

TECHNOLOGY FOR THE PRODUCTION OF NEW GRADES AND TYPES OF FERRO-
ALLOYS USING THERMAL PLASMA

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ABSTRACT

The potential technical and economic advantages of thermal plasma technology over those of submerged-arc furnace processes for the production of ferro-alloys were recognized some 10 years ago. These include the ability of the plasma furnace to treat fine feed, its rapid response to control, and the greater flexibility of its operating conditions.

Ferrochromium with a higher chromium content and at a better chromium recovery than can be achieved in a submerged-arc furnace has been produced in an industrial-scale 16 MVA d.c. plasma-arc furnace at Middelburg Steel and Alloys (Pty) Ltd. The sulphur and phosphorus contents of the alloy are less than half those given in the standard specification.

Pilot-scale developments for new grades of ferrochromium have been undertaken at the Council for Mineral Technology (Mintek) following the successful technology transfer to Middelburg Steel and Alloys of the plasma melting and smelting of high-carbon ferrochromium. The selective carbothermic reduction of chromite to produce a slag with a chromium-to-iron ratio of between 3 and 5 has been achieved at the 1 MW scale. The slag can be used as a synthetic ore to produce alloys containing 65 to 75 per cent chromium. The refining of high-carbon ferrochromium to medium-carbon ferrochromium has also been carried out at Mintek.

Speciality ferro-alloys such as silicides, ferrovanadium, and ferrotitanium are under investigation in small-scale plasma furnaces at Mintek.

INTRODUCTION

The potential of thermal plasma for use in high-temperature process metallurgy was recognized in South Africa in the late 1970s(1). It was foreseen that, subject to satisfactory proving trials and development, this technology could be applied almost immediately to the production of ferrochromium and ferromanganese as an alternative to the existing submerged-arc furnace operations, and that, at a later stage, it might be applied further to the more specialized processing of chromium and manganese ores and the production of other ferro-alloys.

For the smelting of ores, particularly chromium ores, plasma furnaces appear to have several important advantages, both technical and economic, over those of conventional submerged-arc furnaces, as follows.

Plasma furnaces can treat ore fines direct, unlike submerged-arc furnaces, which generally require the costly, and sometimes not entirely effective, agglomeration of such fines.

The furnace can be closed more easily because of its single-electrode operation and simpler feed distribution, and can therefore make use of the excess thermal energy in the furnace off-gases for pre-heating or pre-reduction of the incoming charge.

The furnace responds rapidly to changes in operating conditions or charge inputs because smelting is carried out under open-bath conditions.

Greater degrees of freedom are offered in the metallurgical control of the operation of a plasma furnace. For example, there is no electrical-resistivity restraint like that imposed by the burden or slag in a submerged-arc furnace, and therefore there is greater flexibility, concerning the composition of the charge and the slag.

These last two potential advantages, namely the rapid response time and the greater flexibility in

FERROCHROMIUM GRADES CURRENTLY PRODUCED IN AN INDUSTRIAL PLASMA FURNACE

MS&A are using a d.c. transferred-arc plasma furnace to produce ferrochromium at their Krugersdorp plant in South Africa. The furnace can be used for plasma melting and smelting operations. The design was developed by ASEA on their pilot-scale Elred Process for the smelting of iron-ore fines(2), although the concept of using this approach for ferrochromium arose initially from pilot plant tests at Mintek. ASEA subsequently developed this furnace design also for the d.c. arc melting of steel and stainless steel scrap.

The MS&A furnace and its electrical system were installed by ASEA. The furnace transformer is rated at 16 MVA and the current is rectified to d.c. by silicon diodes. The furnace shell is 7.5 m in diameter and 2.4 m in height. The side walls are

process control, make it possible for a plasma furnace to produce a wider range of alloy compositions than can be produced in a submerged-arc furnace, particularly with respect to ferrochromium and ferromanganese. This aspect forms the subject of this paper. However, a word of caution is necessary. The very same rapid response and flexibility of control seen here as advantages can also prove to be disadvantages since serious operational difficulties can be experienced if appropriate control measures are not available and enforced rapidly. For effective operation, a plasma furnace requires a much stricter level of control than a submerged-arc furnace. This fact can be well attested to by the Council for Mineral Technology (Mintek) after 6 years of practical operation of transferred plasma-arc furnaces ranging from 50 kVA to 3.2 MVA, and by Middelburg Steel and Alloys (MS&A) after over 2½ years of experience with its 16 MVA transferred-arc plasma furnace.

Since 1979, Mintek and MS&A have collaborated closely in the development of plasma for the processing of chromium ores, while Mintek has also carried out plasma investigations on other ores. This work led not only to the installation of an industrial plasma smelter for ferrochromium, but also revealed areas for the even more advanced processing of chromium ores and the production of other ferro-alloys. This paper therefore examines how thermal plasma is being, and may be, used to produce different types and grades of ferro-alloys. It is divided into three main sections, as follows:

the compositional grades of ferrochromium that are currently being produced by plasma on an industrial scale in South Africa,

plasma-processing techniques that are at an advanced or pilot stage of development and could yield entirely new grades of ferrochromium, and

small-scale investigations on the use of plasma for the production of other ferro-alloys, which require considerable development before progressing to industrial realization.

lined with various grades of magnesia bricks and the lined diameter increases from approximately 5 m at hearth level to 6.8 m at roof height. The furnace is closed with an outer roof of water-cooled refractory-lined panels and a central, bricked arched section.

