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THE APPLICATION OF TRANSFERRED-ARC PLASMA  
TO THE MELTING OF METAL FINES

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Synopsis

Thermal plasma has been applied to the melting of high-value metal fines for some time; only recently was attention given to the use of this technology for the melting of materials of lower value. Typically, these materials arise on ferro-alloy plants as undersize when brittle alloys are crushed and then screened to the customer's size requirement. These fines are not usually suitable for remelting in conventional furnaces because of their physical properties.

Promising results were obtained by the Council for Mineral Technology (Mintek) in experimental campaigns on the remelting of ferrochromium, ferromanganese, and silicon fines in transferred-arc plasma furnaces. The results of some of the tests are discussed.

Directly reduced iron can be regarded as a form of metal fines and, as such, should be amenable to processing in a transferred-arc plasma furnace. A strong case is made for the use of plasma technology for that purpose, although the scale of operation will be limited at present owing to the current state-of-development of the art.

Although transferred-arc plasma systems offer many advantages, there are problems associated with the technique, and possible solutions to some of these problems are presented.

## Introduction

For several years, the melting of metal fines in transferred-arc plasma furnaces has been used industrially in the processing of high-value metals such as titanium scrap and sponge iron, for example, Daido Steel in Japan<sup>(1)</sup>. In contrast, it was only recently that the application of transferred-arc plasma technology to the melting of lower-value metals, such as ferro-alloys and sponge iron, received the attention it deserves. Freital Steel in the German Democratic Republic, however, has a long history in the use of transferred-arc plasma to melt steel scrap, particularly high-alloy material<sup>(2)</sup>. An even earlier reference to the use of plasma for the melting of scrap can be traced to the Linde Company, a division of Union Carbide<sup>(3)</sup>.

### THE ORIGIN AND CHARACTERISTICS OF METAL FINES

South Africa has extensive reserves of minerals such as chromium and manganese ores, and has become a major producer of ferro-alloys in recent years. Considerable quantities of metal fines smaller than 6 mm are generated when the rather brittle cast slabs of ferrochromium, ferromanganese, ferrosilicon, and silicon are crushed to meet the size requirements of customers<sup>(4,5)</sup>. When the market is favourable, these metal fines are sold at prices well below that of the lumpy material (normally 25 to 100 mm). In depressed market conditions, these fines cannot normally be sold at all, and represent a serious loss of revenue. Melting is therefore necessary to consolidate these fines into lumpy material, to effect the removal of entrained slag, and to convert them into a salable product.

The application of thermal plasma to the remelting of these fines has received considerable attention at the Council for Mineral Technology (Mintek), which has undertaken several experimental campaigns to investigate its feasibility.

### ALTERNATIVES TO PLASMA-ARC REMELTING

#### Conventional Techniques

Submerged-arc, open-arc, and induction furnace remelting have been considered as alternatives to the plasma-arc furnace, but the following physical and chemical characteristics of the metal fines adversely affect the implementation of these more conventional techniques.

### *Electrical Conductivity*

The recycling of even moderate amounts of metal fines to the conventional submerged-arc furnace in which the original material was produced is detrimental to the process, since the relatively high electrical conductivity of the fines lowers the electrical resistance of the burden. This, in turn, lowers the input of power to the furnace, which affects productivity adversely.

### *Bulk Density*

In the melting of steel scrap in a three-phase three-electrode open-arc furnace, the arc is shrouded by the charge during much of the melt-down operation. Radiation from an exposed bath and arc flare from the arc column reach the roof and walls of the furnace only towards the later stages of the process. Material of high bulk density cannot be charged in batches in a similar manner, and continuous feeding must be used. An open bath and an exposed a.c. arc are therefore present throughout the melting operation. Under these conditions, the thermal load on the refractories or water-cooled panels is high.

### *Reactivity with Oxygen*

Control of the atmosphere is necessary to prevent the re-oxidation of elements such as iron, chromium, manganese, and silicon. These conditions are not readily achieved in a conventional open-arc furnace, and a well-sealed furnace with purging by an inert or protective gas is needed to ensure high recoveries.

