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An Evaluation of Process Alternatives for the Reclamation of Ferrochromium from Slag

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The increasing pressure on the profit margins of ferrochromium producers has stimulated research-and-development departments to look for cheaper production processes and alternative sources of ferrochromium.

Samancor identified existing slag dumps at its Ferrometals and Tubatse works as possible sources of relatively cheap ferrochromium. The dumps were shown to contain significant quantities of ferrochromium, and a study was initiated to evaluate alternative means of reclaiming the alloy from the slag. The following separation techniques were evaluated: jigging, magnetic separation, flotation, tabling, spiralling, and dense-medium separation.

The prerequisite for the study was to recover as much of the metal as possible from the slag dump in a directly saleable form. The recovery requirement was satisfied by a number of processes, but the product requirement was satisfied only by jigging and, with some particle-size ranges, by magnetic separation. The products of flotation, tabling, or spiralling did not conform to any of the set requirements. The best overall results were achieved with jigging.

Introduction

The significant potential of slag dumps as a source of ferrochromium had, until recently, not been fully realized. With ever-increasing production costs and the concomitant shrinking of profit margins, ferrochromium producers have been investigating cheaper alternatives for the manufacture of ferrochromium[1-3]. The reclamation of metal from slag certainly falls within the scope of such projects, as shown by the following information.

The dumps at Samancor's Ferrometals and Tubatse plants are estimated to contain about 10 and 4 Mt of slag respectively. Conservative estimates put the metal content at between 3 and 4 per cent, which is equivalent to between 420 and 560 kt of ferrochromium. This is roughly equivalent to a full year's production at current capacity, and can be recovered at a cost significantly lower than by use of the conventional production process. Clearly, these dumps are a source of ferrochromium that deserves careful consideration in the long-term strategy of the company. The main aim of the present investigation was the evaluation of alternative options for the recovery of ferrochromium from the dumps.

Various techniques are available[4] to separate particles with different properties in a solid mixture. The choice depends on the physicochemical nature of the solids, and on site-specific considerations (e.g. wet versus dry methods). A key consideration is the extent of liberation of the individual particles to be separated.

Because of the nature of the alloy contained in ferrochromium slag (typically, entrained droplets of varying sizes), liberation is a function of particle size. Liberation is rarely complete in any one size fraction, and a physical-separation flowsheet might incorporate a sequence of operations that often are designed first to reject as much unwanted material as possible at a coarse size, and subsequently to recover the valuables after size reduction.

In general, differences in density, size, shape, colour, and electrical and magnetic properties are used in successful commercial separation processes. The particle-size range of the mixture is an important factor in determining the techniques that can be practically applied. A guide to the selection of the generally used separation method is given in Figure 1.

A number of separation techniques are already employed at various ferrochromium plants in South Africa, as well as in other parts of the world. Jigging is used at both the Ferrometals and the Tubatse works, and magnetic separation at the CMI works (Lydenburg) and at Middelburg Steel & Alloys (MS&A). Dense-medium separation (DMS) was used at Hellenic Ferro Alloys in Greece and the CMI works at Rustenburg (formerly Purity Chrome).

The degree of success obtained in the different processes is closely related to the properties of the slag treated. A process that is successful at a specific plant would not necessarily be as successful at other plants. The following example is used by way of illustration. Certain slags (containing high concentrations of chromium and iron