Power is introduced to the furnace via a single central graphite electrode of 560 mm diameter, which acts as the cathode. The current is transmitted via an open arc through the molten bath and the specially designed conductive hearth to the anode, which is an annular copper plate bolted to the inner bottom surface of the furnace shell.

The charge is fed to the furnace as fines through an axial hole in the graphite electrode. Nitrogen

is continuously purged down the same hole to maintain the stability of the plasma.

The furnace is shown in Figure 1.

The production of ferrochromium with the plasma furnace commenced at the beginning of 1984, and this section of the paper discusses the composition of the alloys that are being produced and compares these with the ferrochromium grades that are achieved by conventional submerged-arc smelting

of the same grade of ore.

Chromium Content

For ores with the same ratio of chromium to iron, the chromium content of the alloy from the plasma furnace is generally 0,5 to 1,0 per cent greater than that from the submerged-arc furnace. However, this is simply because the lower content of silicon plus carbon in the alloy has a smaller dilution effect. The chromium contents and recoveries for an ore with a chromium-to-iron ratio of 1.5 are shown in Table 1 for both types of furnace.

Table 1. Comparison of chromium grades and recoveries for plasma and submerged-arc smelting of ores with Cr:Fe of 1.5

MS&A furnace	(C + Si) in alloy (%)	Cr content of alloy (%)		Cr recovery to metal (%)	Cr ₂ O ₃ in slag (%)	Slag-to-metal ratio
		Theoretical	Actual			
16 MVA plasma arc	9.4	54.4	52.8 to 53.6	> 90	2 to 6	0.8
20 MVA submerged arc	11.0	53.4	51.5 to 52.2	75 to 80	11 to 13	1.3

It is evident that in both cases the actual and theoretical chromium contents of the alloys are very similar. However, there is a large difference between the two operations in terms of chromium recovery, and this is corroborated by the much lower level of residual chromium in the slag from the plasma-arc furnace.

It should be noted that, although the slag analyses in Table 1 are expressed as Cr₂O₃, metallographic examination shows that, in the case of the plasma-arc furnace, the small amounts of residual chromium are present mostly as metallic inclusions within the slag itself. In the case of the submerged-arc furnace, however, the larger contents of chromium are present both as metallic inclusions and as partly altered chrome spinels(3). These cases are illustrated in Figures 2 and 3.

The far better chromium recovery for the plasma furnace as compared with that for the submerged-arc furnace is attributed to improved control of the slag fluidity, composition and temperature. This results in more uniform process conditions throughout the slag bath which favours the more complete dissolution and reduction of the chrome spinels.

Silicon Content

Good control over the silicon content of the alloy can be achieved in the plasma furnace, and alloys with very low silicon contents can be made.

Current requirements in terms of alloy grade for the plasma furnace call for less than 1 per cent silicon, and alloys containing 0.2 to 0.7 per cent silicon are being consistently produced. Compared with the submerged-arc furnace, therefore, the plasma furnace has a far smaller tendency to reduce silicon which is more energy intensive. In the submerged-arc furnace, for a similar chromium grade, the silicon contents of the alloy are generally

from 3 to 5 per cent.

Silicon control during plasma smelting is achieved mainly by the carbonaceous reductant. However, where there is a large melting component in the charge, for example when large amounts of ferrochromium fines from the plant operations are recycled to the furnace, the silicon contained in the alloy fines (typically 3.5 per cent silicon) reacts with, and reduces the Cr₂O₃ and FeO in the slag and is itself oxidized to the slag, leaving a low-silicon alloy.

Carbon Content

At present, no attempts are being made to lower the carbon content of the alloy, which is typically 8 to 9 per cent. This aspect will be addressed in the near future. However, it is significant that the total carbon plus silicon in the plasma alloy is less than that in the submerged-arc alloy (typically 9.4 and 11.0 per cent respectively).

Sulphur Content

The plasma operation is independent of the electrical resistivity of the slag, and therefore the possibility arises of desulphurizing the metal to very low levels by the use of high-lime, high-basicity slags. The electrical conductivity of such slags is too great for efficient submerged-arc operation.

Metal with a specified maximum content of 0.015 per cent sulphur, has been produced. The metal often contains 0.012 to 0.013 per cent sulphur, and a sulphur content as low as 0.005 per cent has been achieved. The slags for this purpose have a basicity of up to 2.0, and contain 17 to 22 per cent CaO, whereas the slags from the submerged-arc furnaces have a basicity of approximately 1.5 and contain 7 to 9 per cent CaO.

Phosphorus Content

The plasma furnace is very flexible in relation to the type of reductant that can be used: coke, char, anthracite, and bituminous coals are all suitable. Thus, by the judicious selection of a low-phosphorus reductant, together with the use of chromite concentrates containing a minimum amount of gangue, ferrochromium with a very low phosphorus content can be produced.

chromium that can be produced in the Krugersdorp plasma-arc furnace with that produced in a submerged-arc furnace using ore of a similar composition.

The only additional components shown in Table 2 that have not been discussed are manganese and titanium. Low titanium contents are advantageous for some applications in which ferrochromium is required and, in this respect, the titanium content of the plasma-produced alloy is substantially lower than that from the submerged arc. There is

Table 2 compares the composition of the ferro-

Table 2. Composition of ferrochromium produced in a plasma-arc and a submerged-arc furnace from similar feed materials

MS&A furnace	Constituent (% by mass)						
	Cr	Si	C	S	P	Mn	Ti
16 MVA plasma arc	52.2 to 53.6	<1.5	7.7 to 8.9	<0.015	<0.010	0.3 to 0.4	0.2 to 0.4
20 MVA submerged-arc	51.5 to 52.2	3.5	7.0 to 7.5	<0.030	<0.020	0.3 to 0.4	0.6
ISO spec. (low P)	45 to 55	1.5 to 5.0	6 to 8	<0.05	<0.03	-	-

little difference between the manganese contents of the two alloys.