### *Electromagnetic Susceptibility*

The poor susceptibility of ferro-alloy fines has a detrimental effect on the operation of induction furnaces, since a large molten heel of metal has to be maintained in the furnace to effect heat transfer and to ensure good electrical efficiency<sup>(6)</sup>. Ferromanganese fines are, in fact, remelted in a small-scale (1,75 MW) induction furnace by Temco in Tasmania, but that company is looking into alternative methods<sup>(7)</sup>. The presence of entrained slag in the metal fines produced on most ferro-alloy plants also creates a problem in induction melting owing to the formation of a solid crust of slag on top of the bath. Even liquid slag does not have susceptibility.

### Melting Under a Slag Cover

Ferromanganese metal fines have been remelted in a small-scale (2 MVA) submerged-arc furnace, but the operation required the recycling of a considerable amount of slag to give the furnace the required resistivity<sup>(4)</sup>. Thus, the energy for remelting was almost double the thermodynamic requirement. During some preliminary testwork at Mintek, silicon fines were melted under an acid slag cover in a 60 kW two-electrode single-phase arc furnace. The method used is described in a patent held by Wacker Chemie GmbH<sup>(8)</sup> of West Germany. Not only was the remelting readily accomplished with an excellent recovery of the metal, but the aluminium and calcium levels decreased appreciably.

The process had two disadvantages. To minimize the use of electrical energy, the slag had to be kept in the furnace when the metal was tapped; also, splashes of this slag adhered very tenaciously to the electrodes and eventually prevented their movement through the furnace roof.

#### THE ADVANTAGES OF THE TRANSFERRED-ARC PLASMA SYSTEM

The transferred-arc plasma system has the following advantages<sup>(9)</sup>.

- (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 than can be obtained in a choke-fed furnace. Material of high bulk density such as metal fines can be fed direct into the hot metal bath, where good heat transfer takes place between the liquids and the solids, leading to rapid melting.
- (2) 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.
- (3) The operation of a transferred-arc plasma furnace is not normally affected by the electrical properties of the feed material and the products.
- (4) The transfer of energy is more effective from a d.c. transferred-arc device than from the conventional a.c. system, and mechanical precession<sup>(10)</sup> of the plasma gun or magnetic deflection of the arc can be used to spread the thermal load in the region of the anodic attachment

of the arc column<sup>(1)</sup>.

- (5) Water-cooled non-consumable electrodes have a considerable life expectancy (up to 1000 hours, depending on the current being drawn), and usually have a thermal efficiency of over 90 per cent owing to the relatively small size of the water-cooled protection jacket.
- (6) Although advances have been made, restriction in the current to below 10 to 12 kA limits the power output from a single water-cooled device to between about 5 and 6 MW at 500 V. Hollow graphite electrodes, through which a suitable gas is injected, can be used as an 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 to restrike the arc, which cannot be done readily with water-cooled devices. High-voltage operation is also possible, since stray arcing will not destroy the electrode although other problems may occur.

#### PLASMA FACILITIES USED DURING THE TEST PROGRAMME

Three plasma facilities were used during the testwork. Two were at Mintek, and the third was at Tetronics Research and Development Company Limited, Faringdon, England (TRD).

#### The Three-phase a.c. Diffuse Plasma-arc System

This system was commissioned at Mintek in 1981<sup>(11)</sup>. A 104 kVA three-phase transformer provided with an on-load tap-changer supplies power to three single-phase line reactors. The furnace, of 380 mm inner diameter and 640 mm depth, has three hollow consumable graphite electrodes of 50 mm diameter inclined at 45 degrees from the vertical. These electrodes pass through the side wall of the furnace and are spaced symmetrically at 120 degrees to one another. The feed port is situated centrally in the roof, through which the gas off-take also passes.

The movements of the electrodes are regulated by the use of a current setpoint, and electric-motor drives are used to move the electrodes in or out to control the current to the setpoint. Argon, nitrogen, or any other suitable gas can be passed down the electrodes to form a plasma arc at their tips.

### The Transferred-arc Plasma System

This system, as described in detail by Curr *et al.*<sup>(9)</sup>, uses the transformers and reactors originally purchased for the diffuse plasma system, but with the provision of a diode bridge to give full wave rectification. A single hollow consumable graphite electrode of 50 mm diameter passes through the roof of the furnace. The return electrical connection is made via three steel anodes that pass up through the hearth refractories. The inner diameter of the furnace is 350 mm and its depth is 550 mm. Typically, it operates at 90 V and 800 A, i.e. about 70 kW.