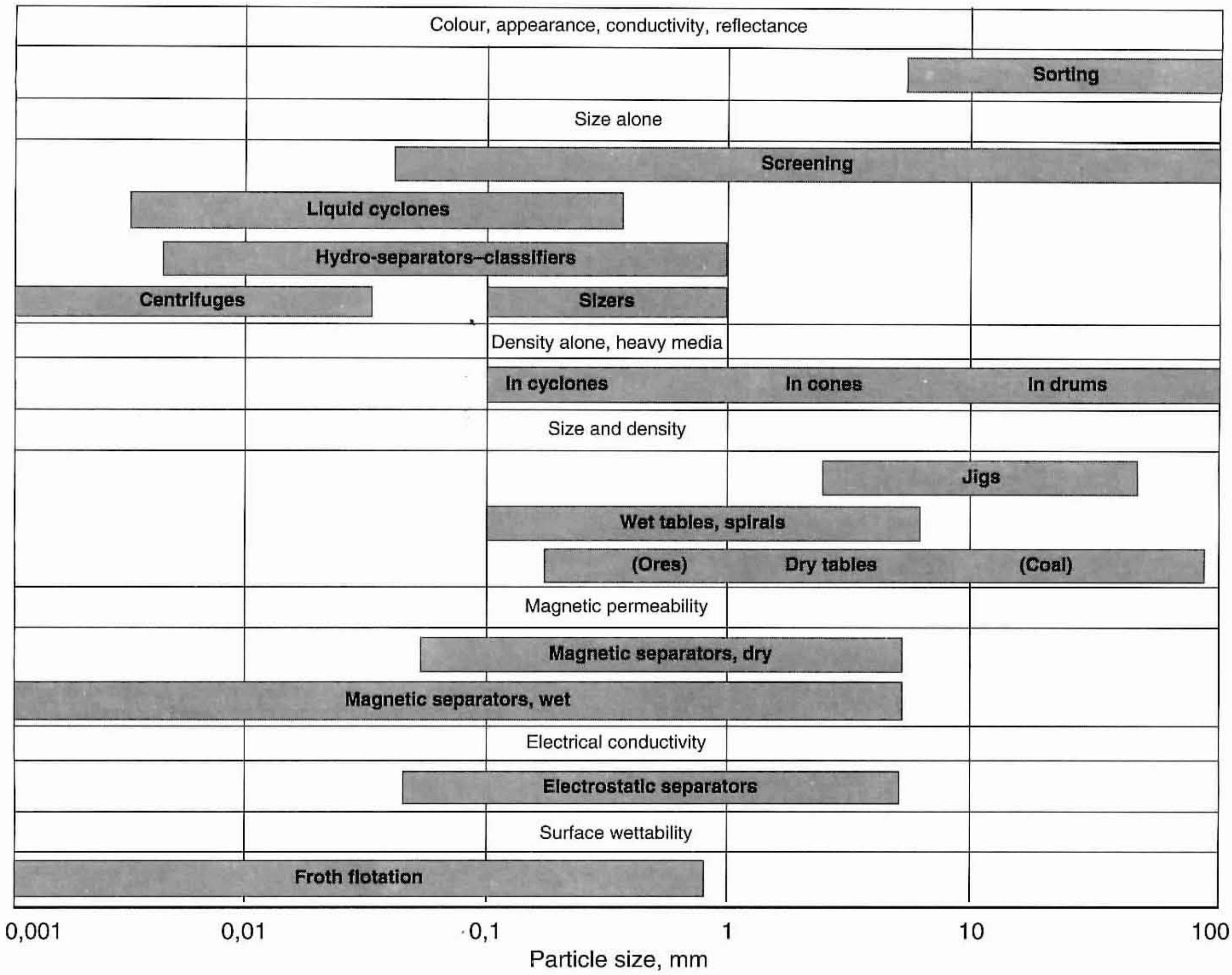

FIGURE 1. Particle size as a guide to the range of applications of various solid–solid separation techniques (after Roberts *et al.*[5])

oxides) do not lend themselves to effective separation by magnetic techniques owing to the magnetic characteristics of the slag itself. Good recoveries may be achieved, but the product quality is generally poor. However, slags with low levels of chromium and iron oxides, such as those from the Showa Denko process, do lend themselves to effective alloy reclamation by magnetic techniques.

In order to process the existing slag dumps at Ferrometals and Tubatse over a reasonable period, a recovery plant with a feed capacity of 150 to 200 t/h would have to be built. Since this constitutes a sizeable investment, it was decided to re-evaluate the various reclamation processes and determine whether in-house technology could be improved on.

Three distinct problems were identified with the process employed at Ferrometals:

(i) the recovery of alloy was not acceptable (85 per cent)

(ii) although the product quality of the coarser fraction was good, the fine product was not directly saleable

(iii) the throughput rates of the jigs were low.

A number of basic preconditions were set to focus the investigation. These included the following.

(a) The product must be recovered in a saleable form (less than 3 per cent slag).

(b) The maximum economic reclamation of alloy from the dump must be obtained (recovery in excess of 95 per cent).

