The Chromothermic Reduction of Chromite

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SYNOPSIS

Chromothermic reduction is a new process for the utilization of ores and concentrates having low Cr/Fe ratios in the production of concentrates for low-carbon ferro-alloys, pure chromic oxide, chromium metal, or chemicals. The process is based on the use of chromium metal as a reducing agent in accordance with the exothermic reaction $3\,FeCr_2O_4 + 2\,Cr = 3\,Fe + 4\,Cr_2O_3$. With theoretically pure chromite, the metal used for complete iron reduction is 25 per cent of the metal content of the chromic oxide production. The practical ratio varies with the grade of the ore, the desired iron removal, and the needs of subsequent processing routes.

Reduction is selective, the chromium acting only on the iron oxide. The reaction is exothermic, and the products are free from carbon or other contaminants. Characteristics and variables of the processes of roasting and leaching are described on the basis of laboratory tests. Hazards such as reoxidation and loss of chromium in leaching are considered.

Iron may be partly reduced and leached to yield products with high Cr/Fe ratios. Alternatively, the complete reduction and leaching of iron may be used for the production of high-purity chromium chemicals. Roasting with 17,5 per cent Cr at 1100°C for a period of 40 minutes followed by leaching with 10 per cent sulphuric acid has permitted the extraction of 100 per cent of the iron from a South African chromite concentrate with Cr and Fe contents of 32,26 per cent and 20,50 per cent respectively. Impurities such as magnesia and alumina need to be removed from the leached product if high-purity chromic oxide is desired. A combination process is suggested, in which a part of a leached product is used in making a metallurgical-grade concentrate of high Cr/Fe ratio by blending with untreated material. The remainder of the leached product is high-purity chromic oxide.

A broad-brush products-and-costs balance for industrial production is projected by calculation from test results.

INTRODUCTION

The chromothermic reduction of chromite, based on the use of chromium metal as a reducing agent in accordance with the exothermic reaction $3\ FeCr_2O_4 + 2\ Cr = 3\ Fe + 4\ Cr_2O_3$, is a process of forming chromic oxide. With theoretically pure chromite, the metal content of the chromic oxide produced would be four times the quantity of metal addition used for the reaction. In practice, the ratio of metal oxide obtained to metal used varies with the composition of the chromite. The South African chromite concentrate used for this project has a chromium content of 32,26 per cent, and a chromium addition of 15,54 per cent is necessary for the reduction of the iron. In the industrial production of chromium metal from the oxide, recirculation of the metal used for the reduction could be envisaged.

The use of chromium metal as reducing agent has the following attractions:

(1) the reduction is selective, because chromium acts only on the iron oxide, whereas other reducing agents also attack the chromium oxide,

(2) the reduction is exothermic, and

(3) the product is free from carbon and is not otherwise contaminated by the reducing agent.

Impurities other than iron in the chromite are commonly present and remain in the product. This is no problem for ferro-alloy use, but, if high-purity chromic oxide is desired, additional processes of physical or chemical separation need to be employed. For example, magnesia and alumina may form several per cent of the chromite spinel crystals.

Of interest within the theme of this Congress is the potential application of chromothermic reduction in the utilization of low-grade chromite ores for metallurgical purposes. This arises from the respective shortage of metallurgical-grade ores with high chromium-to-iron ratios and the abundance of ores with low ratios.

Traditionally, ferrochromium with a chromium content of 70 per cent is most convenient for addition to steel and is derived from ores or concentrates having Cr/Fe ratios of 3 or higher. Ferrochromium with a chromium content above 70 per cent has an undesirably high melting-point. A lower chromium content necessitates more alloy per chromium unit, prolonging the heating time through cooling effects.

Conventional methods of beneficiation – gravity concentration, flotation, etc. – can all play their part in raising the metal content of low-grade ores, but they cannot change the Cr/Fe ratio, which is given by the composition of the chromite spinels. Structural dissociation of the spinels is a basic requirement for making the iron amenable to removal. This has been the subject of considerable research effort on the use of selective reduction of iron oxides and subsequent leaching of metallic iron. Reduction has been attempted mainly with solid carbon, but also with hydrogen, methane, carbon monoxide, and chlorine. Methods involving solid carbon are technically successful on a laboratory scale, but they involve the risks of carbide formation and of chromium losses.

Selective reduction of iron oxides with chromium metal may be applied to concentrates made by conventional methods. Roasting is followed by leaching with dilute sulphuric acid to give any desired Cr/Fe ratio. The efficiencies of roasting and leaching are influenced by various factors – temperature, residence time, physical characteristics of the material, and proportion of chromium addition.

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TEST MATERIAL AND PREPARATION

A South African chromite concentrate was kindly supplied by Union Corporation (U.K.) Ltd; it had the following chemical composition:

%	%	%
Fe 20,50	Mg 5,68	Cr_2O_3 47,15
Cr 32,26	Mn 0,11	
Al 7,88	Si 0,13	Cr/Fe ratio 1,57

The concentrate was ground to the following sieve-size distribution:

$-75+53$ μm	16,60%
$-53+45$ μm	10,30%
$-45+38$ μm	15,64%
-38μm	56,96%

Agglomeration of fine powders is generally desirable for solid-state reactions in roasting, because it promotes high rates of heat and mass transfers through high packing density and large areas of particle contact. This leads to good reaction rates at low temperatures.

In industrial practice, agglomeration by pelletizing would be appropriate, but, for laboratory use, briquetting is preferred for the following reasons:

(1) it provides highly reproducible samples with uniform physical properties,

(2) reproducible rates of heat and mass transfer are assured, and

(3) uncontrolled loss and waste of material during agglomeration are avoided, because individual briquettes can be made without the losses to drums and feeders normally associated with batch pelletizing.