The combination of low silicon with low sulphur and low phosphorus in the plasma alloy is considered to be especially advantageous for some applications.

PILOT-SCALE DEVELOPMENT OF NEW GRADES OF FERROCHROMIUM

In 1980 an experimental programme was begun in which the process flexibility offered by plasma furnaces was utilized in an attempt to develop new grades of ferrochromium alloys. The initial test-work was conducted at 60 to 150 kW and the pilot-scale tests were conducted at 500 to 1000 kW.

The compositions of the metal and the slag confirmed the results of the smaller-scale tests in which feeds with the same composition had been used. The compositions of the slag and alloy shown in Table 4 could therefore be produced in an industrial plasma furnace by varying the composition of the feed.

Selective reduction of chromite

The energy and electrode consumptions measured during the 1 MW campaigns were 3.6 MW.h and 5.9 kg per ton of produced slag respectively. However, in the operation of submerged-arc furnaces with similar sub-stoichiometric additions of carbon, very high electrode consumption and difficulties in maintaining a constant degree of reduction would be expected.

The controlled addition of reducing agents and chromite to a molten bath of slag allows the well-known selective reduction(4-7) of chromite to be realized in a plasma furnace. Chromite, coal, and fluxes were smelted at the 1 MW power level in a transferred-arc plasma furnace (see Figure 4) at Mintek. A standard Transvaal chromite with chromium-to-iron ratio of 1.6 (a total of 150 t of feed material), which was treated in two separate campaigns, yielded a slag that contained 29 per cent Cr_2O_3 and had a chromium-to-iron ratio of 4. The composition of the metal produced is shown in Table 3.

The slag produced should yield an alloy with the compositional range shown in Table 5, depending on the chromium-to-iron ratio of the slag and whether a submerged-arc or a plasma furnace was used.

Table 3. Composition of metal from a selective reduction campaign

Constituent (% by mass)					
Cr	Fe	C	Si	S	P
46	47	5.0	0.30	0.13	0.01

This process would be most suitable for an integrated producer of ferro-alloys and stainless steel because the low-grade metal could be utilized in the stainless steel plant. The wide range of chromium-to-carbon ratios (9 to 20) that can be produced in the low-grade metal would allow the melt shop to deliver hot metal to the decarburization vessel, e.g. argon-oxygen decarburization (AOD), with an optimum carbon content in terms of blowing time and final temperature. The high-grade metal meets the ISO specification (Table 5) for high-

Table 4. Composition of slag and metal (constituents in % by mass)

	Slag		Metal		
	Cr:Fe	% Cr ₂ O ₃	% Cr	% C	% Si
Range	5:1 to 3:1	35 to 29	46 to 42	5 to 2	0.42 to 0.30

Table 5. Compositions of high-grade ferrochromium

Range	Constituent (% by mass)				
	Cr	Si	C	S	P
Upper	72	3.0	9.5	0.02	0.01
Lower	67	1.0	8.0	0.01	0.008
ISO spec. high-C FeCr	65 to 75	1.5 to 5.0	8 to 10	<0.05	<0.03

carbon ferrochromium (65 to 75 per cent), and represents a new grade of ferro-alloy to be produced from Transvaal chromites. This alloy would have an advantage over the 55 per cent ferrochromium normally exported, in terms of lower transport costs per ton of chromium because of its higher chromium grade. The metal could also be used in-house for the manufacture of ferrochromium silicide and low-carbon ferrochromium with higher chromium-to-iron ratios than the existing raw materials allow when processed by conventional methods.

The advent of the plasma furnace has made the selective reduction of chromite a technically feasible operation, and henceforth economic factors will govern its industrial future.

Refining of High-carbon Ferrochromium

The known ability of the plasma-arc furnace to

remelt metal fines (8,9) provides an ideal opportunity to increase the commercial value of the remelted products in the same operation by lowering the silicon and carbon contents of the metal fines. High-carbon ferrochromium fines, chromite, and flux have been reacted in plasma furnaces in the 100 to 500 kW range. That work has been described elsewhere(9,10), and therefore only a summary is given here.

The alloy produced by the plasma furnace from reject metal fines meets the ISO specification for medium-carbon ferrochromium (Table 6) without recourse to pneumatic processes. This technique therefore enables metal fines arising from the plant to be usefully upgraded in a simple one-step operation.

Table 6. Metal compositions

Source	Constituents (% by mass)					
	Cr	Si	C	S	P	Ti
Metal fines (<3 mm)†	50	4.0	7.0	0.03	0.01	-
Plasma-product alloy	53	0.2	3.5	0.03	0.011	<0.01
ISO specification (Medium-C FeCr)	45 to 55	<1.5	2 to 4	0.05	<0.05	-

†Analysis includes the entrained slag (usually 5 to 10 per cent by mass)

SPECIALITY FERRO-ALLOYS PRODUCED IN SMALL-SCALE PLASMA FURNACES

Testwork carried out at Mintek during the past few years has involved the processing of several speciality or 'minor' ferro-alloys. These tests were conducted in plasma furnaces rated at 50 kVA, 100 kVA, and 200 kW. Figures 5 to 7 illustrate these small-scale pilot-plant furnaces.