### The 1,4 MVA Transferred-arc Plasma System at TRD

This furnace<sup>(10,12)</sup> uses a precessing, non-consumable water-cooled plasma gun that has a thoriated tungsten cathode. The stabilizing plasma gas, usually argon, protects the cathode from rapid erosion. The return electrical connection is made via a single anode passing up through the hearth of the furnace and making contact with the melt.

The plasma gun passes through the roof of the furnace and is precessed at about 50 to 60 r/min by a hydraulic motor so that the plasma arc describes a cone. Thus, the energy is distributed over a large circular area on the surface of the melt.

The crucible of the furnace has an inner diameter of 1290 mm and a depth of 1200 mm. The design is characterized by hearth refractories that are about 1 m thick.

### THE REMELTING OF SILICON FINES

The first investigations were done in the 100 kVA diffuse plasma-arc furnace. The object of the trials was to confirm results that had been obtained in some very limited remelting tests done during the commissioning of the furnace. These results indicated that some refining of the metal could be obtained without the use of a slag cover.

Four different grades of material were obtained, and their aluminium and calcium levels are given in Table 1. Material D, which was a sample of material recovered from launders and ladles etc., contained a high proportion of slag.

Table 1

*Impurity levels of the feed materials used  
in the diffuse plasma-arc trial at Mintek  
(All values are expressed as percentages by mass)*

Material	Al	Ca
A	0,47	0,24
B	0,63	0,30
C	0,59	0,40
D	2,68	2,93

The furnace was operated on a batch basis, each charge being 20 kg. The metal fines were fed continuously, by the use of a screw feeder, at a controlled rate commensurate with the power level at which the furnace was operated.

The remelting of the three materials of higher quality was readily accomplished. However, the slag contained in the lower-grade material caused a problem in that splashes of material adhered very strongly to the electrodes and eventually caused them to become stuck in the electrode ports in the side wall of the furnace.

The average levels of the impurities in the silicon tapped from the furnace are shown in Table 2, from which it can be seen that there is a significant decrease in the level of aluminium, and particularly of calcium.

Table 2

*Impurity levels in the silicon produced  
in the diffuse plasma-arc furnace at Mintek  
(All values are expressed as percentages by mass)*

Material	Al	Ca
A	0,25	0,06
B	0,22	0,04
C	0,20	0,03
D	0,44	0,10

The recovery of the silicon during the remelting of the three higher-

grade materials was 89 per cent and, when the loss of energy from the furnace was taken into account, the energy required for smelting was close to that quoted in thermodynamic tables, namely 891 kW.h/t.

Although the tests were successful from a metallurgical point of view and had demonstrated that silicon could be remelted and refined without the use of a slag cover, it was felt that the scale-up of the diffuse plasma-arc furnace, with its inclined electrodes, to the size required to handle the amount of silicon fines generated was not attractive from the engineering point of view. The single-electrode, transferred-arc furnace appeared to offer a far more attractive option. Melting tests were therefore conducted at TRD. The objects of the test were to permit the operators to

- (i) observe the effect on the voltage of feeding silicon fines into a transferred plasma arc, and
- (ii) ascertain the unit energy consumption in order to assess the efficiency of the energy transfer from the plasma to the melt.

No attempt was made in these tests to measure the quality of the silicon, since this melting campaign was conducted immediately after tests that had involved the production of a ferro-alloy, and the silicon produced was contaminated.

For the transferred-arc plasma furnace, the usual operating philosophy was followed. The energy required to melt and superheat each unit mass of silicon was calculated from thermodynamic data, and the loss of energy from the furnace was determined by experiment. Owing to mechanical problems with the feed system, considerable difficulty was experienced in the feeding of silicon fines to the furnace at the required rate. The fines had to be carefully sized to smaller than 12,5 mm for this to be done. It was intended that the furnace should be operated with an open taphole so that a continuous flow of silicon would result. This required the flowrate of the silicon to be sufficiently high to keep the taphole hot and to prevent the silicon from freezing in it. Because of the erratic behaviour of the feed system, this objective was achieved on only three occasions. However, during these periods of stable operation, in which some 500 kg of fines was remelted, it was found that, when the loss of <sup>power</sup>energy from the furnace (108 kW) was taken into account, the <sup>specific</sup>energy required for remelting was only marginally higher than that calculated ~~energy~~ requirement of 891 kW.h/t. This demonstrated



efficient transfer of energy from the plasma arc to the furnace bath.