Briquettes 15 mm in diameter and weighing approximately 4,2 g were prepared from a mixture of chromite concentrate and chromium metal powder, with a 25 per cent solution of sodium chloride as binding agent (5 per cent by mass of the mixture). They were formed in a cylindrical stainless-steel mould, using a hydraulic press at a ram load of 5 tons. The briquettes were dried in air for at least 48 hours before use, and they developed no cracks during drying.

ROASTING PROCEDURE

Firing was carried out in an electric furnace in a dense aluminous porcelain tube under controlled rates of heating and cooling. To ensure the correct completion of the process, oxidation during and after roasting must be prevented. Comparative leaching tests showed that a complete extraction of iron was obtained from samples roasted in enclosed boats, but up to 35 per cent of the iron remained in the samples roasted in the open air.

It was found that oxidation could not be prevented reliably by prior flushing of the furnace tube with argon followed by a continuous flow of argon during roasting. Roasting products free of any oxidation were finally obtained when the samples were enclosed in small cylindrical containers made of silica glass.

The rates of heating and cooling are not regarded as critical for the process and were chosen mainly for convenience and uniformity of procedure, as follows:

Heating sequence: After the sample had been held at 200°C for half a minute, a uniform heating rate of 10°C per second was applied up to the desired roasting temperature.

Cooling sequence: A uniform cooling rate of 10°C per second was applied down to 200°C. The sample was then held at that temperature for 10 minutes.

TEMPERATURE OF ROASTING

The influence of roasting temperature on reduction and on roasting time was investigated at 100°C intervals between 700°C and 1100°C. Each sample contained a chromium addition of 17,5 per cent and was roasted for 1 hour. Figure 1 shows that 1050°C is the minimum temperature at which total reduction of the iron is possible within that time. Below 1050°C, increasingly longer periods of roasting are necessary. Although reaction occurs at temperatures as low as 500 or 600°C, it is too slow for any practical purpose.

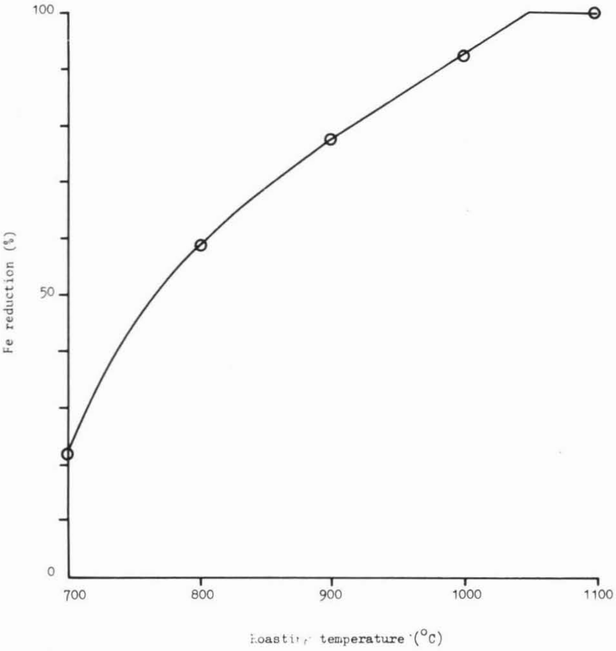

Figure 1

Roasting temperature versus percentage iron (for 60 minutes of roasting)

ROASTING PERIOD

The time required for completion of the reaction depends on the roasting temperature and the amount of chromium metal added. Tests carried out with varying percentages of chromium at 1100°C show that the roasting period is increased with increasing additions of metal up to 16,5 per cent (Figure 2), there being a sharp drop in time at larger chromium additions. For example, a roasting period of 105 minutes is necessary with a chromium addition of 16,5 per cent, but with 17,5 per cent chromium the roasting time is down to 40 minutes. The decrease in roasting period through addition of excess chromium practically ceases with additions beyond about 17,5 per cent. The excess chromium metal remains unreacted and is lost during leaching.

Similar proportional savings in the roasting period apply to the partial reduction of iron. For example, interpolation in Figure 3 shows that, for each additional 1 per cent of chromium metal up to a maximum of 2,5 per cent, the roasting period is reduced by about 30 per cent for the same iron reduction as is obtained with a chromium addition of 7,5 per cent.