Silicide Alloys

The carbothermic reduction of silica to produce silicon in an open-bath transferred-arc plasma process results in high losses of silicon monoxide, and therefore a shaft-furnace process is preferred. However, success was achieved in the co-melting of silicon fines (in the form of an off-grade product from the production of silicon) and reject high-carbon ferromanganese fines or high-carbon ferrochromium fines to produce a wide range of medium- to low-carbon silicide alloys. Compositions that have been produced include those of standard and, in some instances, even better specification(11,12).

During the co-melting and subsequent cooling processes, the carbon in the high-carbon alloys is exsolved as a result of the very limited solubility of carbon in high-silicon alloys. Most of these co-melting tests were carried out in the 100 kVA transferred-arc plasma batch furnace shown in Figure 6.

The relationship between the carbon and silicon contents in the alloys produced are presented graphically in Figure 8. The chemical compositions of typical alloys are given in Tables 7 and 8.

As can be seen from Table 7, the carbon values in the manganese alloys are better than the specification but those for the chromium alloys shown in Table 8 are worse. A patent has been filed to cover the former successful results, and testwork is continuing on the chromium silicide alloys (12).

Table 7. Examples of the chemical composition of FeMnSi with three grades of silicon produced by the co-melting of HCFeMn fines and Si fines(11)

Source	Constituent (% by mass)					Total*
	Mn	Si	C	S	P	
Co-melted	63.1	11.3	2.8	<0.01	0.08	99.18
Co-melted	60.8	23.6	0.8	<0.01	0.08	99.78
Co-melted	54.6	32.8	0.10	<0.01	0.07	99.37
ISO spec. 12	60 to 75	10 to 15	<2.5	<0.03	<0.15	-
ISO spec. 18	60 to 75	15 to 20	<2.5	<0.03	<0.15	-
ISO spec. 22	60 to 75	20 to 25	<1.6	<0.03	<0.15	-
ISO spec. 30	57 to 67	28 to 35	<0.10	<0.03	<0.10	-

*Including Fe

Table 8. Examples of the chemical composition of FeCrSi with three grades of silicon produced by the co-melting of HCFeCr fines and Si fines (12)

Source	Constituent (% by mass)			
	Cr	Si	C	S and P
Co-melted	15.2	54.5	0.67	Not analysed
Co-melted	14.5	71.7	0.07	
Co-melted	19.8	74.4	0.18	
ISO spec.	>20	45 to 60	0.03 to 0.1	

Refined or Low- to Medium-carbon Alloys

The silicide alloys of both manganese and chromium can be refined to effect silicon removal by the reaction of these alloys with oxide material, normally in the form of a lime-ore melt. Medium- to low-carbon ferromanganese or ferrochromium can be produced in this manner. However, it has also been feasible to refine high-carbon ferromanganese with 6.6 per cent carbon to medium-carbon ferromanganese by reaction of the high-carbon alloy with oxide ore in a d.c. transferred-arc plasma furnace (11). The composition of the alloy produced was as follows: manganese 70.4 per cent; carbon 1.8 per cent; silicon 0.12 per cent; sulphur <0.005 per cent; phosphorus <0.08 per cent; balance Fe.

Ferrovandium

Ferrovandium is conventionally produced by the aluminothermic reduction of vanadium pentoxide in the presence of metallic iron. Following the success achieved with the partial carbothermic reduction of chromite described earlier, it was decided to extend this concept to the production of ferrovandium by the use of carbon in place of costly aluminium to reduce the higher oxides of vanadium. The carbothermic reduction of V_2O_5 to produce a vanadium sub-oxide with the approximate stoichiometric relationship VO is thermodynamically feasible. Aluminium can subsequently be used as a reducing agent for VO, and the iron units can be added as metal. The aluminothermic reduction of VO is endothermic, unlike that of the higher oxides, and therefore additional energy has to be supplied. The plasma-furnace process is well suited to this.

The carbothermic reduction of V_2O_5 can also be carried out in a smelting process using a plasma as the source of thermal energy. According to the data of Taniuchi and Mimura(13), it should be feasible to reduce the oxygen content of the vanadium oxide melt with carbon to around 22 per

cent before an unacceptable level of carbon (greater than 0.3 per cent) is obtained. Thus, it appears to be theoretically and practically feasible to reduce the higher oxides of vanadium (V_2O_5 with 43.9 per cent oxygen, and V_2O_3 with 32 per cent oxygen to vanadium monoxide that contains 23 per cent oxygen. The addition of aluminium to complete the removal of oxygen at this stage would thus limit the carbide formation to within the specification of 0.3 per cent.

Preliminary testwork to demonstrate the validity of this concept was undertaken on the 100 KVA plasma furnace at a power level of about 30 kW. The initial results were reasonably encouraging, although the carbon content of the final alloy was too high. The first test focused on the initial addition of the stoichiometric amount of carbon required to reduce vanadium pentoxide to vanadium monoxide. The product obtained is detailed in Table 9. A second test was then undertaken for further reduction of the melt to ferrovandium by the addition of the stoichiometric amount of aluminium required to reduce the vanadium monoxide. The product formed is also detailed in Table 9, where it can be noted that the final carbon content is over 2 per cent. The carbon level in the pre-reduced material is obviously not in equilibrium, as predicted in Figure 9, and requires further investigation.

