The Reduction of Chromite Fines with Ferrosilicon

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SYNOPSIS

A quantitative flowsheet, based on extensive industrial-scale pilot-plant work, is presented for the single-stage reduction of chromium from run-of-mine 1,6/1 ratio chromite fines with 75 per cent ferrosilicon for the production of extra-low-carbon (ELC) (0,0 per cent maximum carbon) 50 to 55 per cent ferrochromium. The quantities of this flowsheet are confirmed by the 5-tonne slag reactions with ferrosilicon recorded by Bobkhova.

The ferrochromium made by this process is magnetic, and is easily handled and induction-melted in conventional silica-lined high-frequency or mains-frequency furnaces.

A major field of utilization of this alloy is the production of chromium steels by the arc-furnace melting of chromium and/or mild-steel scrap to give a converter charge with about 1 to 1,5 per cent silicon, 0,5 to 1 per cent carbon, and less than 10 per cent chromium; ELC iron (blown metal) is refined by the steam—oxygen converter process, and the chromium is brought up to specification by the addition of induction-melted 50 to 55 per cent ELC ferrochromium. This procedure avoids the 1½ to 2½ hours of blowing time required in the argon—oxygen process, uses steam in place of argon, increases the converter capacity, and renders chromium recovery from the converter slag unnecessary.

Owing to the low density (2,5) of disilicon carbide, skimming or bottom-pouring of the 75 per cent ferrosilicon could bring the carbon content of the final alloy down to less than 0,015 per cent at an insignificant increase in the cost of the chromium produced.

From the short *pro forma* cost analysis presented, it is concluded that an extra-low-carbon (ELC) alloy could be produced by the single-stage ferrosilicon process from run-of-mine Transvaal chromite fines under present conditions (4th quarter, 1972) in the Witbank area, Transvaal, at R280 per tonne of chromium. This cost is based on 45 kg of machine-cast, shot-blasted ingots f.o.r. the works site, and on purchased, locally made ferrosilicon. If the plant is integrated with its own ferrosilicon capacity, the production cost is estimated at R265 per tonne of contained chromium.

The reduction of low-ratio chromite fines with ferrosilicon is a means, if not the only means, of producing ferrochromium that will give an adequate return on capital from the immense reserves of low-ratio chromites in the Transvaal and Rhodesia, and that will compete on world markets with ferrochromium made from other sources of chromite.

INTRODUCTION

The argon—oxygen (AOD) process, if it is to avoid the extensive use of low-carbon ferrochromium, must use high-carbon ferrochromium (or the more costly medium-carbon ferrochromium) in the converter charge, and must work with a chromium content of 18 to 20 per cent in the converter charge. Because chromium contents above about 10 per cent in the converter charge greatly impede carbon removal, blowing times in the AOD process are as long as 1½ to 2½ hours.

For this reason, it is preferable to melt stainless-steel and/or carbon-steel scrap in the arc furnace to make a converter charge with contents of silicon about 1 to 1,5 per cent, carbon 0,5 to 1 per cent, and chromium less than 10 per cent, which will yield a blown metal of less than 8 per cent chromium, and to operate the converter by the VLN steam—oxygen process developed by the Steel Company of Wales[1]. Blowing times are thereby reduced to about 30 minutes, and the blown metal has nitrogen contents of the order of 0,001 per cent (10 p.p.m.) and carbon contents of about 0,01 per cent (100 p.p.m.). The chromium content of the steel is brought to specification by the addition of induction-melted ELC ferrochromium to the metal.

This procedure has the following advantages:

(i) steam replaces argon,
(ii) the converter capacity is greatly increased at the cost of a relatively small induction melting capacity,
(iii) steel of very low nitrogen content, as well as low carbon content, is produced, and
(iv) the recovery of chromium from converter slag is not necessary.

From extensive pilot-plant work, it is concluded that the single-stage reduction of 1,6/1 ratio Transvaal chromite fines with ferrosilicon can produce 50 to 55 per cent ELC ferrochromium (0,03 per cent maximum carbon) under present conditions (4th quarter, 1972):

(a) at a cost of R280 per tonne of contained chromium (on the basis of 45 kg of machine-cast, shot-blasted ingots f.o.r. the works site in the Witbank district, and of purchased, locally made 75 per cent ferrosilicon d.d. works site at R150 per tonne) or
(b) at a cost of R265 per tonne of contained chromium (on the same basis, but made with 75 per cent ferrosilicon produced in an integrated ferrosilicon plant at R130 per tonne).