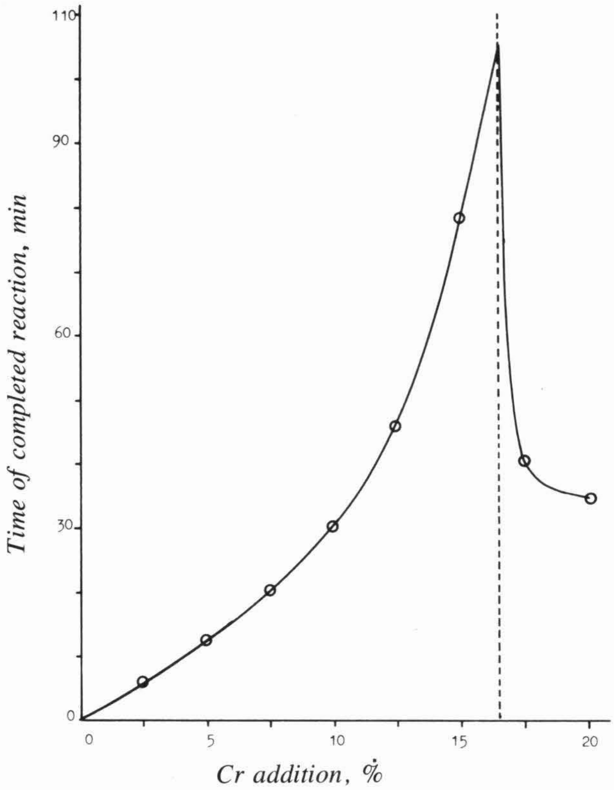

Figure 2
Percentage chromium addition versus time of completed reaction

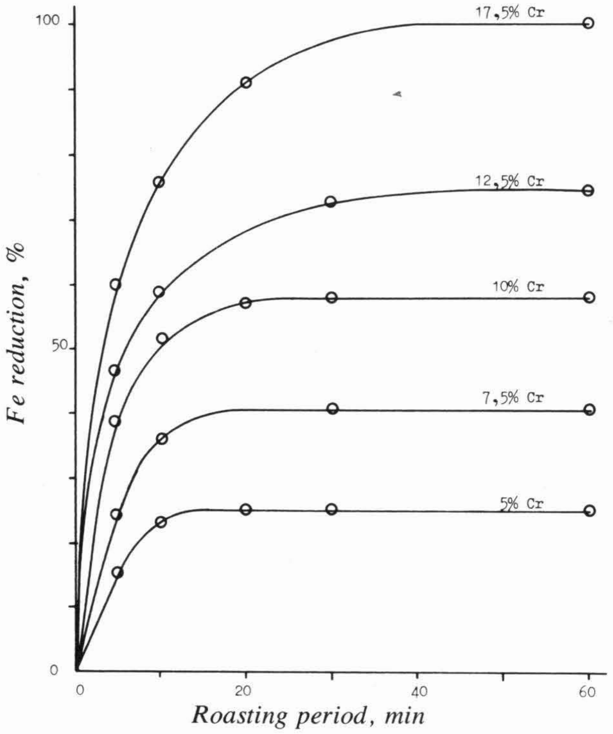

Figure 3
Roasting period versus percentage iron (for various chromium additions)

RATE OF REACTION

The relevant reaction rate is defined as the rate at which a given percentage of iron reduction is attained. It depends on

(1) the temperature of roasting,
(2) the percentage addition of chromium metal,
(3) the length of residence time at the roasting temperature, and
(4) the packing density of the sample.

Table 1 shows that an increase in temperature raises the reaction rate. An increase in chromium addition causes the reaction rate to rise during the initial stages (Table 2), but, over the whole period of roasting, a decrease is followed by an increase, with a minimum at an addition of chromium metal of 16,5 per cent.

Table 1
Roasting temperature versus rate of iron reduction

Roasting temperature °C	Average Fe reduction per minute (during 60 minutes of roasting) %
700	0,36
750	0,77
800	0,99
850	1,14
900	1,29
950	1,43
1000	1,56
1050	1,66

Table 2
Percentage chromium addition versus rate of iron reduction

Cr addition %	Average Fe reduction per minute, %	
	During the first 5 minutes	Over the period of completed reaction
2,5	2,1	1,98
5,0	3,3	1,98
7,5	4,9	1,97
10,0	8,2	1,92
12,5	10,2	1,63
15,0	11,2	1,17
16,5	11,7	0,71
17,5	12,6	2,50
20,0	14,1	2,86

As reaction proceeds, the rate changes continuously, giving a characteristic graph of time against percentage iron reduction, which rises rapidly from zero time, then flattens, and approaches maximum reduction asymptotically (Figure 3).

The packing density of the sample determines the total area of contact between particles in a briquette. The number of points of contact may be increased by a reduction in the particle size and by an increase in the packing density through greater compaction. For example, tests under identical conditions showed 43,8 per cent reduction for an uncompacted powder and 100 per cent reduction for the same material in briquetted form.

Tests were carried out with briquettes of varying compaction, each with chromium additions of 20 per cent and each being roasted at 1100°C for 10 minutes. Increasing pressing loads up to 1 ton were found to raise the iron reduction. Thereafter, no significant improvement could be observed, and it is assumed that the given mixture attained maximum compaction at a load of 1 ton (566 kg/cm^2 pressure).

METAL OXIDATION DURING ROASTING

The oxidation of iron and chromium was assessed under various conditions, by means of precise mass comparison before and after roasting. Separate heating of iron and chromium metal powders to 1100°C in air for 45 minutes produced mass increases of 9,5 and 11,7 per cent respectively. On the assumption of the formation of FeO and Cr_2O_3, these gains represent 35 per cent oxidation of iron and 25 per cent oxidation of chromium. Similar treatment of briquetted and powder samples, prepared for chromothermic reduction with a chromium addition of 17,5 per cent, produced mass increases of 2,07 and 3,35 per cent respectively. If it is assumed that the chromium metal in a compact briquette is wholly surrounded by grains of chromite, oxidation in a briquette can be taken as being confined mainly to iron. On the other hand, oxidation in powder samples is likely to affect mainly chromium metal that is partly exposed to air. No mass changes occur when samples are roasted in sealed boats.

CHROMIUM METAL REQUIREMENTS FOR REDUCTION

The complete reduction of iron in pure $FeO.Cr_2O_3$ would require a theoretical chromium content of 15,47 per cent by mass, in accordance with the reaction $3\,FeO.Cr_2O_3 + 2\,Cr = 3\,Fe + 4\,Cr_2O_3$. However, natural chromite spinels can contain iron in various forms, such as $FeO.Al_2O_3$, $FeO.Fe_2O_3$, and $MgO.Fe_2O_3$. Hence, the amount of chromium necessary for the reduction of the iron may vary from ore to ore according to the types and proportions of the iron compounds present. The necessary amount of chromium needs to be determined experimentally for any given ore.