Compared to the conventional exothermic aluminothermic processes, this process requires extra energy from the plasma to accomplish the reduction, but a 63 per cent saving in the aluminium requirement can be realized by the substitution of 30 kg of carbon per 100 kg of vanadium. This saving in aluminium is an incentive for continued attempts on a small scale to produce improved grades of ferrovandium (in particular the carbon levels). Any progress achieved would then advance the work to the pilot scale at Mintek and could well provide a novel commercial means for the production of ferrovandium by the use of thermal plasma.

Table 9. Chemical composition of ferrovandium alloys

Source	Constituent (% by mass)				
	V	Fe	C	Si	Al
Pre-reduced	78.3*	2.7	1.4	-	-
Plasma product	84.8	11.0	2.2	0.7	0.2
ISO spec.	75 to 85	Bal	<0.3	<2.0	<2.0

*Expressed as VO

Ferrotitanium

Attempts were made to produce ferrotitanium from a locally produced high-titania slag. The aim was the production of an alloy containing about 70 per cent titanium. This grade is usually produced by the comelting of titanium scrap with iron, and makers of stainless steel often prefer it to the lower-grade

alloys produced by the aluminothermic reduction of ilmenite because of its low melting point (1150 to 1200°C), which ensures its rapid assimilation when it is used as a ladle addition.

While the titanium content of this ferro-alloy is of importance, the aluminium content is regarded

as being equally so by a local potential user of this alloy. A specification of a titanium-to-aluminium ratio of 15 has been given because there are fears that a higher content of aluminium will result in blockages of the sliding gate under the tundish of the continuous-casting machine used on this plant.

Alloys produced in the 200 kW d.c. transferred-arc plasma furnace shown in Figure 7 were analysed(14), and were found to have the following composition:

Titanium 56.4 per cent; iron 14.5 per cent; silicon 21.8 per cent; aluminium 13.5 per cent. The mass ratio of titanium to aluminium was 4.

During this particular campaign, the recovery of titanium was only 46.5 per cent and, although slag could be tapped from the furnace, the metal remained behind and was recovered only when the furnace had cooled.

Further investigation showed that the metal had a liquidus temperature in excess of 1700°C, and this was ascribed to its oxygen and nitrogen contents, which were found to be typically 3 and 0.5 per cent respectively. A study of the relevant equilibrium diagrams shows that even minor quantities of either of these elements results in a large increase in the liquidus temperature of the alloy.

In a further test conducted in a specially designed 30 kW furnace (Figure 5) from which air could be effectively excluded, the nitrogen content decreased tenfold, but the oxygen content was unaffected. This indicates that the oxygen content is not primarily a function of the oxidation by the atmosphere but is determined by the degree to which the reduction reaction proceeds, i.e. at whatever concentration of reactants and products equilibrium is reached.

Lower-grade alloys analysing typically 24 per cent titanium and having a melting point of about 1500°C were produced when iron was added with the charge. These alloys could be tapped, and had an oxygen content of about 0.5 per cent and a nitrogen content of 0.02 to 0.05 per cent. The titanium-to-aluminium ratio was, however, typically 7.

It was concluded from the test that the aluminothermic reduction of titania-rich slag to meet the required titanium-to-aluminium ratio of 15 is probably not feasible in practice in a single-stage operation owing to thermodynamic constraints.

Two options are available, as follows:

- (1) A sufficiently large excess of aluminium could be used to make a titanium-aluminium alloy with an oxygen content sufficiently low for the alloy to be tapped. This would also ensure an improved recovery of titanium. The excess aluminium could then be removed by evaporation in an electron-beam(15) or plasma furnace. The cost of this route would be high, and the process would not be economically viable while adequate supplies of titanium scrap are available at a favourable price.
- (2) The influence of iron additions on the liquidus temperature of alloys containing 30 to 40 per cent titanium and having an improved titanium-to-aluminium ratio and, it is hoped, a lower oxygen content, needs to be investigated on a large scale in a sealed furnace. This approach seems to be the most likely to succeed economically.

CONCLUSIONS

Industrial-scale Developments

1. Ferrochromium alloys have been produced for over 2 years in a 16 MVA d.c. transferred-arc plasma furnace at the Krugersdorp Works of Middelburg Steel and Alloys (Pty) Ltd. At the previous Infacon meeting in Japan in 1983, the potential of this technology was addressed (16). It is now an industrial-scale reality for the remelting of ferrochromium metal fines and for the smelting of chromite fines.
2. The chromium content of slags tapped from the 16 MVA d.c. plasma-arc furnace is very low compared with that of slags from the submerged-arc furnace, demonstrating the ability of plasma technology to achieve high recoveries of chromium (greater than 90 per cent).
3. The composition of the metal tapped from the 16 MVA d.c. plasma-arc furnace is different from that tapped from the submerged-arc furnace. The chromium contents are about 1 per cent higher as a result of the much lower silicon contents (but somewhat higher carbon levels). The sulphur and phosphorus contents are about

half those of the metal from the conventional submerged-arc furnace, and are very well below the ISO specification.

Pilot-scale Developments

1. The carbothermic selective reduction of Transvaal chromite has been successfully demonstrated at the 1 MW scale to yield 75 t of slag containing 29 per cent Cr_2O_3 at a ratio of chromium to iron of 4.
2. It has been demonstrated that, by utilizing an open-bath in conjunction with a d.c. plasma arc, good graphite-electrode consumptions are possible in the plasma furnace, even when operation involves a process using substantially understoichiometric additions of carbon.
3. With the advent of the plasma furnace, it has become technically possible to implement the carbothermic selective reduction of chromite on an industrial scale since the major difficulties of submerged-arc furnace operation in such circumstances are avoided, namely high electrode consumption, variable degrees of

reduction and unstable operation.