The ferrosilicon-reduced ferrochromium is magnetic, and is easily handled and induction-melted in the steel plant. It has a significant advantage over standard grades of 68 to 72 per cent ELC ferrochromium in having a low enough melting range to permit economical machine casting into small (e.g., 40 kg) ingots that are of the right size for direct charging into the induction furnace by magnetic crane. Moreover, the high melting-point and superheating temperature required for the melting and handling of 68 to 72 per cent ELC ferrochromium demands a basic lining for the induction furnace, thereby causing great difficulty in operation. The ELC ferrochromium made by ferrosilicon reduction normally has a silicon content of about 0,5 to 1 per cent, and it can be melted without difficulty in the normal industrial design of silica-lined high-frequency or mains-frequency induction furnace.

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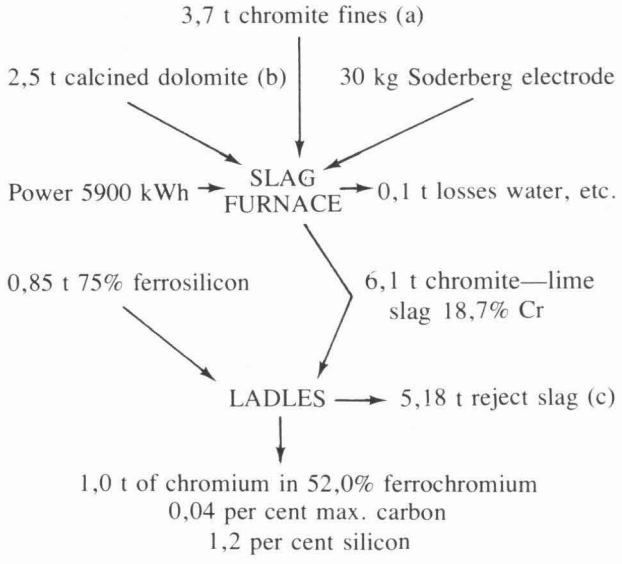
FLOWSHEET OF FERROSILICON-REDUCTION PROCESS

The quantitative flowsheet of Figure 1 is self-explanatory. It is based on pilot work undertaken by Rand Mines Ltd under the direction of the author at Driehoek, Transvaal, from 1960 to 1963, in which over 4000 tonnes of ELC (nominal 0,03 per cent maximum carbon content) ferrochromium was produced from 1,6/1 ratio Transvaal fines.

In this work, a 4t and a 7t Heroult arc furnace, a 20t ladle crane, and 5t ladles were used. The reducing agent was ferrosilicon having a silicon content of between 45 and 75 per cent and an aluminium content of between 2 and 13 per cent. Varying amounts of chromium were added to the ferrosilicon by the addition of revert ELC ferrochromium scrap and ordinary 6 per cent charge chromium to the charge fed to the pilot ferrosilicon furnace (3 MVA), so that the chromium content of the reducing agent varied from 0 to about 32 per cent. The 32 per cent chromium-bearing reducing agent was in actuality ferrosilicon—chromium made from 1,6/1 ratio chromite fines.

This pilot work showed that, in the Perrin two-stage process, extensive reoxidation of chromium occurs in the first stage of the Perrin reaction wherein hot chromite—lime slag reacts with the recycled second-stage partly reacted ferrosilicon—chromium having only about 20 to 25 per cent silicon but over 40 per cent chromium. This adverse factor is so marked in the Perrin two-stage reduction of 1,6/1 ratio chromite, which normally has about one-half of its iron in the ferric state, as to render the process unworkable on a competitive basis[2].

As a result of this pilot work, the author concluded that the single-stage reduction of 1,6/1 or 2,2/1 ratio fines (on the lines of Figure 1) with ferrosilicon (containing aluminium if desired, but specifically devoid of chromium or having less than about 10 per cent chromium) offered a means of reducing these low-grade ores, and also high-grade 3/1 ratio ores, on an industrial basis that is superior to the Perrin two-stage procedure and its modifications, ferrosilicon—chromium being used as reductant.