Normally, an excess of chromium is necessary to compensate for imperfect admixture in the feed and also to ensure high reaction rates with short roasting periods. However, the addition of excess metal needs to be restricted because unreacted chromium is usually lost in leaching. For industrial use, a financial balance would have to be sought between the benefits of high reduction rates, attainable through excess chromium, and the associated metal losses. For metallurgical purposes, the choice of chromium addition needs to be based mainly on the Cr/Fe ratio of the feed and that of the desired product.

With the chromite concentrate used for this work, varying chromium additions in the range 2,5 to 20 per cent were used in an examination of their influence on maximum iron extraction, new Cr/Fe ratio attained, roasting period, and chromium losses during leaching.

THE INFLUENCE OF CHROMIUM ADDITION ON MAXIMUM IRON REDUCTION

Briquetted samples containing chromium additions of 2,5, 5,0, 7,5, 10,0, 12,5, 15,0, 17,5, and 20 per cent were roasted at 1100°C and were then analysed to determine the extent of iron reduction. This yielded a straight-line relation (Figure 4) between the percentage of chromium added and the percentage of iron reduced. Maximum reduction with any given addition of chromium can be obtained only from completed reactions. This completion requires different minimum roasting periods with different percentages of chromium.

According to Figure 4, total reduction of iron is obtained with a chromium addition of 16,5 per cent. At this addition, a chromium loss of 5,8 per cent occurs during leaching. If it were assumed that this loss represents unreacted chromium metal, it would appear that 100 per cent iron reduction in this ore could be achieved with a chromium addition of 15,54 per cent.

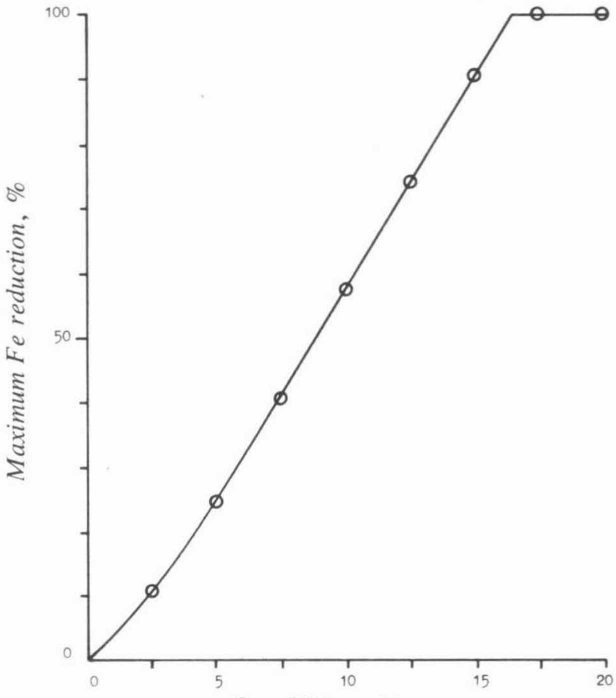

Figure 4

Percentage chromium addition versus maximum percentage iron reduction

EXTRACTION OF IRON BY LEACHING

Dilute sulphuric acid (10 per cent) was used for leaching because it is well known to be effective for metallic iron, and its industrial use is well established. The leaching rate increases with decreasing pulp density owing to the larger volume of leaching agent per unit volume of solids. Theoretically, 10 per cent sulphuric acid is required in the following quantities:

9,54 cm^3/g of iron for conversion to $FeSO_4$,

14,30 cm^3/g of iron for conversion to $Fe_2(SO_4)_3$, and

15,36 cm^3/g of chromium for conversion to $Cr_2(SO_4)_3$.

With a chromium addition of 17,5 per cent, the maximum amount of metal going into solution is 0,1895 g per gram of sample, comprising 0,1727 g of iron and 0,0168 g of chromium if one assumes a chromium loss of 2 per cent during leaching. Hence, theoretically 2,73 cm^3 of 10 per cent H_2SO_4 per gram of sample should be sufficient. In practice, some 7 to 10 times the theoretical quantity is necessary, and, in this project, approximately 23 cm^3 of 10 per cent H_2SO_4 was used per gram of sample. Except for investigation of the leaching characteristics of briquettes, all leaching was carried out with finely ground samples so as to obtain high rates.

TEMPERATURE OF LEACHING

Leaching rates, measured as the rate of metal extraction, were observed at room temperature and 60°C with briquetted samples. At 60°C, the dissolution of iron proceeds at a high rate during the early stages, diminishes rapidly, and reaches completion in a short period (Figures 5 and 7). At room temperature, the dissolution of iron proceeds more slowly at first and, after extraction of about 60 per cent of the iron, proceeds at decreasing rates and extends over long periods. Similar conclusions apply to the dissolution of chromium metal (Figures 6 and 10). The progressive decrease in the leaching rate is taken to be due to the increasing concentration of the metals in the solution and the decreasing supplies of undissolved metal and leaching agent.