The following points were noted during the campaign

- (a) The atmosphere in the furnace was fairly conductive, and the shortest plasma gun available (1016 mm) had to be used so that a suitably high voltage (260 V) could be obtained. The arc length was about 600 to 700 mm. At a later stage, when the starting door for the probe, through which the arc is transferred from the gun to the bath, was left open and some air was allowed to enter the furnace, there was an improvement in the resistance of the furnace atmosphere, and 350 V was obtained. The recovery of silicon is no doubt impaired under this condition, as is borne out below.
- (b) Although the entry of some air into the furnace improved the voltage, it compounded the problem that already existed, i.e. that the feed ports tended to become blocked by a mixture of silica and silicon. When the starting door was open, a further build-up occurred, which hindered the precession of the gun.
- (c) The generation of fume in the furnace caused operating difficulties, but it was found that the actual loss of fume from the furnace was low in mass. On two occasions when this loss of dust was determined and 2500 kg of silicon fines were processed, it amounted to only 2,25 per cent.

#### TESTS ON THE QUALITY OF THE SILICON

Because the quality of the silicon produced at TRD could not be assessed, Mintek conducted a campaign in a 100 kVA transferred-arc plasma furnace using a hollow, consumable, graphite electrode to determine the quality of the silicon.

Two different qualities of material were used in this test campaign. The calcium and aluminium levels are given in Table 3.

Table 3

*Impurity levels of the two materials used  
in the transferred-arc plasma trial at Mintek  
(All values are expressed as percentages by mass)*

Material	Al	Ca
E	0,45	0,27
F	0,39	0,19

On this scale of operation, the generation of fume from the melt and the deposition of material in the feed ports caused greater problems than had been experienced at TRD. Because of these problems, continuous feeding at the rate dictated by the operating power of the furnace (as is usual in plasma-arc practice) was not possible. The fines had to be fed in small batches of about 1 kg, each batch being melted down before the next was added.

The electrical stability of the operation was not as good as had been obtained on the 1,4 MVA furnace, but the problem was within reasonable bounds and the furnace operators were able to maintain the melting operation.

The analysis of the final products is given in Table 4, from which it can be seen that a significant reduction in the concentrations of aluminium and calcium was again achieved. Even though vaporization of the silicon and the oxidation of this vapour caused considerable operational problems, the overall recovery of silicon was calculated as 96 per cent. A total of 590 kg of metal fines was processed.

Table 4

*Impurity levels of the silicon produced  
in the transferred-arc plasma trial at Mintek  
(All values are expressed as percentages by mass)*

Material	Al	Ca
E	0,29	0,01
F	0,23	0,01

This series of melting trials demonstrated that, at least on a small scale, silicon fines can be remelted in a plasma-arc furnace, and that a good yield of upgraded silicon results. In the design of a large-scale furnace, however, adequate provision must be made for clearing of the feed

ports when they become blocked. This work culminated in the filing of a patent<sup>(13)</sup>.

#### THE REFINING OF FERROCHROMIUM

Before the advent of the argon-oxygen decarburization (A.O.D.) process for stainless steel<sup>(14)</sup>, the only economic route available involved the use of low-carbon ferrochromium produced by the Perrin process as the source of chromium. The A.O.D. process has been used with limited success in the decarburization of high-carbon ferrochromium from carbon levels between 7 and 7,5 per cent to carbon levels of between 5 and 4,5 per cent<sup>(15)</sup>. Decarburization is desirable because it improves the chromium-to-carbon ratio of high-carbon ferrochromium, and thus shortens the blowing times in the subsequent making of stainless steel by the A.O.D. process.

It has been known for some time that partial refining of high-carbon ferrochromium by chromite ore can occur in the solid state and under atmospheric pressure<sup>(16)</sup>. The carbon and silicon in the high-carbon ferrochromium act as reducing agents for the chromite. More extensive refining can be achieved under sub-atmospheric pressure, as in the Simplex Process<sup>(17)</sup>.