	%		%		%
(a) Cr_2O_3	45,4	(b) CaO	53,6	(c) SiO_2	30,4
Fe_2O_3	13,9	MgO	37,3	Al_2O_3	11,5
FeO	12,5	Al_2O_3	1,8	MgO	25,4
Al_2O_3	15,1	SiO_2	6,4	CaO	26,2
MgO	10,4			Cr_2O_3	4,0
SiO_2	1,7			FeO	1,2

Figure 1

Flowsheet for the single-stage reduction of chromium

The validity of this conclusion is shown by three large-scale reactions performed at the R.M.B. Alloys plant at Middelburg, Transvaal, on 20th August, 1965. In these reactions, 12 tonnes of chromite—lime slag from 1,6/1 ratio Transvaal fines was reacted with nominal 75 per cent commercial ferrosilicon produced by Ferrometals Ltd at Witbank (actual silicon contents 79,6 per cent), the results being as detailed in a previous publication[2]. The quantities given in Figure 1 are based on these reactions, as well as on the results of the extensive pilot-plant work at Driehoek.

Bobkhova[3] compared the single-stage reduction of chromite—lime slag (a) with that of 80 per cent ferrosilicon and (b) with standard grades of ferrosilicon—chromium.

In ten 5-tonne slag reactions with an average of 19,27 per cent chromium in the slag and an average of 80,57 per cent silicon in the ferrosilicon, Bobkhova records an average chromium yield of 85 per cent, a reject slag having an average of 3,41 per cent chromic oxide, and an average silicon consumption of 0,599 tonne per tonne of chromium reduced to ELC 68 to 72 per cent ferrochromium. This ferrochromium averaged 70,7 per cent chromium and was produced from *ca* 3/1 ratio ore.

When reducing the same slag with ferrosilicon—chromium, Bobkhova records that the reject slags averaged, over twenty 5-tonne reactions, 5,5 per cent chromic oxide, and the yield of chromium dropped to between 70 and 75 per cent.

Bobkhova's results with ferrosilicon completely confirm the quantities of Figure 1 for 1,6/1 ratio chromite.

An important aspect of the ferrosilicon single-stage reduction process is that the carbon content of 75 per cent ferrosilicon can be reduced to low levels by skimming and bottom pouring because of the low specific gravity of disilicon carbide (2,36). For this reason, it is considered that the production of ELC ferrochromium of carbon content less than 0,015 per cent is feasible by this process at a negligible increase in the cost of the chromium produced over that of the 0,03 per cent carbon alloy. Because of the high specific gravity of the chromium carbides present in the ferrosilicon—chromium used in the Perrin two-stage process for ELC ferrochromium (*ca* 6,8), the attainment of these low levels of carbon content by separation of the carbon from the ferrosilicon—chromium is both costly and difficult.

Owing to the basicity of the slag and the conditions of the ferrosilicon-reduction reaction, the sulphur and the phosphorus contents are both low. Sulphur contents approaching 1 p.p.m. have been found in successive runs in pilot-plant operation. The upper limit of phosphorus in the finished alloy is estimated as 0,02 per cent and that of sulphur as 0,01 per cent. These factors are of significance in chromium-steel production using this ELC ferrochromium, in comparison with AOD chromium-steel production using 4 to 6 per cent carbon ferrochromium made from pelletized chromite of high sulphur content (*ca* 1 per cent or more), which is costly and difficult to reduce to below 0,01 per cent in the finished steel.

A further factor of considerable significance in steelmaking with this ELC ferrochromium is that, with every tonne of chromium put into the steel from this alloy, there

is added to the refined converter metal 0,85 tonne of highly refined iron of very low carbon, nitrogen, phosphorus, and sulphur contents, and a minimum of oxides owing to the highly reducing conditions under which the alloy is made. In the cost estimates given in this paper, no credit is taken for this refined iron, although the benefit to the steelmaker is, under present conditions, of the order of R35 per tonne of chromium added to the steel by means of this alloy.

In the flowsheet of Figure 1, some or all of the ferrosilicon can be added to the slag furnace. Both the carbon content of the finished alloy and the loss of silicon by oxidation with water vapour from the calcined lime or dolomite flux both increase in direct proportion to the ferrosilicon so added. Reladling as in Figure 1 is, in any case, necessary to bring the reaction to completion.

