The Rotary Hearth Furnace Direct Reduction Process - a coal-based route to substitute electrical energy in ferro-alloy production

W. Hofmann, T. Vlajcic and G. Rath
Mannesmann Demag Hüttentechnik

Introduction

The original Inmetco process for the recovery of metallic materials from waste oxides can look back on 10 years successful operation (1-6). The Inmetco process reduces the metal oxides on a rotary hearth with coal as a reductant and melts the sponge metal in a follow-on submerged arc furnace.

The underlying technical and economic concept which led to the development of this process was to carry out as much of the energy-intensive reduction work as possible outside the electric smelting equipment in a direct reduction plant using economical primary energy in the form of coal.

Since there is considerable world-wide demand in the iron and ferro-alloy producing industries for processes using cost-saving fuels and reductants, i.e. in most cases non-coking coal, the applicability of the Inmetco process was first of all successfully tested in large-scale tests for iron ore (7, 8).

The substitution of expensive electric energy by cheap primary energy using a coal-based direct reduction unit is, however, of particular economic significance for the energy-intensive production of ferro-alloys.

During the last two years the original Inmetco process has been further developed. Chromium and manganese ores can now be preheated and pre-reduced to high metallization levels in the rotary hearth furnace using coal as reductant and energy supply. The modified smelting process in the SAF thus requires only a fraction of the electric power needed in conventional processing.

In the following the rotary hearth process will be introduced and it will be reported on the reduction of chromium and manganese oxides as well as on the technology for the smelting of highly metallized feed material for the production of ferro-chromium and ferro-manganese.

Principle of the rotary hearth process

Mannesmann Demag obtained the sole licensing rights for the world-wide marketing of the rotary-hearth process. This process was developed by International Metals Reclamation Company Inc. (Inmetco), a subsidiary of the Canadian INCO Group. Since 1978 INMETCO has been operating a plant with a capacity of 80.000 tons/year of sponge iron made from waste products and iron ores in Ellwood City, Pa., USA.

The core element is the rotary hearth furnace.

Fig. 1 shows the rotary hearth furnace in Ellwood City.

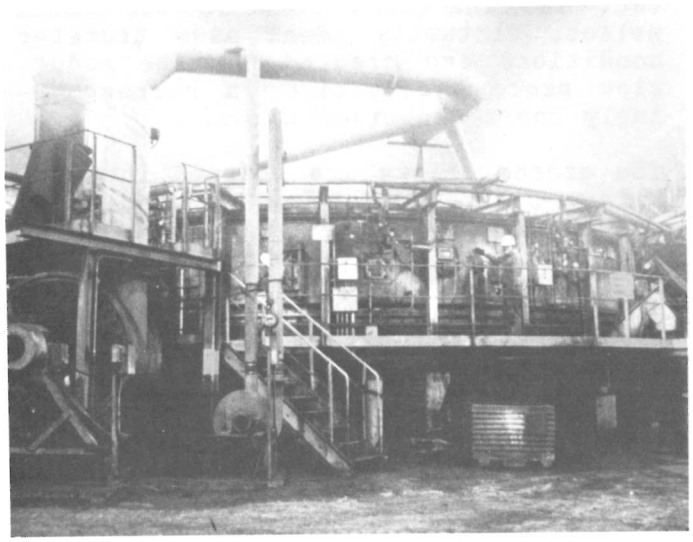

Fig. 1: Rotary Hearth Furnace

Figs. 2 and 3 show schematic cross-sections of such a furnace.

In the furnace, green pellets made from fine sized oxides and coal or coke as reductants are reduced to a highly metallized product with energy supplied by the combustion of coal, gas or oil.

Coal is mixed together with oxides and pelletized into self-reducible green pellets. The carbon content of these green pellets can be set to meet the

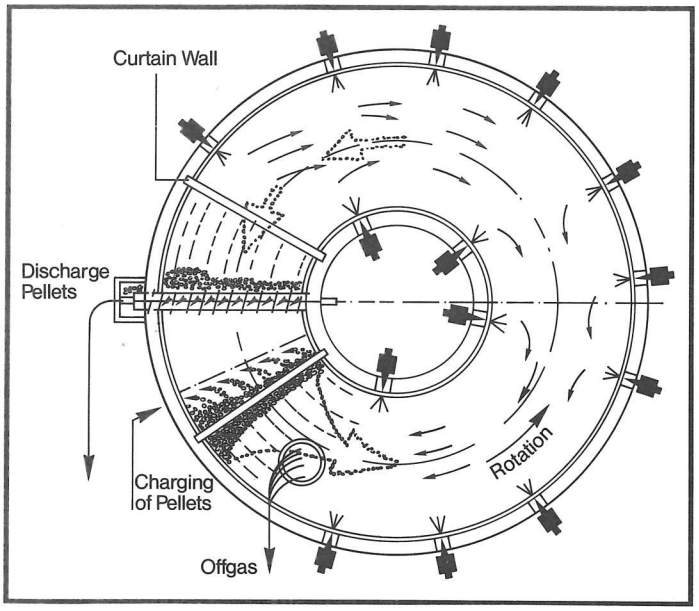

Fig. 2: Rotary Hearth Furnace (cross-section)