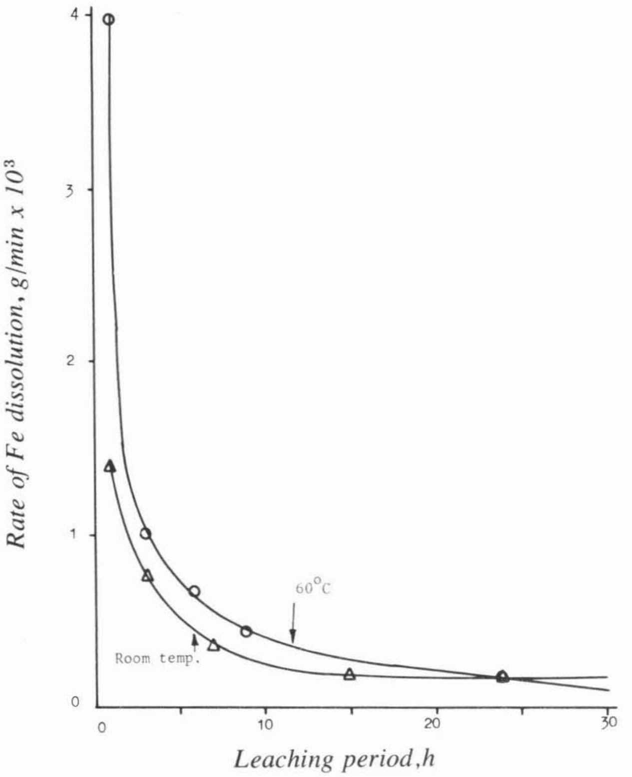

Figure 5
Rate of iron dissolution versus leaching period (in briquetted samples)

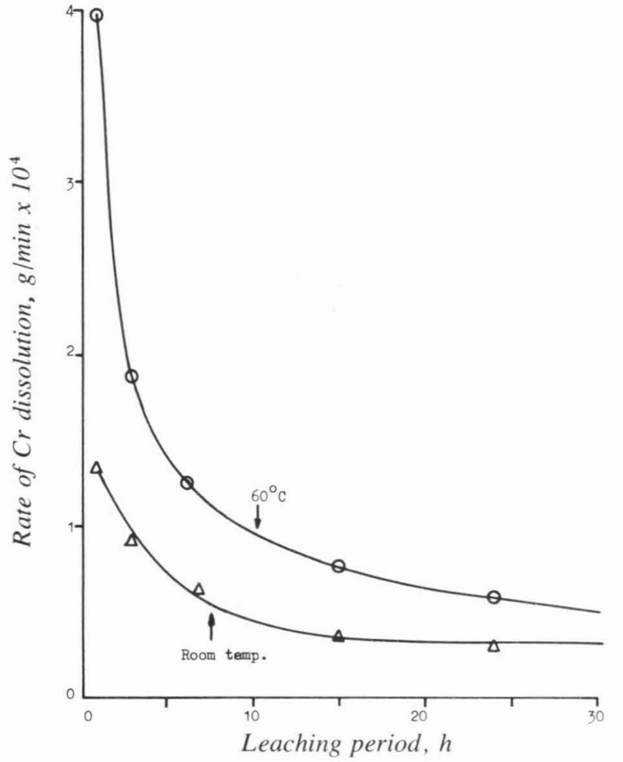

Figure 6
Rate of chromium dissolution versus leaching period (in briquetted samples)

LEACHING PERIOD

The length of time needed for extraction of the reduced iron depends upon the leaching temperature and the physical condition of the sample. At 60°C, the leaching of iron from completely reduced samples requires a maximum of 30 minutes with powdered material and up to 40 hours with briquettes (Figure 7). Briquettes are extremely compact after roasting; so the leaching agent reaches the interior mainly through pores produced by the removal of metal. At room temperatures of leaching, powdered samples require a minimum of 2½ hours and briquettes need about 5 days for complete removal of the reduced iron.

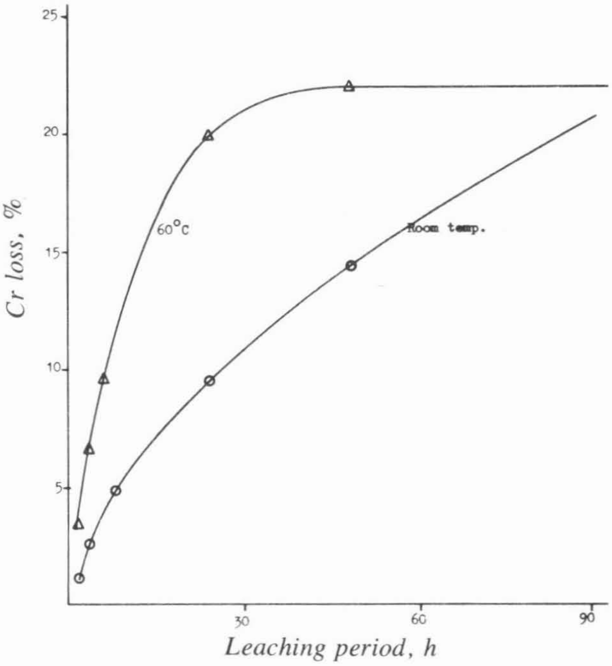

Figure 7
Leaching period versus percentage iron extraction (in briquetted samples)

The greater part of the total leaching period is taken by the late stages of iron removal. For example, when briquettes are leached at 60°C, iron extraction of about 80 per cent is attained in the first quarter of the total leaching period. Extraction of 94 per cent of the iron takes 50 per cent of the total time, an equal period being needed for removal of the remaining 6 per cent of the iron. These observations apply to samples roasted for complete reduction of the iron. Samples roasted for partial reduction need progressively shorter periods of leaching for extraction of the reduced iron.

RELATION BETWEEN CHROMIUM ADDITION AND NEW CR/FE RATIO

The tests on iron reduction were used to calculate the new Cr/Fe ratios resulting from roasting and leaching. A plot of chromium additions against new Cr/Fe ratios meets the ordinate at 1,57, the original Cr/Fe ratio of this concentrate, and becomes asymptotic to a vertical axis at a chromium addition of 16,5 per cent (Figure 8). The graph indicates the necessary metal addition for obtaining any desired Cr/Fe ratio with the ore. For example, a chromium addition of 6,8 per cent would yield a Cr/Fe ratio of 3.