RELADLING OPERATION

During the large-scale pilot work, there was considerable difficulty in causing cold-crushed ferrosilicon to react with the chromite—lime slag. If pregnant slag is poured onto crushed ferrosilicon lying in the bottom of the ladle, the slag freezes on the ferrosilicon without reacting. If crushed ferrosilicon is added to the slag after a charge of slag has been poured into the ladle, the slag freezes round the ferrosilicon without reacting. If molten ferrosilicon is poured into the reaction ladle at the same time as the chromite—lime slag, the reaction may become so hot that it causes excessive refractory wear. In practice, it is found that the reaction can be initiated easily and controlled effectively if the chromite—lime slag is poured into the reaction ladle while a stream of crushed ferrosilicon (100 per cent less than 2 cm) is run into the ladle by chute and shaking feeder simultaneously with the slag over the course of the slag pouring.

For maximum refractory life, any available scrap on-grade ferrochromium and, if necessary, machine-cast ingots are placed in the bottom of the reaction ladle to cool the reduced metal, and at the same time an amount of dry chromite fines replacing its own weight of chromite in the pregnant slag is run into the reaction ladle together with the ferrosilicon.

The contents of the reaction ladle are poured into a second ladle as soon as possible (usually within a few minutes) and, if necessary, from the second ladle to a third ladle before slag separation and machine casting of the metal and slag granulation. By adjustment of the amounts of either or both coolants added in this way, and by use of the ladles in rotation from reaction ladles to dummy and pouring ladles, it is possible to attain a build-up on the bottom and walls before the ladles are returned to reaction. Twelve ladles would normally be required to work one slag furnace, nine being reaction, dummy, and pouring ladles, and three being standby ladles. Provision is made for any ladle to be set aside for cooling and mandril lining with reject slag taken from the final pouring ladle before slag granulation.

A ladle designed for the reaction of 20 tonnes of pregnant slag from a 20 MVA Soderberg-electrode slag furnace (1 reaction per hour) containing, for example, 17,5 per cent of chromium would have a total hoisting mass approximately as follows:

	tonne
steelwork (ladle and bridle)	20,0
lining (a) magnesite	15,0
(b) superduty brick	7,5
chromite—lime slag	20,0
reducing agent	2,6
coolant (metal and chromite fines)	10,0
	75,1

The crane required for this duty would have a rated capacity of 80 tonnes, and the cross-shop travel and ladle pit would be designed to accommodate three ladles at each reaction.

During operation in this manner, the rated performance is 100 reactions per ladle before total relining.

ESTIMATE OF COSTS AND PROFITABILITY

The cost estimates set out in this paper are relevant to the fourth quarter of 1972. The present rates of inflation throughout the Western World appear to be likely to continue unchecked in the foreseeable future.

While it is manifestly impossible to set down a generally applicable statement of the cost of the operation and the profitability for the process shown in Figure 1, the following *pro forma* estimate of costs and profitability for the use of purchased 75 per cent ferrosilicon is submitted on the basis stated.

Plant site	Witbank district, eastern Transvaal
Main items of plant	1 x 20 MVA chromite—lime slag furnace 1 x 80 t ladle crane 12 reaction ladles 1 pig-caster 1 slag granulator
Rate of output	20 000 t of chromium per year as 50 to 55 per cent ELC (max. 0,03 per cent carbon).

It is assumed for the purpose in view that the ferrochromium plant would be sited on, or adjacent to, an existing ferrosilicon plant using mined-out colliery ground for slag dumping.

The estimated capital cost of this plant under present conditions is R3,0 million as set out in Table 1.

Table 1

Estimate of capital cost

	R(x 10^3)
1. Site preparation and fencing	35
2. Services, drainage, road culverts, earthworks	50
3. Internal transport, and railways, loco and rolling stock, internal motor vehicles	175
4. Weighbridge and loco-shed	25
5. Water supply	100
6. Materials handling: chromite fines and calcined dolomite	125
7. 20 MVA slag furnace incl. paste plant, plant housing, bins, conveyors, cranes, ladles, pig-caster, slag granulator, refractory shop .	1500
8. Ferrosilicon handling, crushing, and grading	30
9. Electrical equipment and housing e.h.t. substation, circuit breakers, l.t. transformers, switchboards, cables	250

10. Workshops, laboratory, store, office, canteen, change houses, garages, car shelter, first-aid	125	
11. Estate layout, slag disposal, sewage	125	
12. Staff housing: manager, resident engineer, superintendent, etc. ...	150	
13. Compound	100	
14. Preliminary and general, consulting fees	125	
15. Contingencies and sundry items .	85	R3,0 x 10^6

At the current cost of power, labour, and raw materials in the Witbank district, it is assumed for the purpose in view that lumpy, nominal 75 per cent ferrosilicon is delivered to the ferrochromium plant at R150 per tonne. This price is consistent with the present price for 75 per cent ferrosilicon f.o.b. European port of about R185 per tonne, allowing R35 for transport, dock charges, warehousing, c.i.f. charges, etc., and a selling price of R150 per tonne of lumpy naked f.o.r. works site.