Laboratory tests were conducted in small crucibles in which partial refining was attempted in the liquid state. The results were promising, and Mintek decided to conduct trials using the transferred-arc plasma furnace at TRD, in which not only would the ferrochromium fines be remelted but attempts would be made to refine them. In these refining tests, 100 parts of ferrochromium fines were mixed with 28,6 parts of Winterveld ore and 4,3 parts of quartz. The composition of the fines and the chromite are given in Tables 5 and 6 respectively. These proportions were chosen on the basis of the laboratory tests.

Table 5

*Composition of the ferrochromium fines  
(slag-to-metal ratio = 0,129:1)  
(All values are expressed as percentages by mass)*

Metal component (88,6% of total)		Slag component (11,4% of total)	
Cr	52,8	Cr <sub>2</sub> O <sub>3</sub>	27,0
Fe	36,2	FeO	13,0
Si	3,0	CaO	2,2
C	6,6	SiO <sub>2</sub>	47,7
		MgO	1,0
		Al <sub>2</sub> O <sub>3</sub>	7,4

TABLE 6

*Composition of the Winterveld chromite  
(All values are expressed as percentages by mass)*

$\text{Cr}_2\text{O}_3$	FeO	$\text{SiO}_2$	CaO	MgO	$\text{Al}_2\text{O}_3$
44,6	23,3	2,23	0,20	11,2	13,7

The furnace was operated in the normal fashion, i.e. the feed rate and the operating power of the furnace were matched so that the metal and the slag formed were maintained at a constant selected process temperature. The slag and the metal were tapped after all the feed had been added.

The analysis of the metal showed that the silicon content had decreased from 3 to 0,84 per cent. The carbon content decreased from 6,6 to 4,1 per cent.

Further tests were done at Mintek in the 100 kVA furnace with a consumable electrode instead of the water-cooled device used at TRD so that the effect of a graphite electrode on the refining process could be investigated. The charge to the furnace again consisted of 100 parts of ferrochromium fines and 28,6 parts of chromite, but limestone (11,5 parts) was used as a flux. The ferrochromium produced had a silicon content of 0,11 per cent and a carbon content of 3,9 per cent. This refining was slightly better than that obtained at TRD. However, other factors such as temperature could have influenced the degree of refining. It can be concluded from the results that similar degrees of refining can be obtained with a non-consumable plasma gun as with a graphite electrode.

This series of tests demonstrated clearly that the transferred-arc plasma furnace is not only suitable for remelting ferrochromium fines but also provides a probable alternative to the modified A.O.D. process for refining ferrochromium down to at least medium-carbon levels. A patent for the process has been filed<sup>(18)</sup>.

#### THE REMELTING OF FERROMANGANESE FINES

Preliminary investigations were carried out in the 100 kVA transferred-arc plasma furnace using a hollow graphite electrode. The test, during which 180 kg of fines was remelted, was done so that the behaviour of the plasma arc while melting this alloy could be observed and the loss by vaporization of manganese determined. The analyses of the feed and the product are shown

in Table 7.

Table 7

*Analyses of the feed and product obtained  
in remelting of ferromanganese fines at Mintek  
(All values are expressed as percentages by mass)*

Element	Feed	Product
Mn	73,7	75,3
Fe	13,5	17,1
Si	1,8	0,5
C	6,6	5,8
S	0,025	0,01
P	0,12	0,084
Total	95,7	98,8

It can be seen from Table 7 that the manganese content of the product is higher, and the manganese-to-iron ratio lower, than in the feed. This was probably due to the removal of the entrained slag, which usually has a manganous oxide content of approximately 25 per cent but negligible amounts of ferrous oxide, indicating that some of the manganese that was in the feed (as analysed) is ultimately lost to the separated slag phase after remelting.

This preliminary test gave the investigators the confidence needed to embark on larger-scale testwork, which was carried out on the 1,4 MVA furnace at TRD. The analysis of the feed material is shown in Table 8.

Table 8

*Analysis of the feed for the TRD test  
(All values are expressed as percentages by mass)*

Feed	Mn	Fe	Si	C	S	P
FeMn fines 50% <4 mm	75,5	14,5	0,68	6,95	0,006	0,07

Two separate consecutive tests were done, and the furnace was operated at a mean power level of 450 kW. The alloy was tapped continuously from the furnace. The analyses of the metal produced in the two campaigns is given in Table 9.