RELATION BETWEEN CHROMIUM ADDITION AND CHROMIUM LOSSES IN LEACHING

The chromium loss attributable to unreacted metal was negligible for additions up to about 12,5 per cent, good mixing being important in this respect. At a chromium addition of 16,5 per cent, the loss is 5,8 per cent, and losses rise rapidly for higher additions (Figure 9). A comparison of Figures 7 and 10 shows that complete dissolution of leachable chromium takes place within the period needed for iron dissolution at 60°C.

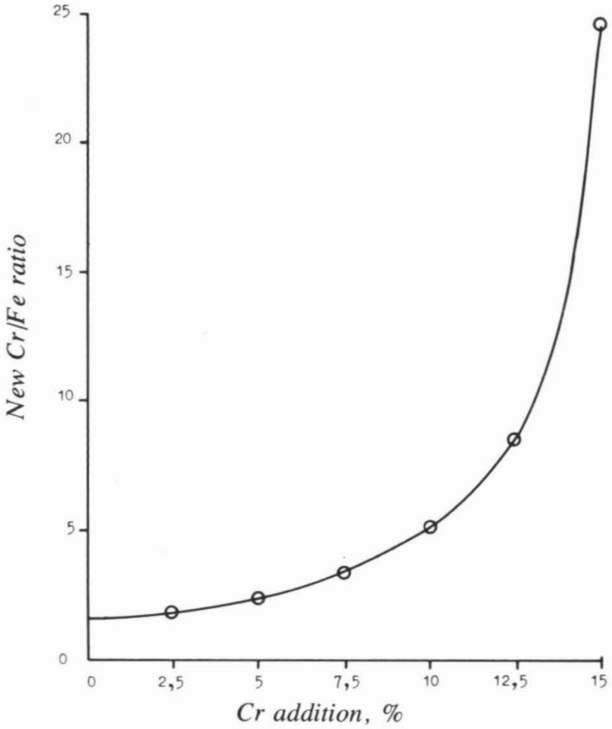

Figure 8
Percentage chromium addition versus new Cr/Fe ratio attained

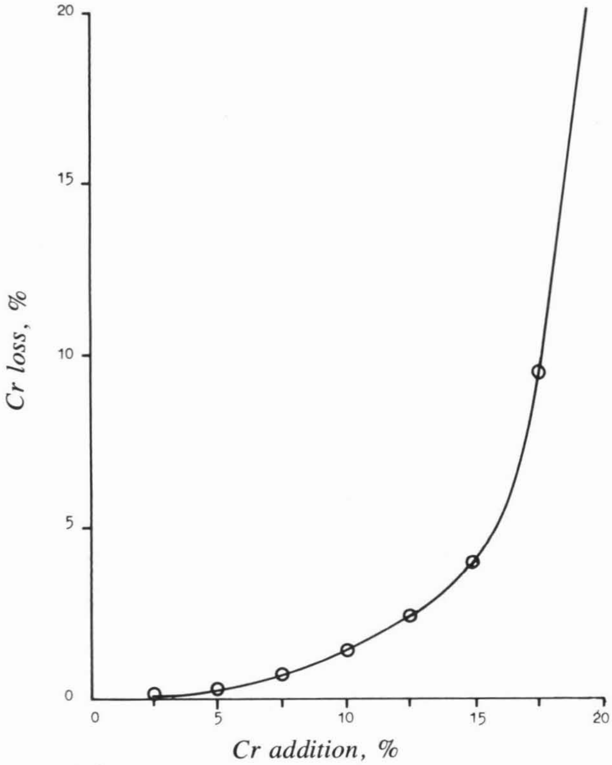

Figure 9
Percentage chromium addition versus average percentage chromium loss during leaching (in terms of chromium added)

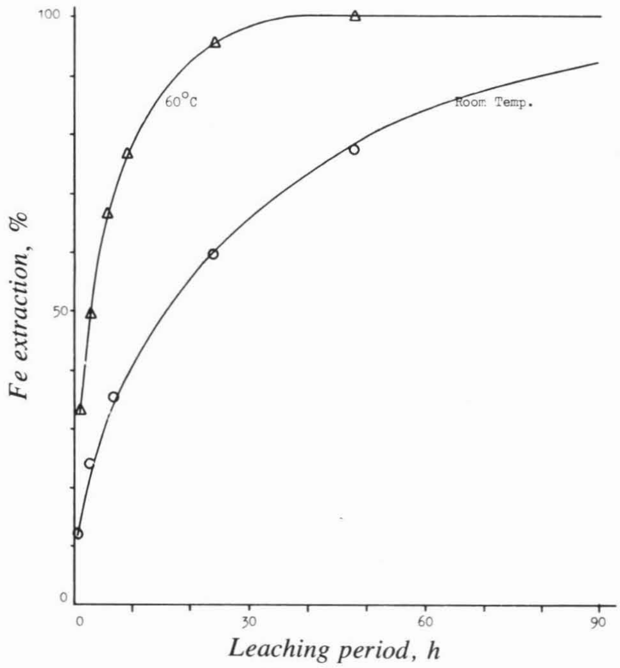

Figure 10
Leaching period versus percentage chromium loss in briquetted samples (in terms of chromium added)