4. The production of standard medium-carbon ferrochromium from reject high-carbon ferrochromium fines has been achieved by the use of a transferred-arc plasma furnace to remelt and refine this material in a single operation.

Small-scale Developments

1. Silicide alloys of both manganese and chromium have been produced by the co-melting of high-carbon ferro-alloy fines and silicon fines in an open-bath d.c. transferred-arc plasma furnace. It should be feasible to carry out this process at a large scale using reject fines to produce a saleable product or an intermediate alloy that could be refined to yield a low-carbon product.
2. Ferrovanadium containing 85 per cent vanadium has been produced in a small-scale plasma furnace. This involved the pre-reduction of vanadium pentoxide with solid carbon to produce a sub-stoichiometric, i.e. lower oxide material, which was then reduced with aluminium to produce a ferrovanadium alloy, albeit with too high a carbon content. Further development work is needed, however, to improve the process.
3. Ferrotitanium with a 56 per cent titanium content but with too low a mass ratio of titanium-to-aluminium has been produced. Although the nitrogen contamination problem has been solved, the oxygen levels are still too high to permit tapping of the alloy. Dilution with iron appears to be the only possible means by which this tapping problem can be alleviated.

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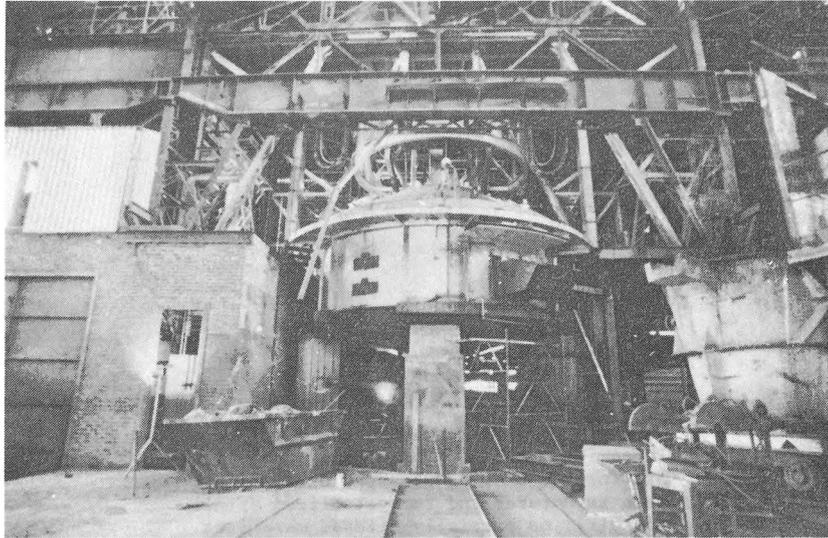


Fig. 1 The MS&A 16 MVA d.c. plasma-arc furnace for ferrochromium production at Krugersdorp.

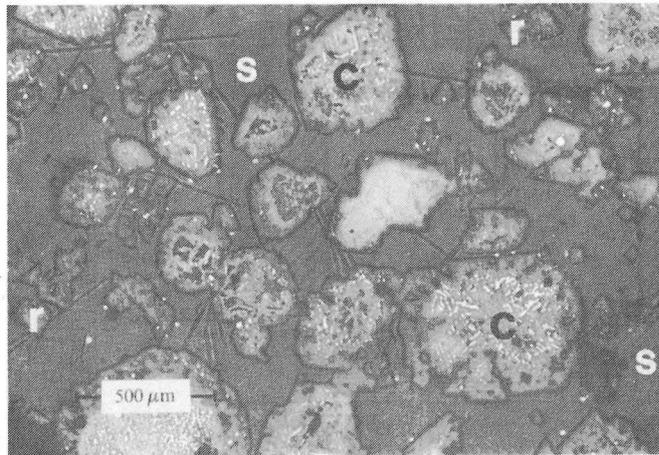


Fig. 2 Photomicrograph of typical slag from submerged-arc furnace showing glassy slag(s) with occasional lath structures, recrystallized spinel(r), and partially altered chromite (c) containing metallic blebs and unreduced chromic oxide.

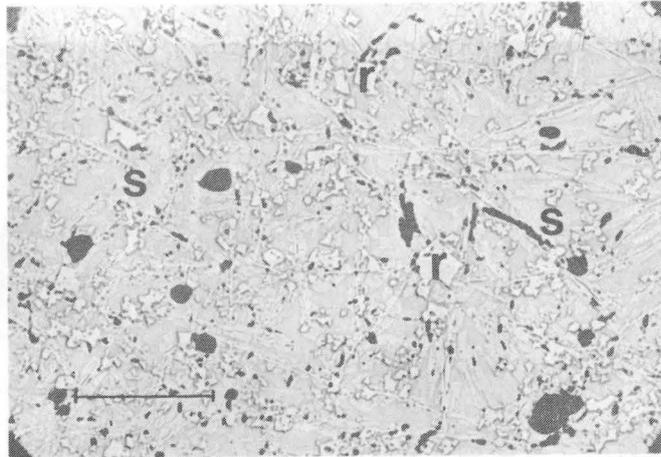


Fig. 3 Photomicrograph of typical slag from plasma-arc furnace showing glassy slag(s) with lath structures and recrystallized spinel only (r); no partially altered chromites or metallics are visible.