Table 9

*Analyses of the metal remelted at TRD  
(All values are expressed as percentages by mass)*

Test no.	Mn	Fe	Si	C	S	P
1	74,0	17,1	0,22	6,00	0,008	0,09
2	76,2	15,8	0,10	6,81	0,008	0,09

The overall accountability for the two tests was 97 per cent, and only 0,65 per cent of the manganese fed to the furnace reported to the dust collected in the baghouse plant.

The net specific energy used for melting was within 15 per cent of the assumed value of 500 kW.h/t. This was calculated from the gross specific energy and the known loss of energy from the furnace.

#### THE REFINING OF FERROMANGANESE FINES

It was observed from the results of the remelting tests that some lowering of the carbon and silicon contents of the metal occurred. This refining was thought to be due to the metal oxides in the slag, which is entrained in the fines. It was decided that this refining should be investigated further and that manganese ore should be used as the oxidant.

This testwork was carried out at Mintek on the 100 kVA furnace. A stationary water-cooled non-consumable plasma torch was used instead of a graphite electrode so that any contamination of the metal from this source during the refining process would be prevented.

The analyses of the materials fed to the furnace and their masses are given in Table 10.

Table 10

*Analyses and quantity of feed material  
for refining tests at Mintek  
(All values are expressed as percentages by mass,  
except where stated otherwise)*

Material	Mn	Fe	SiO <sub>2</sub>	CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	C	Si	Mass of feed kg
Mamatwan ore	36,7	5,84	8,57	16,7	3,0	0,19	-	-	16,5
Dolomite	0,81	0,57	1,77	30,4	20,0	0,35	-	-	3,3
FeMn fines	74,7	13,8	-	-	-	-	6,6	1,33	33,0

The furnace was run at a high temperature (1750 to 1950°C) to increase the activity of the carbon in the metal. The results were highly satisfactory, and the carbon and silicon levels were reduced to 0,80 and 0,36 per cent respectively.

Two more tests were conducted on a smaller scale with a hollow graphite electrode. These tests were run at a lower temperature (1590 to 1620°C) so that the effect of this on the refining could be observed.

The effect of basicity on the refining process was investigated by the use of two synthetic ores, prepared by the melting of ore and fluxes, as the oxidants and a new metal-to-ore ratio of 2:1.

The analyses of the feed materials are given in Table 10, and the analyses of the metal produced in Table 11.

Table 10

*Analyses of the feed materials  
in the second refining tests at Mintek  
(All values are expressed as percentages by mass)*

Material	Mn	Fe	Si	C	MnO	FeO	MgO	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>
FeMn fines	73,8	13,4	0,8	6,6	-	-	-	-	-	-
Ore A	-	-	-	-	54,6	13,7	4,22	10,7	10,8	0,82
Ore B	-	-	-	-	52,1	12,2	3,60	17,5	8,01	0,93

Table 11

*Analyses of the metal produced  
in the second refining tests at Mintek  
(All values are expressed as percentages by mass)*

Metal	Mn	Si	C
A	67	0,17	3,0
B	70	0,12	1,8

From Table 10 it can be seen that, although the degree of refining achieved previously was not attained, the effect of lower temperature and the use of a graphite electrode still permitted a useful amount of refining. Ore B, with the higher basicity ((CaO + MgO)/SiO<sub>2</sub>=2,37 compared with 1,38) gave a stronger refining action, particularly on the carbon.

The manganese grade of the material produced is lower than that of the

starting material, indicating that losses to the slag and losses due to vaporization of manganese were high, and may prove to be a greater problem in a refining process than in a remelting process, where carbon can be added to control the loss to the slag.

A patent covering the treatment of ferromanganese fines and their conversion to a more massive form, with or without refining, has been filed<sup>(19)</sup>.