BLENDING FOR PRODUCT GRADE

The cost of the process is affected very little by the attained Cr/Fe ratio, the main additional cost for higher ratios being in the additional amount of chromium metal needed. It is suggested that overall processing costs could be reduced by treating only part of a product to a high Cr/Fe ratio and blending this with untreated concentrate. Figure 11 shows the amount of untreated concentrate that could be blended with a unit of treated product, as a function of percentage chromium addition. The relation is represented by the expression $T=0{,}1773\ R-1{,}2056$, where $T=$ the blending ratio (untreated/treated material) and $R=$ the percentage chromium addition. For example,

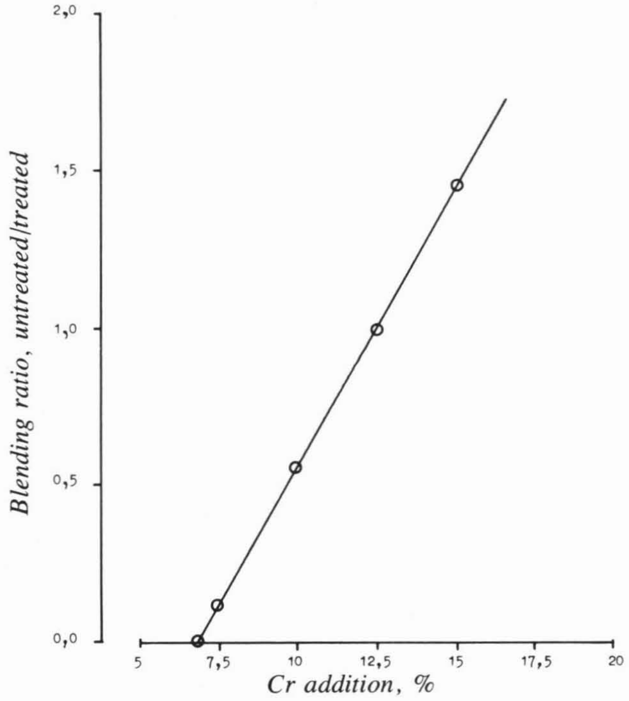

Figure 11
Blending for a Cr/Fe ratio of 3

with a chromium addition of 12,5 per cent, blending can be in the ratio 1:1, thus reducing the cost of treatment per unit mass by approximately 50 per cent.

PRODUCTION OF HIGH-PURITY CHROMIC OXIDE

The production of chromic oxide of high purity after reduction and leaching depends on the successful removal of the remaining impurities, such as magnesia and alumina. These oxides form part of the original spinel structure and are thus very finely disseminated through the leached concentrate.

Only very casual tests of removal have been carried out with conventional physical methods such as wet magnetic separation and elutriation. Recoveries of the order of 55 per cent of pure chromic oxide appear to be realistically obtainable. Tentative trials with further acid leaching have yielded about 80 per cent recovery of a product assaying 99,3 per cent Cr_2O_3. Clearly, the process technology of final cleaning is important and needs systematic investigation, but recovery of about 50 per cent of the contained chromium as a high-purity oxide seems a feasible projection.

INDUSTRIAL PROSPECTS

The above considerations lead to a possible industrial application of the chromothermic reduction of chemical-grade concentrates for the combined production of chromic oxide and of metallurgical concentrates with a high Cr/Fe ratio for low-carbon ferrochromium. It is beyond the scope of this paper to attempt a detailed economic analysis, but a broad-brush assessment provides the following picture, using prices of U.S. $25 per long ton for chemical-grade concentrates and $50 per long ton for metallurgical concentrates. It is further assumed that the chromium metal used for reduction is charged at $1,30 per lb, the price of electrolytic chromium.

Product	Cr %	Fe %	Cr lb wt	Fe lb wt	Cost 'price' U.S.$
2240 lb of chemical-grade concentrate	32,26	20,50	722,62	459,20	25,00
Add 15,5% Cr metal	100,00	—	347,20	—	451,36 ($1,30 per lb)
2587,20 lb of roasted product			1069,82	459,20	
Removal by leaching of 4 per cent of Cr added and 98 per cent of Fe in feed:					
2121,95 lb of leached product	49,75	0,37	1055,73	7,84	476,36

The entire treatment costs (roasting + leaching + pure-oxide separation) are assumed as $12 per long ton of feed, and this is charged to the pure-oxide product.

Two cases are now considered: separation of 50 per cent or of 65 per cent of the chromium in the leached product as pure oxide, the remainder to be blended with untreated chemical-grade concentrate to make a mixture of metallurgical grade.

50% separation

Product	Cr %	Fe %	Cr lb wt	Fe lb wt	Cost 'price' U.S. $
1350,45 lb for blending	39,08	0,58	527,87	7,84	30,14 ($50/t)
771,50 lb of pure Cr_2O_3	68,42	—	527,86	—	446,22 + 12,00
			=$0,594/lb of Cr_2O_3 =$0,866/lb of Cr		
or *65% separation* 1120,00 lb for blending	33,05	0,70	370,20	7,84	25,00 ($50/t)
1001,95 lb of pure Cr_2O_3	68,42	—	685,33	—	451,36 + 12,00
			=$0,462/lb of Cr_2O_3 =$0,675/lb of Cr		

Blending from the 50% oxide separation

Product	*Cr* %	*Fe* %	Cost 'price' U.S. $
1350,45 lb of treated conc.	39,08	0,58	$30,14 ($50/t)
1350,45 lb of untreated conc.	32,26	20,50	$15,07 ($25/t)
2700,90 lb of mixture	35,67	10,53	$45,21 =$37,49/long ton
Cr/Fe ratio 3,38			

Blending from the 65% oxide separation

1120 lb of treated conc.	33,05	0,70	$25,00 ($50/t)
1120 lb of untreated conc.	32,26	20,50	$12,50 ($50/t)
2240 lb of mixture	32,65	10,60	$37,50/ ton
Cr/Fe ratio, 3,08			

ACKNOWLEDGEMENTS

This project forms part of the work carried out by T. Yalcin for the degree of Ph.D. of the University of London. He gratefully acknowledges financial assistance by Union Corporation Ltd. A patent covering the process has been assigned to that company.