Table 2

Estimate of production cost

	R/t Cr	R/t Cr
(i) materials		
3,7 t of chromite fines 1,6/1 ratio @ R7,5 d.d. works site	27,8	
0,85t of 75% ferrosilicon @ R150	127,5	
2,5 t of calcined dolomite @ R14 d.d. works site	35,0	
53 kg of magnesite refractories @ R115 d.d. works site	6,1	
30kg of Söderberg-electrode paste and casings @ R0,20 d.d. works site	6,0	
electric power 5900 kWh @ 0,45c	26,6	229,0
(ii) cost above materials		
labour and supervision	14,0	
maintenance labour	4,0	
maintenance stores	2,0	
works power	0,5	
internal transport and materials handling	0,8	
water supply	0,7	
refractories (superduty firebrick for ladle linings, tun-dishes etc.) @ R55/t d.d. works site, 22 kg	1,2	
pig-casting, shot-blasting, handling, weighing, loading, and records	2,5	
slag granulation and dumping ..	2,0	
general works charges and administration	2,7	
head-office charges	2,0	
sundry expenses including insurance, assessment rates, telephones, travelling costs, weighbridge maintenance, estate maintenance, patent licences, site rental (R20 000/year), entertainment, and other sundries	2,8	
depreciation, straight line and sinking fund R80 000/year	4,0	
interest on working capital (8% p.a. on R1,5 x 10^6) R120 000/year	6,0	
contingencies (R100 000/year) .	5,0	50,2
Total	R279,2	R279,2

say R280 per tonne of contained chromium.

If integrated with its ferrosilicon capacity whereby ferrosilicon would be available at about R130 per tonne delivered to the ferrochromium plant, the process could produce ELC ferrochromium on the basis quoted at a cost of the order of R265 per tonne of contained chromium.

The cost of labour and supervision for the single-stage process is in normal circumstances less than that of the Perrin two-stage process because of the inherent simplicity of the flowsheet (Figure 1) and its operation. The estimated total complement to operate the process at the rate of production of 20 000 tonnes per annum of contained chromium is 127, of whom 73 are unskilled workers. Under present conditions, the total wages amount to R414 000 per year, including holiday leave and long-leave allowance, accident insurance, medical aid, and provident-fund contributions.

Because of the lower melting range of the 50 to 55 per cent ELC ferrochromium, which is about equivalent to normal steelmaking temperatures (*ca* 1550 to 1600°C), the consumption of magnesite refractories is lower than that required in making a 68 to 72 per cent chromium alloy of melting range *ca* 1650 to 1750°C.

CONCLUSION

The advent of chromium steels containing 20 p.p.m. of carbon but devoid of nickel, which are competitive in properties with 18/10 chromium—nickel steel[4], is likely to lead to changes in stainless-steel production. The high proportion of stainless-steel scrap at present remelted essentially for its nickel and molybdenum contents may cease to be economical for the reason that straight 18 per cent chromium-steel scrap even now sells for very little more than the price of pig iron.

The AOD process is not developing as rapidly as expected, and demand for ELC ferrochromium has recently (mid-1973) been very strong, especially for the 0,05 per cent carbon grades[5]. Given the low-cost of 50 to 55 per cent ferrochromium described in this paper, a highly competitive route for ELC chromium steels, as such, or for conversion to 20 p.p.m. carbon steels, would be the decarburization of carbon-steel scrap and pig iron by the ordinary basic-oxygen furnace or by steam—oxygen converters and the alloying to specification with induction melting of ELC 50 to 55 per cent ferrochromium.

From the data presented in this brief paper, it is concluded that the reduction of chromite with ferrosilicon is a means, if not the only means, of producing ferrochromium, with an adequate return on capital, from the immense reserves of low-ratio chromites in the Transvaal and Rhodesia, in competition on the world markets with ferrochromium from other sources of chromite.