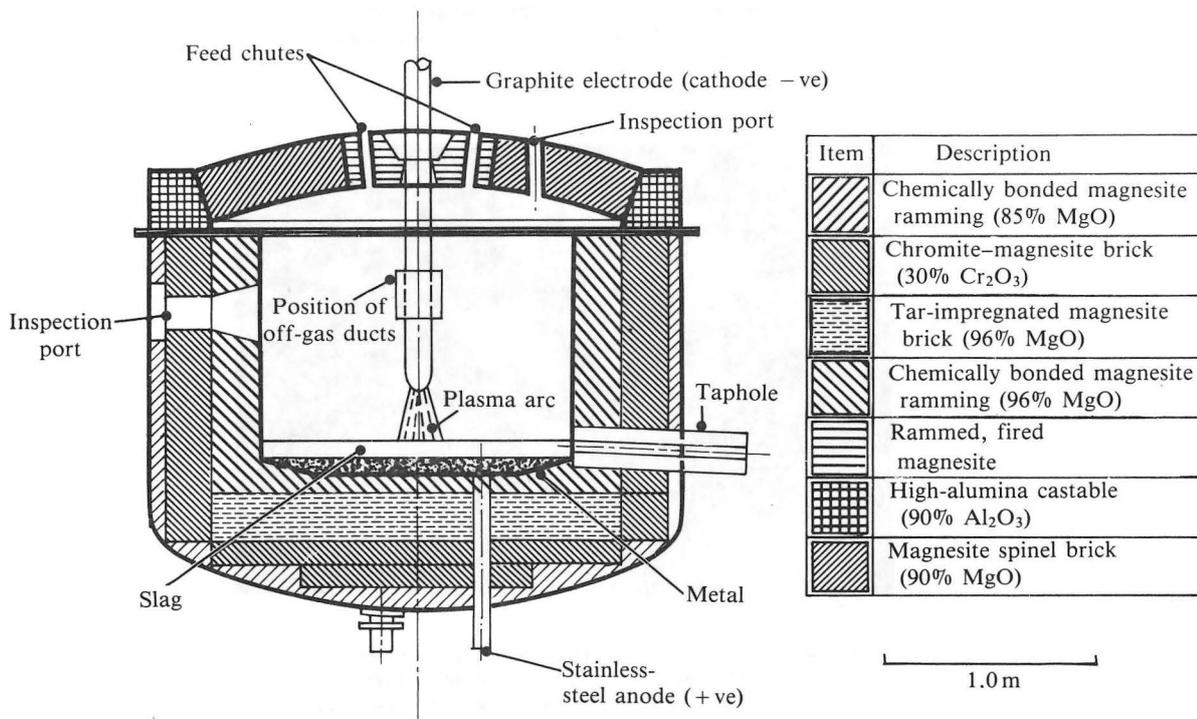


Fig. 4. Mintek 3.2 MVA open-bath transferred-arc system with material feed into the bath via the furnace roof

Fig. 5 Schematic representation of the sealed 50 kW furnace. (1) Argon supplied to water-cooled hollow copper-graphite composite electrode. (2) Electrode support mechanism, clamp, and power cable. (3) Stainless-steel bellows and electrode seal. (4) Observation window. (5) Off-gas system with water-cooled baffle box. (6) Off-gases to water seal. (7) Replaceable magnesite crucible with anodic connection through bottom. (8) Graphite plate with external anodic connection. (9) Refractory-lined bottom portion of furnace. (10) Water-cooled middle section of furnace. (11) Refractory-lined upper portion of furnace. (12) Feed pipe from sealed hopper

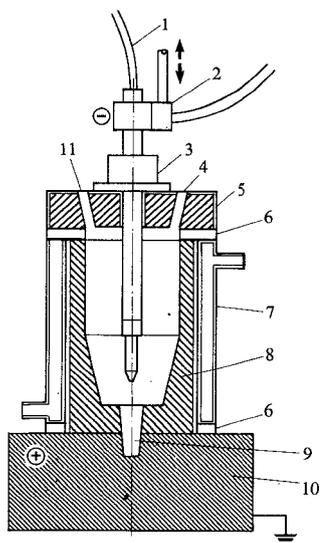


Fig. 7 Schematic representation of the 200 kW plasma furnace. (1) Argon supply to hollow graphite electrode. (2) Electrode support mechanism, clamp, and power cable. (3) Feed chute from sealed feeder (4) Domed refractory roof (later replaced with a steel-backed, electrode-paste hot-faced magnesia roof). (5) Rammed magnesia lining (later replaced by alumina brick lining). (6) Water-cooled panel (fitted at later stage). (7) Anodes. (8) Tap-hole launder. (9) Gas offtake. (10) Water-cooled electrode seal. Dimensions of crucible: Depth 600 mm (later increased to 750 mm), diameter 500 mm