In presenting his paper, **Dr Cohen** paid particular tribute to the fundamental work done by his co-author, Dr T. Yalcin.

Dr Cohen went on to outline briefly the background and reasons that prompted the undertaking of this particular research. In doing so, he remarked upon his early association with the chromium-ore mining and processing industry in Rhodesia. In this respect he enumerated the many difficulties experienced by this industry, such as its segmented nature, selective mining techniques, unsophisticated mineral-processing techniques, and vast distances that the ore has to be transported. His opinion was that these factors led to a low recovery of chromium ore, and, in many instances, much of the ore was lost for future use.

Dr Cohen was complimentary of the evident use of low-grade ores and stressed the need for this in the future. He stated that this need had, in fact, precipitated early work on the production of chromium-ore pellets, using carbothermic reduction, during the early sixties. This was terminated when it became evident that , at that time, the industry required mainly low-carbon, and not high-carbon, ferrochromium. He and his colleagues had then redirected their efforts towards this requirement. Despite the recent reversal in this trend and the development of processes for the efficient use of high-carbon ferrochromium in the production of stainless steel, they continued their line of research. Dr Cohen gave, as reasons for this, the time delay in motivating fundamental research and his opinion that the industry might, in the future, once again reverse its needs and require more low-carbon ferrochromium.

He stated that the most efficient means of utilizing low-grade ores, in his opinion, was by producing a concentrate. Such a concentrate would require agglomeration for use in producing a ferro-alloy and could most effectively be done by pelletizing. In considering the production of a chromium-ore pellet, Dr Cohen outlined the more conventional techniques such as the use of no binder or a dilute inorganic salt and the use of both high-carbon and low-carbon additives to the pellet, giving varying degrees of reduction of iron or both iron and chromium.

The concept of producing a chromium-ore pellet containing chromium metal as a selective reducing agent had come out of this research. This had the attraction of providing an exothermic reducing agent, which caused no dilution or contamination. The end product was attractive in that, after leaching, it could produce a chromium oxide product of increased chromium-to-iron ratio. Dr Cohen stressed that the paper presented a concept approached from a fundamental point of view and that, despite indications of the economics of such a process in the paper, these were speculative. He would welcome comment on the thoughts put forward.

DISCUSSION

Question from the audience:

What is the efficient use of energy in the utilization of chromium metal to reduce iron oxide?

Dr Cohen :

The total production cost of $12 per ton of feed does not include grinding costs, which will be considerable. This will be a cost incurred in producing the concentrate. However, I agree that the costs indicated could be regarded as low and therefore controversial.

Question from the audience .

Is the use of a dilute inorganic-salt solution in producing a pellet satisfactory?

Dr Cohen :

Yes, when the pellet dries, the salt is concentrated at points of contact between particles and in this manner will eventually 'cement' particles together at these points. In this way a very small amount of salt can effectively act as an efficient binder in producing a pellet. Furthermore, pellets containing metallic chromium require a lower firing temperature than the carbothermic types, and display final pellet strengths equivalent to those of iron-ore pellets.

Dr A.M. Edwards :*

Dr Cohen's paper provides another interesting contribution to the vast amount of work that was undertaken in the past with a view to improving the Cr/Fe ratio of low-grade chromite ores.

I should doubt the viability of a process that utilizes chromium metal for the purpose of reducing the iron oxide to metal followed by acid leaching of the iron from the ground product. However, we must appreciate that this has been a very thorough, academic approach to the subject. The usefulness of such an academic approach is that one is provided with a basis on which to formulate further ideas. The one that immediately comes to mind is that, possibly, chromium metal could be replaced by charge chromium as the reducing agent. By so doing, one would be using a much cheaper chromium unit to satisfy the chemistry. I should visualize that the charge chromium would result, after roasting, in an alloy phase with a chromium content of 20 per cent and an improved Cr/Fe ratio in the residual chromite product. This would mean that the reaction need not be taken to completion.

This could be followed, after grinding, by magnetic separation, to produce a 20 per cent chromium alloy and, say, a feed stock with a Cr/Fe ratio of 3:1 for subsequent ferrochromium production. The 20 per cent chromium alloy could also, then, be turned to profitable account after smelting, to produce a chromium steel.

During the roasting stage, by retaining a reasonable percentage of chromium in the iron-rich product, one would possibly not have to resort to stringent steps to prevent reoxidation of the iron, since the chromium present would provide a resistance to reoxidation.

I must stress that this is only a concept that resulted from my reading of Dr Cohen's paper. The viability of such a scheme would depend on a careful economic assessment.

Present trends seem to be towards an acceptance of lower-ratio chromium alloys, where the overriding factor is the unit price of the chromium in preference to the Cr/Fe ratio of the alloy. It has often been mentioned that low-ratio chromium alloys offer the steel producer free iron units. In view of the current high prices of iron scrap, this will be a significant factor to be borne in mind in the future.

Returning to Dr Cohen's paper, I get the impression that the extreme selectivity of chromium metal for iron oxides during reduction could offer distinct benefits in the analytical sense. It has always been difficult, and therefore rather empirical, to determine the proportions of FeO and Fe_2O_3 in chromites. By use of chromium metal it may well be possible not only to determine the overall iron content, but in addition, the proportions of both these iron oxides.

Thank you for this interesting paper.

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