating of the feed to a plasma furnace also permits increased throughputs without uprating of the furnace transformer, and results in a lower cost per ton of metal produced.

## RECENT APPLICATIONS

### Steel-plant dusts

A recent growth area for the application of plasma technology has been the development of processes for the recovery and recycling of metals from industrial residues and wastes. Plasma processing is particularly well suited to the treatment of wastes, due to its capability of high-temperature chemical processing and handling of fines, and because electricity is a relatively clean source of energy with minimal environmental impact at the process site. The economic potential is particularly attractive for the disposal of hazardous materials as determined by environmental economics, and not necessarily by the value of the useful products.

During steelmaking in an electric-arc furnace (EAF), 10 to 15 kg of dust, consisting of various metal oxides, is generated per ton of steel product. In many countries, the disposal of EAF dust in landfill sites is regarded as an environmental hazard, since toxic metals may be leached into drinking water supplies. In the USA, EAF dust is classified as a hazardous waste, and regulations require it to be treated chemically or thermally to remove or stabilize the leachable toxic metals.

Steel-plant dusts can be grouped into four broad categories. They may be grouped according to their content of alloying elements (particularly Ni, Cr, Mo, and Mn) as carbon-steel or alloy-steel dusts, and as either low- (< 15 per cent) or high-zinc dusts. Low-zinc carbon-steel dusts represent the least valuable category, and their treatment is generally dictated by environmental rather than economic considerations. Cheaper chemical or recycling routes may be sufficient for their treatment. However, alloy-steel dusts (even those low in zinc) require fairly strong reducing conditions to lower the chromium in the slag phase to acceptable levels, thus rendering them suitable for disposal. The other three dust categories are therefore potential candidates for treatment via electrically-based thermal routes.

Electrically-based thermal processes allow sealed reactor design, high-energy-density operation at low oxygen potentials, reduced gas volumes, and suitably high off-gas temperatures. These features have the following major process advantages for the treatment of steel-plant dusts:

- the potential to process the ultra-fine dusts directly, without prior agglomeration, especially when central feeding through a hollow graphite electrode is used,
- the potential to condense valuable metals, specifically zinc, directly from the furnace off-gases, and

- the potential to strip the slag phase of oxides of chromium and other alloying elements, resulting in the generation of an innocuous disposable slag, and in the case of alloy-steel dusts, in the concomitant generation of a valuable alloyed metal.

The Enviroplas process<sup>10</sup>, currently under development at Mintek, is a DC plasma-arc process that can treat EAF dust, alloy-steel dust, or a mixture of both. The dust is fed to the furnace directly down a hollow graphite electrode. The process is based on the reduction of selected metal oxides at high temperatures by means of a carbonaceous reducing agent, with the production of an innocuous slag. In the case of EAF dust, lead and zinc oxides are reduced to their respective metals, volatilized, and then either re-oxidized to a mixed oxide or condensed as metals. At present, fume is combusted to ZnO and collected in a bag filter. In the case of alloy-steel dust, a ferro-alloy rich in chromium and nickel is tapped. From 1989 to date, about 100 t of lead blast-furnace slags and steel-plant dusts have been processed at Mintek at various pilot scales up to 1 MW, and the process is at present being further developed to recover metallic zinc directly in a lead splash condenser.

A proposed 3 MW unit could process around 18 kt of EAF dust per annum, or 10 kt of alloy-steel dust. It appears that the proposed units could be operated profitably, even before the avoided costs of disposal are taken into account.

The disposal problem should be solved at its primary source. This is compatible with operation on a contracted-out basis. On-site treatment minimizes potential environmental legal liabilities, and minimizes or eliminates road transport (and the associated cost and taxes). The waste-management installation could be wholly operated by a contractor. In this way, the system can be run with no capital costs to the client, with a charge being made purely for services. This requires no responsibility on the part of the steelmaker for the supervision of operating personnel, or for the maintenance of the equipment.