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In the presentation of his paper, **Dr Bleloch** said:

South Africa possesses reserves of chromite that have been competently estimated[1] at 18 000 million tonnes to a vertical depth of 1600 metres and that contain some 5000 million tonnes of chromium, but the production of ferrochromium in other countries is at present hindered neither by lack of plant nor by lack of reserves of chromite. In point of fact, the only advantages that South Africa has are low bulk power costs and the low mining costs of 1,6/1 chromite fines from seams outcropping with a thickness of about 1 metre[2].

It is precisely here that the ferrosilicon process outlined in the present paper presents an opportunity to produce and market ferrochromium from these immense reserves of low-ratio chromite fines. The object of the process is to make extra-low-carbon (ELC) 50 to 55 per cent ferrochromium from run-of-mine Transvaal and Rhodesian chromite fines. This alloy is intended for the production of chromium steels of very low nitrogen and carbon contents by the steam—oxygen and AOD converter processes using not more than about 10 per cent of chromium in the initial converter charge.

The argon—oxygen process is apparently difficult to operate with the chromium in the initial converter charge, over and above that added in scrap, all coming from high-carbon ferrochromium or charge chromium. This is reflected not only in the stable prices of ELC ferrochromium of 68 to 72 per cent chromium content but also in the development of several so-called vacuum oxygen decarburization (VOD) processes originally developed at Witten. Among these processes is prominent the decarburizing of chromium steel by the LD converter down to 0,6 to 0,8 cent carbon, at which level losses of chromium to the slag are minimal, followed by oxygen blowing in the RH vacuum degassing vessel, as developed by Nippon Steel[3] and the process recently patented by the V.O.S. in Linz[4].

The argon—oxygen process, if it is to avoid extensive use of low-carbon ferrochromium, must use high-carbon ferrochromium (or the more costly medium-carbon ferrochromium) in the initial converter charge, and must work with the full chromium content of 18 to 20 per cent in the initial converter charge. Because chromium contents above about 10 per cent in the initial converter charge greatly impede carbon removal, blowing times in the AOD process are as long as 1½ to 2½ hours.

For this reason, it is proposed in the text to melt chromium or carbon-steel scrap in the arc furnace to make a converter charge containing about 1 to 1,5 per cent silicon, 0,4 to 1 per cent carbon, and less than 10 per cent chromium to yield a blown metal of less than 8 per cent chromium and to operate the converter by the VLN steam—oxygen process developed by the Steel Company of Wales. Blowing times are thereby reduced to about 30 minutes, and the blown metal has nitrogen contents of the order of 0,001 per cent (10 p.p.m.) and carbon contents of about 0,01 per cent (100 p.p.m.). The chromium content of the steel is brought to specification by the addition of induction-melted 50 to 55 per cent ferrochromium to the metal.

This procedure has the following advantages:

(i) steam replaces argon,
(ii) converter capacity is greatly increased at the cost of a relatively small induction melting capacity,
(iii) steel of very low nitrogen content as well as low carbon content is produced, and
(iv) recovery of chromium from converter slag is unnecessary

The principles of this procedure are equally applicable to existing installations of the more expensive AOD process and the various vacuum degassing procedures modifying the original AOD. The procedure outlined in the text will utilize about 60 per cent of chromium-steel scrap in the initial converter charge in both the AOD procedure and the steam—oxygen process.

The ferrosilicon-reduced ferrochromium is magnetic, and is easily handled and induction melted in the steel plant. It has a significant advantage over standard grades of 68 to 72 per cent ELC ferrochromium in that it has a low enough melting range to permit economical casting into small (e.g., 40 kg) ingots that are of the right size for direct charging into the induction furnace by magnetic crane. Moreover, the high melting-point and superheating temperature required for melting and handling 68 to 72 per cent ELC ferrochromium demands a basic lining for the induction furnace, thereby causing great difficulty in operation. The ELC ferrochromium made by ferrosilicon reduction normally has a silicon content of about 0,5 to 1 per cent, and it can be melted without difficulty in the normal design of silica-lined high-frequency or mains-frequency induction furnace.

Owing to the low density (2,5) of disilicon carbide, skimming or bottom pouring of the 75 per cent ferrosilicon could bring the final carbon content down to less than 0,015 per cent at an insignificant increase of the cost of the chromium produced. The extremely low sulphur content of the ferrochromium reduced by ferrosilicon obviates the possible difficulty caused by the sulphur content of high-carbon and charge chromium made from pelletized ores.