During the early stages of the investigation it became apparent that the coarse product could be recovered successfully in a saleable form by more than one process. The decision was then made to reclaim all the coarse material using jigging technology, since it was relatively cheap and Samancor had extensive experience in that field. The project was therefore aimed primarily at the evaluation of reclamation processes for the finer fraction, which was a problem both in terms of recovery and product quality. The low throughput rates of the existing jigs were – as mentioned in the previous paragraph – a problem, and alternative jigging technologies were investigated in order to find a more efficient jig than that employed at either Ferrometals or Tubatse.

Process Evaluation

The main purpose of the process-evaluation phase was to evaluate as many recovery techniques as possible, and to screen the results and so identify the most promising alternatives. In cases where pilot and industrial plants were available, tests were run on these units. These plants were designed to produce material in specific particle-size ranges, which were not changed for this investigation.

Development of Analytical Techniques

So that the efficiency of recovery of the various processes could be evaluated, reliable techniques for the analysis of metallic (recoverable) alloy in the slag, as well as slag in the finer product, were essential.

An acid-leaching technique (similar to that used for the analysis of metallic chromium in the Showa Denko process) was used for determining the concentration of alloy in the slag. This method was not very accurate at high concentrations of alloy. In these cases, X-ray fluorescence (XRF) analysis, based on the components present in the slag (but not the alloy), was used. Figure 2 shows the accuracy of the acid-leaching method, and Figure 3 the accuracy of the determination of the slag contamination in alloy-rich mixtures.

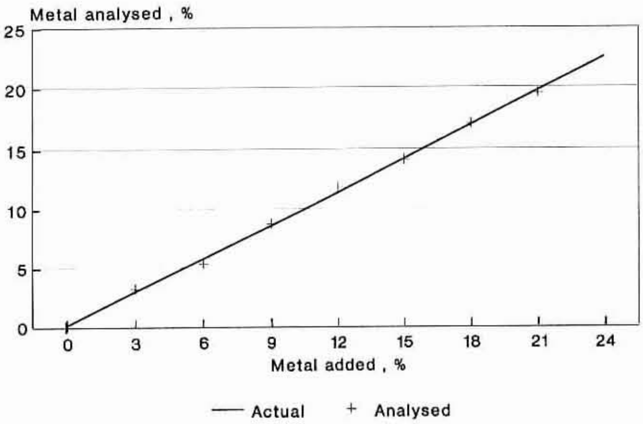

FIGURE 2. Accuracy of metal analysis

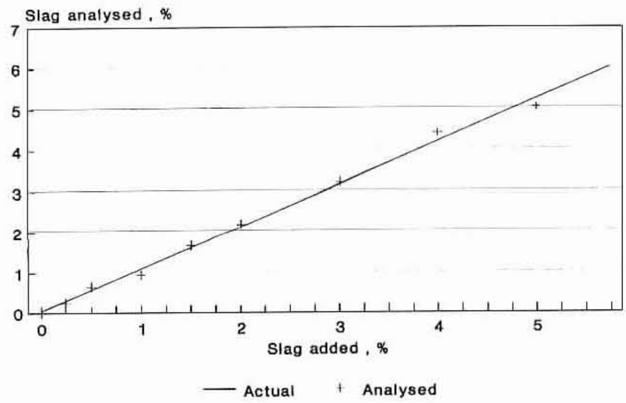

FIGURE 3. Degree of slag contamination

Characterization of Slag-dump Material

To obtain a better understanding of the slag composition and structure, samples of the material from the slag dumps at Ferrometals were subjected to mineralogical analysis by X-ray diffraction (XRD), reflected-light microscopy, and scanning electron microscopy (SEM).

XRD showed that the major component was a slag phase (pyroxenitic in nature, i.e. an SiO_3^{2-} type of silicate), with at least one phase having a spinel structure, and a metallic phase.

A slag phase containing two types of spinel and a metallic phase were clearly visible under the petrographic microscope. The metal phase occurred in two forms:

(a) as small inclusions in slag, and

(b) as large free grains up to 600 μm in size.

'Locked' metal particles were generally smaller than 30 μm.

SEM revealed that the small metal inclusions consisted of iron and chromium, the iron content being much greater than the chromium content. In a few inclusions, the chromium content exceeded that of iron. Large free fragments of metals consisted of either iron and subordinate chromium, or chromium and subordinate iron, or a mixture of the two types. When the chromium content of the ferrochromium particle exceeded the iron content, a trace of silicon was usually also present. Metal particles in the slag were usually surrounded by a chromium–iron spinel that contained minor concentrations of magnesium and aluminium. Similar results have been reported previously[6].