#### THE PROCESSING OF DRI IN THE PLASMA-ARC FURNACE

Although World production of directly reduced iron (DRI) has increased dramatically in the past ten years, it has not kept pace with installed capacity. However, the projected production for 1985 is 20 million tons out of a capacity for 31 million tons<sup>(20)</sup>. Blast furnaces are being phased out in countries with limited supplies of coking coal, and steel is to be produced to an ever-increasing extent from recycled scrap supplemented with directly reduced iron<sup>(21)</sup>. The technology for the processing of scrap and DRI is available, but the processing of charges consisting of DRI alone is still under development<sup>(22,23)</sup>. There is a good incentive in some instances to move away from scrap and to process DRI alone<sup>(23)</sup>. The use of the open-arc furnace has several disadvantages in this regard, the main one being due to the high bulk density of DRI (2 to 4 t/m<sup>3</sup>) and the presence of unreduced oxide and gangue minerals. As mentioned previously, the melting of material of high bulk density results in radiation from the open bath to the furnace roof and in arc flare to the side walls. The presence of non-metallic constituents results in the formation of a slag, which complicates the operation. Krupp, in Germany, have developed a sponge-iron melting process in which the electrodes dip into the slag and generate heat by virtue of the electrical resistance of the slag<sup>(23)</sup>. The sponge iron is fed near the furnace wall to protect the lining. The energy liberated in the furnace is thus limited by the electrical conductivity of the slag, and the addition of any carbonaceous reducing agent to recover the unreduced iron oxides would worsen the situation. This type of resistance furnace has not gained favour in the metallurgical industry.

DRI, by its very nature, has a low carbon content. The basic oxygen furnace (B.O.F.) depends on the energy available from the decarburization of the pig iron charged to it, and there is a limit to the amount of steel scrap it can remelt. DRI, being lower in carbon than most steel scrap, has even



less chemical energy, and so even smaller amounts can be melted during the B.O.F. process to convert pig iron into steel.

The injection of carbon in the form of coal fines to the B.O.F. vessel, together with oxygen to improve its ability to melt feed with a low carbon content, is still at an early stage of development<sup>(24)</sup>. The specification of the coal in terms of ash, sulphur, and phosphorus limits the operation to the use of good-quality coals.

DRI and sponge iron can be classified as types of metal fines, since the average particle is often smaller than 25 mm and, in some of the DRI processes even finer particles are produced. The application of thermal plasma to the melting of these DRI fines is therefore of great interest in a country like South Africa, where an additional DRI capacity of 600 000 t/a is being installed<sup>(21)</sup>.

In the melting of DRI, a plasma-arc furnace offers some attractive advantages over other processes. The presence of slag or of highly metallized charge does not adversely affect the operation. If economics dictate that, for increased throughput in a DRI plant, the degree of metallization must be decreased, further reduction can be readily done in a plasma furnace. In the processing of DRI, the use of plasma technology as a complete replacement for conventional technology presents problems that are due to the currently limited state-of-development of the art.

DRI plants with production capacities of more than 1 million tons per annum are in operation in several countries. The rating of a single furnace to melt this level of production would therefore have to be about 80 MW (at 570 kW.h/t or, say, two 40 MW units). This rating is well beyond the present scale of operation of single water-cooled non-consumable transferred-arc devices. Multiple devices would have to be used, for example four 10 MW torches. As this technology is not yet available at that level of power, eight 5 MW torches would have to be used (500 V by 10 kA). However, the use of multiple devices mounted vertically in the furnace roof with a d.c. supply has the disadvantage that there is interaction between the plasma-arc columns, which tend to coalesce as a result of the attraction of their magnetic fields<sup>(25,26)</sup>. A very high energy spot is caused by this localized anode-root attachment on the bath, and this is undesirable.

Inclined configurations for plasma devices, such as that used by Freital Steel, must therefore be used if this interaction between the arcs is

is to be avoided. In fact, the Freital Steel system is better suited to the melting of scrap of a higher bulk density (2 to 3 t/m<sup>3</sup>) or of metal fines, than to the melting of scrap of a lower bulk density (1 t/m<sup>3</sup>), since the height to which the scrap of low bulk density can be charged is limited by the inclined torches.

Another method by which interaction between the plasma-arc columns can be avoided is the use of an a.c. supply as proposed by Krupp<sup>(26)</sup>. This technology is still limited to currents of 3,3 kA, although operation at higher currents (6 kA) is being developed.

Graphite electrodes are the only alternative to water-cooled non-consumable metallic electrodes<sup>(27)</sup>. A furnace having a capacity of 40 MW could be operated with a single prebaked graphite electrode of 600 mm diameter. It is estimated that this would operate at 80 kA and 500 V.