The conclusions stated regarding induction melting of ferrosilicon-reduced 50 to 55 per cent ELC ferrochromium are based on fifteen 2-tonne induction melts and two 15-tonne arc-furnace melts all utilizing 50 per cent of 16 to 18 per cent chromium-steel scrap in the charge. The steel produced in all of these melts was on-grade standard ELC stainless steel.

Chromium yields obtainable by the ferrosilicon process have been calculated on the iron balance and on the percentage of chromium in the final alloy, allowing for the reduction of 97 per cent of the iron in the chromite and all of the iron in the ferrosilicon into the final alloy.

The chromium yields referred to in the text as having been established by reduction of chromite with ferrosilicon as well as ferrosilicon—chromium at the Serov plant are those recorded by the Serov administration itself.

The ferrosilicon process uses run-of-mine chromite fines without agglomeration or upgrading. It is inherently dependent on maintaining bulk power costs competitive with those of foreign countries, but in South Africa this seems assured in the short term at least. The *pro forma* costs of its operation set out in the text are based on the level of inflation existing in the third quarter of 1972. Higher levels of inflation have been reached since then, and the international monetary system has become disturbed. As stated in the text, it is therefore manifestly

impossible to set down a generally applicable statement of the cost of operation of the process and its profitability. The cost estimates have been put forward under some thirty headings, of which all but one are virtually common to any plant making any grade of ferrochromium. The single exception is the cost of purchased or integrally produced ferrosilicon. The estimates are intended for comparison with the capital and operating costs of plant for upgrading, pelletizing, submerged-arc-furnace reduction to high-carbon ferrochromium (with its inherently low yield of chromium), and converters or other apparatus for improving the chromium-to-carbon ratio.

South African high-carbon and charge chromium made from 1,6/1 chromite fines, or the so-called local 'lumpy-friable' ores, has a chromium-to-carbon ratio of the very low value of about 7/1 and is not always competitive either in price or quality with high-carbon chromium of chromium-to-carbon ratio of 12/1 or higher from other sources, which supplies the bulk of the world demand.

The South African industry is at present endeavouring to better this situation through ore upgrading by physical methods, chemical removal of iron from low-ratio chromites, pelletizing, and diminishing the carbon content of high-carbon ferrochromium made in the submerged-arc furnace in order to increase the chromium-to-carbon ratio. If South Africa is to compete in the sale of high-carbon ferrochromium made from its 1,6/1 chromite fines for use in the AOD and other chromium-steel processes against high-carbon ferrochromium from, or based on ore from, the U.S.S.R., Turkey, Albania, the Philippines, and, no doubt very soon, other sources including East Asia, its selling price must bear this upgrading and the low yield of chromium in the submerged-arc-furnace process. The yield of chromium in the submerged-arc process when high-carbon ferrochromium is made from South African chromites is correctly quoted by Urquhart[5] as being of the order of 70 to 75 per cent. As that author states, it happens in practice that, contrary to expectation, a 'ferrochromium that has a high carbon content goes hand in hand with a high chromic oxide content in the slag'.

Apart from all these considerations, the advent of 20 p.p.m.-carbon chromium steels devoid of nickel but competitive in properties with 18/10 chromium—nickel steel is likely to lead to changes in chromium-steel production. The high proportion of stainless-steel scrap remelted at present essentially for its nickel and molybdenum contents may cease to be economical for the reason that straight 18 per cent chromium-steel scrap even now sells for very little more than the price of pig iron.

Possibly owing to the necessary use of ELC 68 to 72 per cent ferrochromium, or to the necessary oxygen blowing under vacuum, or possibly to both of these causes, the AOD process is not developing as rapidly as expected and the demand for ELC ferrochromium was recently very strong, according to *Metals Week* (mid 1973).

From the data presented in this brief paper, it is concluded that the reduction of chromite with ferrosilicon is one means, if not the only means, of working to ferrochromium, with an adequate return on capital, the immense reserves of low-ratio chromites in the Transvaal and Rhodesia in competition on the world markets with ferrochromium from other sources of chromite.

I take this opportunity to state that the process described in the paper is covered by *S.A. Patent 68/2545*, and to thank Rand Mines Ltd for permission to publish the operational data of the text.

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DISCUSSION

Mr L.A. Kok:*

I agree with the process described but should like to contribute the following remarks on the economics of the process.