Jigging

Samples from the Ferrometals slag dumps were pre-crushed to smaller than 19 mm. (Experience gained from the operation of a jigging plant at Ferrometals has shown that a good degree of liberation is obtained at that particle-size range.) This material was then processed on two different jigs, both of which were 'over-the-bed' types, one being a Denver-type jig (a two-compartment all-steel diaphragm-actuated jig, comprising a rougher and a cleaner stage), and the other a Wemco–Remer type jig (using a slow, long stroke with a secondary motion, with a superimposed shorter stroke of higher-frequency motion).

For the test on the Denver jig at Ferrometals recovery plant, pre-crushed slag was split into –19+3 mm and –3 mm size fractions, the different samples being treated separately. In both instances, the –1,5 mm product was drawn through the hutch.

For the test on the Wemco–Remer type of jig (carried out on a pilot-scale plant), the –19 mm material was split into –19+7 mm and –7 mm fractions. When the coarse particles were treated, –2 mm material was drawn through the hutch while, for the test on the finer particles, the screen size was changed to 1 mm and a –1 mm fraction was drawn through the hutch. Because of the success achieved with the processing of the fine fraction, it was decided to process on this jig the –3 mm material generated during the preparation of the feedstock for the Denver-type jig.

Material from the Tubatse slag dump was pre-crushed to –15 mm. The –0,5 mm material was screened out, and the –15+0,5 mm fraction was processed on an industrial jigging plant, employing a 'through-the-bed' type of jig. The top size was determined by the experience gained from the Ferrometals operation for the liberation of alloy from slag, as well as by the punch plate and ragging available on the specific jig.

Magnetic Separation

Samples from the slag dumps at both Ferrometals and Tubatse were treated on a pilot-scale plant using a wet magnetic-separation technique. The slag was crushed, and alloy was recovered in the size fractions –50+25 mm, –25+13 mm, –13+1 mm, and –1 mm.

Samples of slag from the Tubatse plant were treated on an industrial dry magnetic-separation plant. Metal was reclaimed in the following size fractions: +50 mm, –50+25 mm, and –25+3 mm. The –3 mm fraction was treated by a laboratory unit that uses an uplift system of separation against gravity.

Samples from the Ferrometals dump were pre-screened into –3+1 mm and –1+0,3 mm size fractions. Magnetic separation was carried out using a coarse dry-lift roll magnet in conjunction with a low-powered hand magnet in a laboratory.

Dense-medium Separation[7]

Material from the Tubatse slag dump was pre-crushed to –12 mm. The –3 mm size fraction was screened out, and the –12+3 mm fraction was treated on an industrial dense-medium separation facility at one of Samancor's chromite mines. Two tests were conducted using different media densities. For the first trial, ferrosilicon was used at a relative density of 3,3. During the second run, the density was increased to 3,6.

Flotation

The –0,3 mm fraction was screened out of material from the Ferrometals slag dump. Froth flotation was carried out on this material using a 4-litre flotation cell and a Denver laboratory flotation machine running at 1500 r/min. The following conditions were varied:

- attritioning
- desliming
- amount and type of frother
- amount and type of froth modifier
- amount and type of collector
- amount of depressant.

Tabling

From pre-crushed slag from the Ferrometals dump, the –3+1 mm, –1+0,3 mm, and –0,3 mm size fractions were screened out. These materials were fed to a pilot-scale James table. Concentrate, middlings, and tailings were recovered.

Spiralling

Samples of the –3 mm fraction of ferrochromium slag (pre-crushed for treatment in a jig plant) were processed on a pilot-scale spiral separator. The separator consisted of a rougher and a cleaner stage, with the middlings being recycled.

Results and Discussion

Table I gives a summary of the results obtaining during the course of the investigation.