Mintek is currently engaged in small-scale experimental work using the 100 kVA transferred-arc plasma furnace<sup>(28)</sup>. The results so far have been promising.

#### PROBLEMS ASSOCIATED WITH THE USE OF TRANSFERRED-ARC PLASMA FURNACES

Several problems associated with plasma-arc furnaces are common to most pyrometallurgical processes. However, some are particular to this type of operation, of which the following are the most important.

- (i) For the current carried in the torch to be reduced for a specific power level, operation at as high a voltage as possible is desirable. This can cause stray arcs that can jump from the gun to the roof or side wall of the furnace. These arcs usually cause catastrophic damage to a water-cooled plasma gun. A possible solution to this problem would be electrical insulation of the furnace roof from the rest of the furnace structure; another is the protection of the water-cooled gun with a conductive shield<sup>(29)</sup>.
- (ii) The anode connection to the bath can give rise to problems, especially at high current levels and when the bath is to be tapped dry. Reasonably satisfactory solutions appear to have been found, such as the conducting hearth proposed by ASEA<sup>(30)</sup> and the water-cooled bottom electrode proposed by Freital - Voest-Alpine<sup>(31)</sup>. The Mintek approach is to maintain a thick solid metal heel in the furnace. M·A·N G H H. GmbH use a system in which air is ducted to a number of contact pins to

ensure uniform cooling<sup>(32)</sup>. The cost of anode maintenance could, however, be fairly high if the chosen design is not adequate.

(iii) Problems relating to roof refractories are a feature of any open-bath operation. It is not the radiation from the arc column itself that causes the problem, but rather the radiation and the reflection of the arc from the hot surface of the bath, since these can cause the roof refractories to fail<sup>(33)</sup>. The height from the bath to the roof must be designed in such a way as to reduce the heat flux on the roof, but arc length and torch length are constraints. Water-cooling will almost certainly be necessary if high power densities (above  $5 \text{ kW/m}^2$ ) are aimed at, since the thermal flux to the roof can reach values of 75 to  $87 \text{ kW/m}^2$  under open-bath conditions<sup>(34)</sup>. This latter concept can place a limit on the advantages to be gained from a decrease in the physical size of a furnace.

The slag attack on the side walls can be minimized by correct design of the lining and by suitable additions of flux to the charge.

#### CONCLUSION

Thermal-plasma technology has achieved acceptability on an industrial scale in several pyrometallurgical applications. Middelburg Steel and Alloys (MS&A) in South Africa recently announced their intention to install a 20 MVA d.c. transferred-arc plasma facility for the co-melting and smelting of ferrochromium and chromite fines<sup>(35)</sup>. Samancor, also in South Africa, has commissioned an 8 MW plasma furnace at its Metalloys plant<sup>(36)</sup>. This furnace is to be used initially for the remelting of ferromanganese and ferrosilicon fines, but will also be used as a test furnace for the possible production of all ferro-alloys. The design of the furnace to be installed at MS&A is based largely on ASEA's experience on a 9 MVA pilot plant in Sweden, whereas the furnace at Samancor's Metalloys plant is based on the Freital - Voest-Alpine system.

It was the recognition by Mintek in 1976 of the potential of thermal-plasma technology for the direct processing of fine material and the cost benefits to be derived from the use of this technology that aroused the interest of the local industry. The confidence to proceed with the installation of plasma furnaces for the remelting of ferro-alloy fines stems primarily from the pilot-plant work conducted at Mintek and at TRD in collaboration with MS&A and with Samancor. The developments by Linde, ASEA,

M·A·N G H H, Freital - Voest-Alpine and, more recently, Krupp<sup>(37)</sup> have helped to build this confidence.

A more fundamental understanding of many of the phenomena that occur in the application of thermal plasma to pyrometallurgical processes lags well behind the commercial implementation. The potential for the improvement and optimization of the design of the plasma torch, the furnace, the anodes, and so on is great, but an improved understanding of the mechanism involved in the transfer of electrical energy to the plasma arc and of thermal energy to the process under various operating conditions is essential.

Mintek has a commitment to investigate these matters, and it is hoped that the design and operation of plasma furnaces will benefit from this involvement.

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