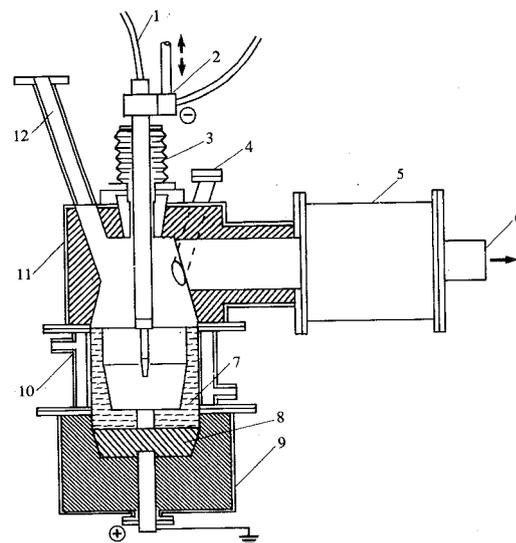
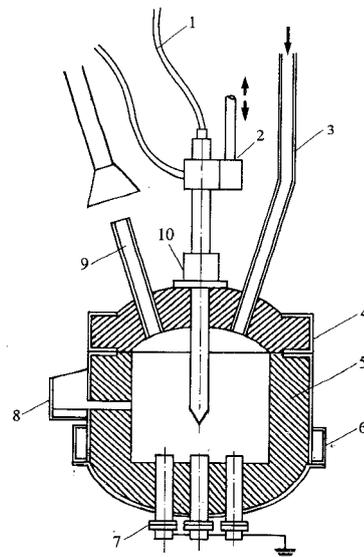


Fig. 6 Schematic representation of the 100 kVA water-cooled batch furnace. (1) Argon supply to hollow graphite electrode. (2) Electrode support mechanism, clamp, and power cable. (3) Water-cooled electrode seal. (4) Gas offtake. (5) Steel roof with magnesia lining. (6) Ceramic-fibre insulating gaskets. (7) Water-jacket. (8) Replaceable refractory crucible. (9) Anode connection. (10) Graphite block. (11) Feed port.



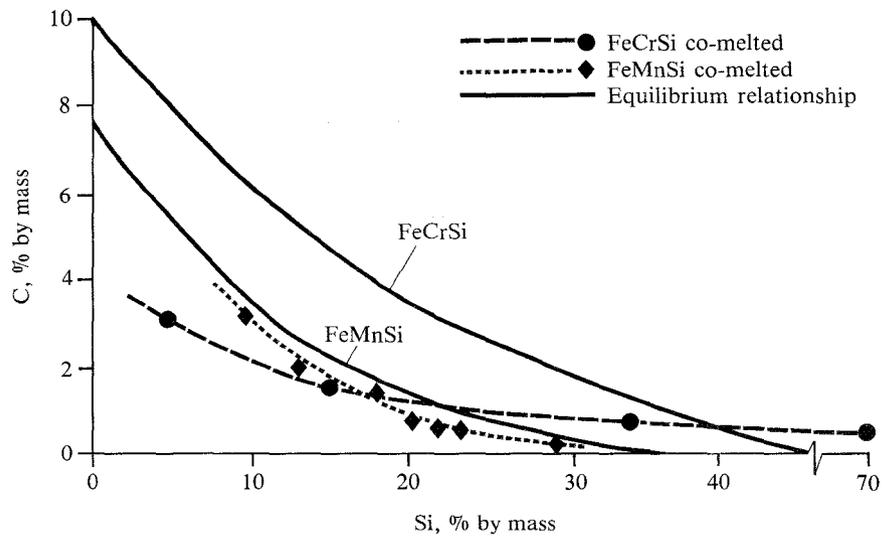


Fig. 8. Carbon solubilities in ferro-alloys as a function of silicon content^{11,12}

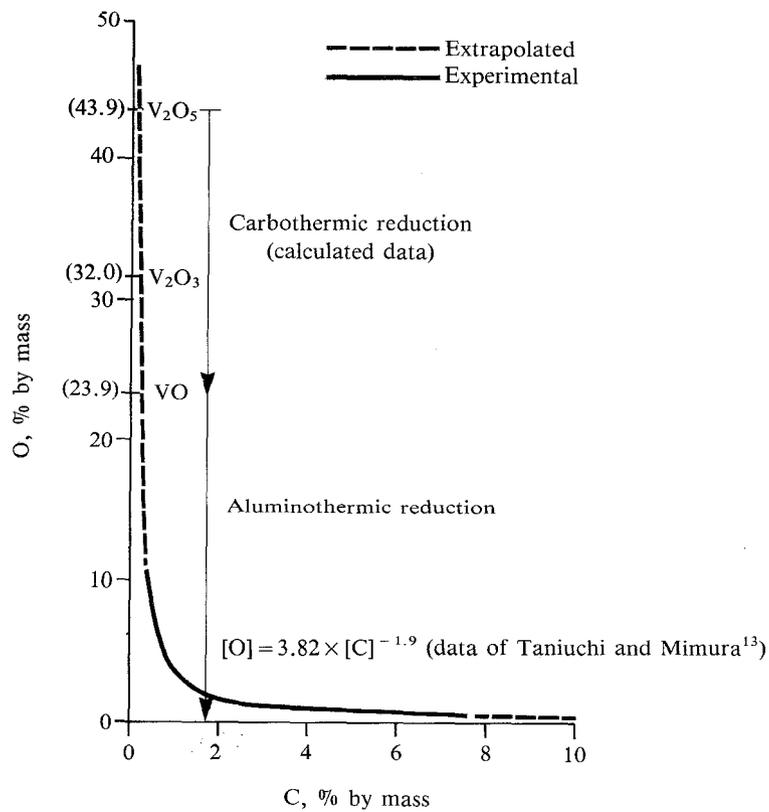


Fig. 9. The combined carbo-aluminothermic reduction of vanadium pentoxide en route to ferrovanadium