TABLE I
SUMMARY OF TEST RESULTS

Process type	Process employed	Scale	Product size mm	Metal in product %	Metal recovered %	Product saleable
Jigging	Denver	Industrial	19 x 5	97,3	88,1	Yes
	Wemco–Remer	Pilot	19 x 7	98,7	>95	Yes
			7 x 1	97,6		
			–1	97,8		
	Through bed	Industrial	15 x 0,5	96,0	85,0	Yes
Magnetic separation	Wet	Pilot	50 x 13	>95,0	>97	Yes
			–1	70		No
	Dry	Industrial	75 x 3	85,0	>95	No
		Industrial	–3	76,0		
	Dry roll	Laboratory	3 x 1	77,0	98	No
Dense-medium separation	Density 3,3	Industrial	12 x 0,3	26,9	>97	No
	Density 3,6	Industrial	12 x 0,3	28,3	>97	No
Flotation	Different conditions	Laboratory	–0,3	32,6	26,7	No
		Laboratory	–0,3	45,8	60,2	No
		Laboratory	–0,3	49,7	83,0	No
		Laboratory	–0,3	51,7	46,0	No
		Laboratory	–0,3	34,8	39,0	No
		Laboratory	–0,3	48,7	66,8	No
		Laboratory	–0,3	48,1	73,5	No
Tabling	James table	Laboratory	3 x 1	No separation achieved		
		Laboratory	1 x 0,3	45,9	34,6	No
		Laboratory	–0,3	81,0	55,4	No
Spiralling		Pilot	–3	36,0	61,7	No

Jigging

The results from the Denver-type jig, as well as the 'through-the-bed' jig, indicated that a directly saleable product could be recovered from the +3 mm size fraction. The –3 mm fraction was less promising; however, it was thought that, with suitable changes to the plant, the product quality of the finer material could be improved. The recoveries on these plants were also substandard, mainly because the jigs were not able to cope with the fluctuating concentration of alloy in the feed material. It was thought that this would be a problem with any jigging process, and a method had therefore to be developed to ensure good recovery.

This method has a scientific origin, but was developed rather empirically at Ferrometals. It employs a float system that is located in the jig bed at the interface of the alloy-rich layer and the slag layer. The float moves vertically up and down as the thickness of the metal bed fluctuates due to changes in the alloy content of the feedstock. (The float system is shown schematically in Figure 4.) The position of the float was used for process control.

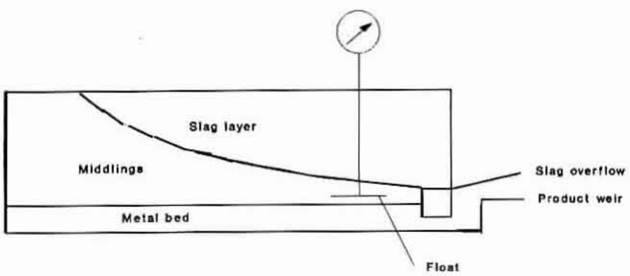

FIGURE 4. Schematic diagram showing the position of the float in the jig bed

The jigging process was normally controlled by actions such as adjustments to the height of the product-overflow weir, the feed rate, or water pressure, etc. Experience has shown that the adjustment of the product-overflow weir was normally the only adjustment needed because of the strong relationship between metal losses in the tailings and the degree of contamination of the final product (Figure 5).

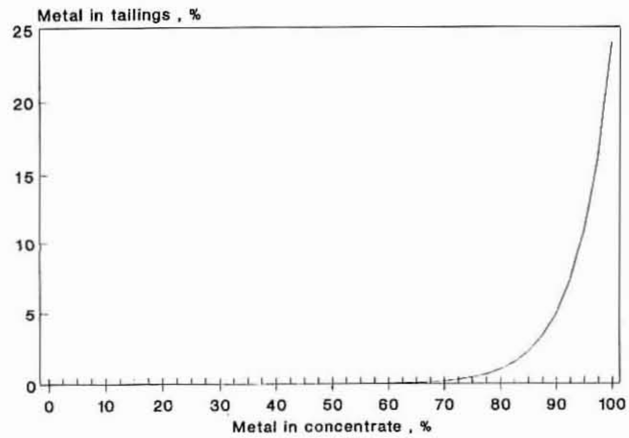

FIGURE 5. Relationship between stream compositions

Jigging in the Wemco–Remer type of jig produced saleable products in all the product sizes. In these tests, all the products contained less than 2,5 per cent slag and were directly saleable. It was also apparent that this type of jig was relatively insensitive to changes in the metal concentration of the feed-stock.