Our Company has had experience since 1962 in the production of low-carbon ferrochromium from Transvaal chromite fines, using, as a source of silicon, an alloy with a 55 per cent silicon content. The silicon is produced by a two-stage process using charge chromium as a first step. We also have experience in the production of charge chromium with a 52 per cent chromium content. Charge chromium is also produced from Transvaal chromite fines. Based on this experience are the following two remarks.

1. If the same installed MVA, to produce the 20 000 tonnes per annum of contained chromium by the method described in the paper, is utilized to produce charge chromium, it is conservatively estimated that approximately 40 000 tonnes of contained chromium can be produced per annum. The benefit of the higher output in absorbing fixed costs and therefore reducing the unit cost of chromium is obvious and needs no further explanation.
2. The at-works cost differential per pound of contained chromium for chromium produced as low-carbon ferrochromium and charge chromium is conservatively estimated at 10 to 12 U.S. cents per pound of chromium contained in favour of chromium produced as charge chromium. Considering the effect of the higher carbon content of charge chromium, maximum 7 per cent carbon as produced by our company, on the cost of steel production using the AOD or the VOD process, it is also conservatively estimated that the increased cost, for the purpose of comparison related to a pound of chromium contained, varies from 3 to 5 U.S. cents per pound of chromium. This differential tips the scale very obviously in favour of charge chromium as the source of chromium units for stainless-steel production.

Dr Bleloch:

The cost differentials quoted by Mr Kok refer to low-carbon ferrochromium made with silicochromium as reducing agent, which is itself made in a two-stage process from charge chromium. The use of silicochromium as reducing agent itself requires a two-stage reduction to low-carbon ferrochromium, entailing a large circulating load of partially processed metal, or clean-up of slags with ferrosilicon, or both of these. For these reasons, the cost differentials quoted by Mr Kok are entirely irrelevant to the single-stage ferrosilicon-reduction process described in the text.

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That submerged-arc reduction of chromite fines to high-carbon ferrochromium is at best an unsatisfactory operation has long been realized and is confirmed by the continued efforts in the industry to achieve some payable means of agglomeration of chromite fines for submerged-arc-furnace reduction to high-carbon ferrochromium.

Over and above the cost of the original ore before pelletizing, the cost of pelletizing and upgrading the chromium-to-carbon ratio by converter cannot be reasonably placed (as at the last quarter of 1972) at less than about R80 per tonne of chromium reduced from pelletized 1,6/1 ore into high-carbon ferrochromium by the submerged-arc process with its inherently low yield of chromium.

Per tonne of chromium reduced into the final alloy, the ferrosilicon process uses about 6000 kWh more than the submerged-arc high-carbon ferrochromium process, but it thereby effectively uses the only low-cost, high-grade, non-labour-intensive raw material with which we are really well endowed – cheap bulk power based on high-ash steam coal at shallow depths.

At 0,5 cent per kWh, this 6000 kWh is worth R30 per tonne of extra-low-carbon chromium reduced into ferrochromium, which pales into insignificance in comparison with the unit cost of reduced chromium incurred in pelletizing and chromium-to-carbon-ratio upgrading by converter in high-carbon ferrochromium production.

Mr W.D. Winship:*

It appears, from reading the conclusion in Dr Bleloch's paper, that it is possible to manufacture extra-low-carbon stainless steel of the order of 20 parts per million carbon and 10 parts per million nitrogen. Could Dr Bleloch explain how, with the equipment described, he would manufacture this extra-low-carbon stainless steel? I am of the opinion that only carbon levels of 200 p.p.m. and nitrogen levels of 150 p.p.m., at best, could be obtained.

Just a comment on the melting of low-carbon ferrochromium in induction furnaces:

from experience, difficulty with chromium oxidation and crust formation can be expected when low-carbon ferrochromium is melted in an induction furnace; Southern Cross has an AOD furnace installation, and no difficulty has been experienced in the removal of carbon, especially from ferritic steels.

Dr Bleloch:

Nowhere does my text claim to make 20 p.p.m. carbon steel. As stated on page 61 of the text, the carbon limit in my proposal is about 100 p.p.m. in blown metal before alloying. Nitrogen is recorded in the text as about 10 p.p.m., not 1 p.p.m. as stated by Mr Winship.

Hard crust on extra-low-carbon ferrochromium induction melted with basic refractories is possibly due to formation of $MgO.Cr_2O_3$. In my experience, there is no significant difficulty in melting 50 to 55 per cent extra-low-carbon ferrochromium in silica refractories.

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