## **Ilmenite smelting**

Richards Bay Minerals (RBM), currently the only South African producer of titania slag, employs four rectangular six-in-line graphite-electrode furnaces for the smelting of ilmenite. Each furnace is 19 m long, 8 m wide, and has a power supply rated at 105 MVA (each pair of electrodes being supplied by a 35 MVA transformer).<sup>11,12</sup> Each of these three-phase open-arc furnaces is rated at 69 MW. The process technology, originally developed by Quebec Iron & Titanium (QIT Fer et Titane) of Sorel, Canada, was supplied to RBM in the mid-1970s, and was adapted to smelt fine ilmenite obtained from a beach-sand deposit on the north-eastern coast of South Africa. The first furnace started up in early 1978, and the fourth furnace started up in mid-1991. An open-bath approach is employed, for which careful control is

required to avoid erosion of the refractories of the side- and end-walls by the very reactive titania slag. The installed electrical capacity possibly makes these furnaces the largest scale AC transferred plasma-arc operation to date. RBM has an annual production capacity of some 2 Mt of ilmenite ( $\text{FeO}\cdot\text{TiO}_2$ ) and 125 kt of rutile ( $\text{TiO}_2$ ). The ilmenite is smelted to produce about 1 Mt of slag and 550 kt of pig iron per annum.<sup>13</sup> RBM's ilmenite is of too low a grade to be used directly for the production of pigment or synthetic rutile. The company, therefore, followed the slag-beneficiation route, and currently produces about half of world titania slag output.

Small-scale batch tests have been carried out in a 50 kW DC transferred plasma-arc furnace at Mintek, and in a 40 kW water-cooled plasma furnace at the Mineral Resources Center of the University of Minnesota<sup>14</sup>, to investigate the reduction of ilmenite to yield a high-grade titania slag and a pig iron by-product. The work was aimed at producing a slag suitable for use as a feedstock for the fluidized-bed production of titanium tetrachloride. The tests were conducted on three different ilmenite concentrates with widely differing chemical compositions and geological histories. The influence of parameters such as the particle size of the reducing agent, the amount of carbon addition, and the reaction time on the grade of the slag and the recoveries of titanium and iron were studied. The thermal balance of the furnace was carefully controlled to maintain a protective 'freeze lining' to ensure that the graphite crucible and titania slag did not react chemically. The electrical and physical characteristics of the DC transferred plasma-arc furnace were found to be well suited to the smelting of ilmenite. Stable furnace operation was observed during the processing of all three ilmenite concentrates, and slags containing more than 80 per cent titanium dioxide (by mass) were readily obtained.

Several companies are investigating the possibility of developing new titanium projects in Southern Africa, including deposits in Natal, Transkei, and Mozambique. Of these, only Anglo American's Namakwa Sands project has been formally announced. This R1000 million (£200 million) project on the Cape west coast was approved in November 1992. The project will comprise a mining operation near Brand-se-Baai, where heavy mineral concentrates will be produced and transported by road to the Koekenaap plant where ilmenite, zircon, and rutile will be recovered. Zircon and rutile will be exported as high-purity concentrates, whilst the ilmenite will be smelted at a plant between Vredendal and Saldanha. Production is scheduled to start in 1994, at an initial mining rate of 4 Mt of sand per annum. The full production rate is expected to reach 16 Mt/a. Reserves are in excess of 500 Mt.

In order to proceed with the project, Anglo American needed to develop a new process to smelt ilmenite, as the QIT/RBM process is held under licence. (The high electrical conductivity of titania slags and the requirement for accurate control of the slag composition

effectively rule out the use of conventional submerged-arc technology for the smelting of ilmenite.) The corporation has successfully developed a process, in partnership with Mintek, based on single hollow-electrode plasma furnace technology.<sup>13,15,16</sup> Initial production is expected to be at a level of 106 kt of slag<sup>13</sup> from one furnace, which will come onstream around 1995/1996. The scheduled addition of a second furnace should double production. When the mine is at full production, the operation is expected to treat 1200 kt of primary concentrate per annum, to produce 195 kt of ilmenite slag, 120 kt of pig iron, 140 kt of zircon, and 38 kt of rutile.<sup>16</sup>

## **SIMULATION AND CONTROL**

### **Pyrosim**

Pyrosim<sup>17</sup> is a general-purpose computer program, developed at Mintek, for the steady-state simulation of pyrometallurgical processes. One of the primary strengths of the program is its built-in capability to calculate multicomponent multiphase equilibria, along with the automatic performance of energy-balance calculations. This predictive ability allows the program to simulate novel processes with a high degree of accuracy.

The program was originally developed for the purpose of simulating processes for the production of raw stainless steel. However, it has also been applied successfully to the processing of ferro-alloys, metal carbides, base metals, and refractory metals, as well as preheating, prereduction, and combustion processes. Models (empirical / phenomenological as well as predictive) have been developed for a number of process units and process steps, including a heater / drier, fluidized bed, and rotary kiln, as well as for electric-arc furnaces. Some of these models also provide a significant quantity of derived information, such as the liquidus temperature, viscosity, and basicity of slags, as well as gas ratios and degrees of reduction.