Magnetic Separation

Certain magnetic-separation techniques provided saleable alloy in the larger particle-size ranges. The process employed at the pilot plant gave the best results; however, it had two specific disadvantages. Product sizes larger than 13 mm had to be hand-picked to get a saleable product, and all the recovered product less than 13 mm diameter had to be milled to increase the degree of liberation before it could be concentrated further. This material would have to be remelted so that the alloy could be reclaimed. Further developmental work on this process is continuing, and recent preliminary results appear very promising.

The plant tests gave high alloy recoveries, but the product was not directly saleable in any particle-size range. The results from the laboratory work using magnetic-separation techniques were similar to the results obtained in the plant test.

The reason for the high degree of contamination can be explained in terms of the nature of the feed material. The metallic inclusions, consisting largely of reduced iron, were responsible for the magnetic properties of the slag particles, and reported as a magnetic product. (This also explains why the –13 mm fraction reclaimed during the pilot-plant runs had to be milled before significant concentration could be reached.)

Dense-medium Separation

Dense-medium separation recovered more than 97 per cent of the alloy, but not in a directly saleable grade (Table I). Two distinct problems were experienced: no fine material could be handled in the process, and high losses of ferrosilicon were experienced as a result of slag porosity.

Conclusions

In general, all the processes aimed primarily at the treatment of the fine size fraction (–5 mm), i.e. flotation, tabling, and spiralling, gave disappointing results, with low alloy recoveries and high degrees of slag contamination (Figure 6).

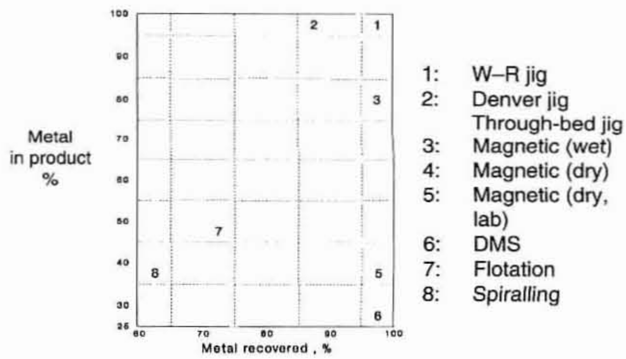

FIGURE 6. Comparison of separation techniques

The processes evaluated can be divided into two main groups: those which produced directly saleable alloy and those which did not.

Of the first group, the processes that were gravity based (jigging) gave the best results. When the different jigging processes were rated, the Wemco-Remer type of jig was at the top of the list – it produced saleable alloy in all size ranges and treated material at a rate that was an order of magnitude greater than any of the other jigs.

Of the processes that did not produce directly saleable alloy, the magnetic process employed in the pilot plant was considered to be the best, producing a saleable product on some particle-size ranges (after a degree of hand-picking) and concentrating the rest of the alloy to 70 per cent.

It was therefore recommended that Samancor utilize Wemco–Remer jigging technology for the reclamation of metal from the slag dumps.

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References

1. Senga, T., *et al.* (1989). The reduction of ferrochromium by the smelting reduction with top and bottom blowing converter. *Proceedings of the 5th International Ferro Alloys Congress, INFACON 89, New Orleans.* pp. 69–79.
2. Hoffman, W., Vlajcic, T., and Rath, G. (1989). The rotary hearth furnace direct reduction process. *Ibid.*, pp. 185–195.
3. Basson, J. (1985). Development of Krupp technology for producing ferrochromium. Samancor Internal Report (series of five).
4. Perry, R.H., and Green, D.W. *Perry's chemical engineers' handbook,* 6th edn, eds. W.M. Goldberger *et al.* McGraw-Hill Book Company, New York. Section 21, pp. 21-1–21-55.
5. Roberts, E.J., Stavenger, P., Bowersox, J.P., Walton, A.K., and Mehta, M. (1971). Solid/solid separations. *Chem . Eng. (Deskbook Issue),* Feb. 15, pp. 89–98.
6. Slatter, D., and Ford, M. (1989). Reactions and phase relationships in a DC arc plasma furnace producing ferrochromium. *Proceedings of the 5th International Ferro Alloys Congress, INFACON 89, New Orleans.* pp. 103–111.
7. Apostolides, G.A. (1986). Industrial application of dense media separation for recovery of FeCr entrained in slag and discarding slag admixed with ferrochromium fines. *Proceedings of the 4th International Ferro Alloys Congress, INFACON 86, Rio de Janeiro.* pp. 157–160.