Predictive modelling of plasma-arc furnaces has been particularly successful, as these furnaces often come close to allowing multi-reaction multi-phase equilibrium to be attained. Pyrosim has recently been used successfully to model the plasma-arc treatment of electric-arc furnace dust, a process that is inherently complex because of the number of chemical elements involved.

### **PlasmaSim**

Work is currently underway at Mintek towards the development of a computer program to model the dynamic behaviour of the bath of a plasma-arc smelting furnace. The techniques of computational fluid dynamics (two-dimensional, axisymmetric) are to be used to study the

variation in temperature, fluid flow, voltage, current, phase changes, and chemical composition (in a multiphase reacting system) throughout the bath of the furnace. The variation of these quantities with time can then be studied to predict and add to the understanding of such aspects of the process as the position of the freeze-line in water-cooled furnaces, and the effects (on temperature and chemical composition of products) of introducing feed materials at different areas of the bath. This will allow side-feeding to be contrasted with centre-feeding.

## **Control**

The control of an open-bath process is extremely critical, because of the ease with which unwanted reactions can become significant if a suitable temperature and feed distribution are not maintained. The reaction rate is rapid because small particles are used. The vapour loss from the hot zone of the furnace can be high because of the rapid and direct evolution of gases from the surface reaction layer, with little possibility that the vapour will condense on cooler, incoming solid material.

No reliable, direct, and continuous means for the measurement of the average temperature of the bulk slag or metal has been developed for the open-bath furnace. Hence, considerable emphasis is placed upon the balance between the feed rate and the power input as a means of process control. This approach allows a reasonably steady-state condition to be established so that the desired product can be produced, but variations in the ratio of the feed rate to the power level will cause deviations from steady-state conditions. The ratio of feed rate of raw materials to power input is not constant, and it has to be updated regularly as furnace conditions change. At higher power fluxes, imbalances are more critical, so more stringent control is required.

As a result of the short response time of the system, there is a need for a higher level of control than is currently required in the operation of a submerged-arc furnace. The short time-constants associated with the process emphasize the necessity for the feed of raw materials to be set at the correct rate, and for a wide range of other variables to be maintained and controlled. Stable metallurgical performance is obtained when there is an adequate level of control over the operation.

Quite clearly, there is a possibility that localised imbalances will occur on the surface of the bath upon the introduction of cold unreacted feed materials. If, for example, excessive feed should arrive in an area of the bath, causing local cooling, this feed and any new feed arriving in the same area would not attain the desired reaction temperature. Since the input energy would not be used by this feed, localised overheating would occur in a different region of the furnace. To avoid segregation of raw materials in the feed hopper (which could cause



periodic imbalances in the recipe with subsequent imbalances in the energy requirements), each raw material should be fed through a separate hopper-feeder arrangement.

To control the feed rate effectively, a multiple-hopper system with a ramp feed-rate controller was designed and constructed at Mintek. This enables the different feed materials to be proportioned very accurately at all times. In addition, it is important that feeding continues whenever the power is on. If an arc is maintained while no raw material is being fed, localised bath temperatures increase rapidly, damaging the refractories and causing unwanted side-reactions.

## CONCLUSIONS

Plasma furnaces have been successfully applied to the production of a variety of materials, especially ferro-alloys. For example, ferrochromium is produced on an industrial scale in a 40 MVA plasma furnace at Palmiet Ferrochrome in Krugersdorp, with an increase in chromium recovery relative to conventional submerged-arc furnace production. Plasma furnaces have the advantage of allowing the direct use of fine feed materials. Because the input of power is not limited by the electrical conductivity of the materials being processed, independent control of feed rate and power can be achieved. High power-fluxes lead to the use of smaller reaction vessels.

Pilot-scale DC open-bath transferred-arc plasma furnaces of up to 1 MW in power, using single hollow graphite electrodes, are in place at Mintek. These furnaces have been used to produce power fluxes of over 2 MW/m<sup>2</sup> of hearth area. When coupled with a fluidized-bed preheating unit, the efficiency of utilization of electrical energy increases markedly, allowing an increase in throughput of almost 40 per cent at constant electrical power input.

Plasma furnaces are also well-suited to the treatment of electric-arc-furnace dusts. High-temperature treatment of this hazardous waste material allows the recovery of zinc and some useful alloys, and the production of an innocuous slag.

Plasma technology is also being applied to ilmenite smelting, where a process (developed in partnership between Anglo American and Mintek) based on single hollow-electrode plasma technology has been announced for the Namakwa Sands project on the Cape west coast.

Computer programs have been developed at Mintek for the simulation of processes using plasma-furnace technology.

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