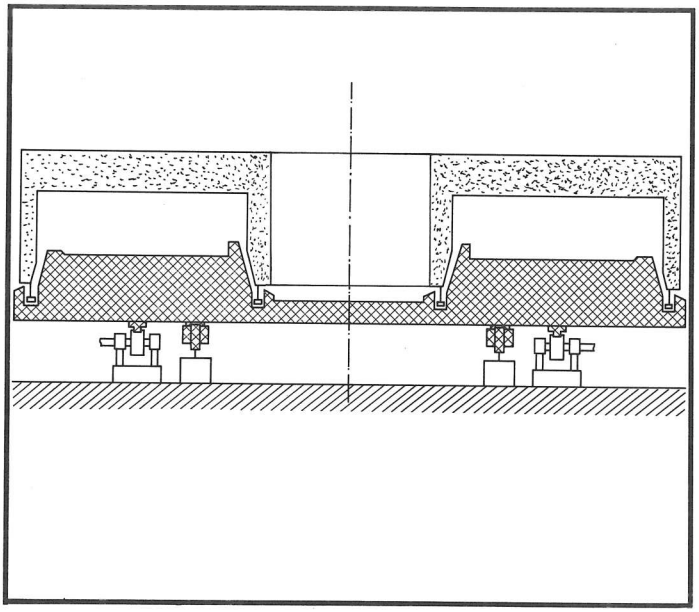

Fig. 3: Rotary Hearth Furnace (cross-section)

requirements of metallization and the carbon content in the final product.

By bringing the metal-bearing oxides and the reductant into intimate contact in fine-grain form in the green pellet, virtually ideal mass transfer conditions are created for the reduction process resulting in correspondingly short reduction times.

The green pellets are charged into the rotary hearth furnace (RHF) where they are heated up to the temperature required for direct reduction.

To ensure rapid heating up, the max. bed thickness is a triple pellet layer as shown in Fig. 4.

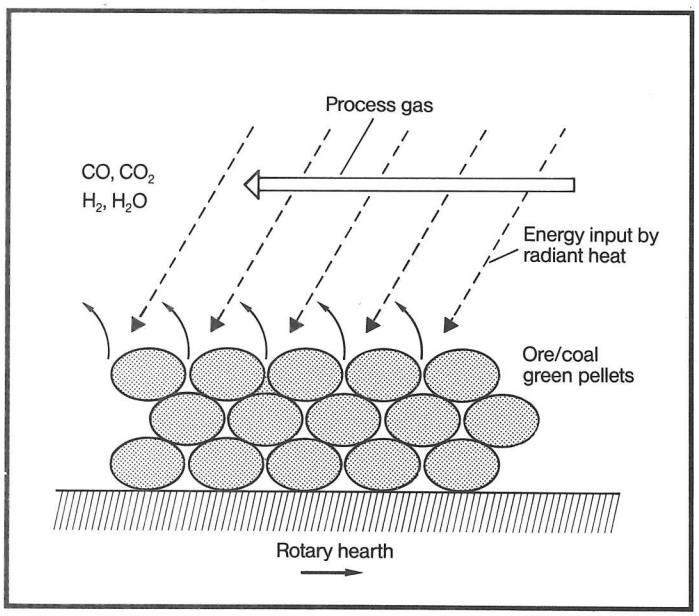

Fig. 4: Principle of the Rotary Hearth Furnace Process

The metallized product obtained is removed at the end of the reduction process. During the process the green pellets are not subjected to any mechanical stresses.

During transportation through the RHF the green pellets are heated up by heat supplied from burners, which can be fired by any kind of fuel and by the combustion of process gas. The temperature progression and atmosphere control in the RHF can be set by precise control of the burners, resulting in optimum reduction conditions.

The carbon monoxide generated is not only used for oxide reduction and combustion purposes. It also acts as protection for the freshly reduced metal, forming a thin carbon monoxide layer above the pellet bed. This avoids reoxidation of the pellet layer.

The rotary hearth furnace operates as a counter-flow heat exchanger.
The waste gases from the combustion process are transferred counter to the flow of the charge material passing through the preheating and reduction zones. After leaving the furnace the sensible heat of the off-gas can be used for preheating the burner air or other applications such as generation of steam and/or hot water.

The RHF process is capable of reducing any kind of oxidic material if the reduction temperature is within the technical and economical limits achievable in such a furnace.

Large-scale and laboratory tests have

been carried out in Ellwood City and at the pilot plant rotary hearth furnace at INCO's research centre in Port Colborne, Ontario, Canada for direct reduction of chromium and manganese ores. The high degrees of chromium and manganese metallization achieved showed the potential of this process.

The attractiveness of the rotary hearth process in comparison to other coal-based processes is based primarily on the following points:

- Green pellets can be charged into the furnace because the charge rests on the rotating hearth and is not subjected to any mechanical stresses,
- The carbon content in green pellets can be adjusted according to requirements,
- There are no sticking problems in the rotary hearth and discharge area,
- The reduced pellets are ideal for hot charging into the smelting unit because of their uniform physical size and adjustable carbon content.

Apart from these process benefits, the rotary hearth furnace is of relatively simple construction and consist of well-tested plant parts.

For this reason, little plant maintenance is required.

The Reduction of Chromium Ores

Phenomenology of Chromium Reduction

Chromium ores in which the chromium and iron oxides are bonded in the shape of spinels of the type $(Fe, Mg)\ O \cdot (Fe, Cr, Al)_2O_3$ mainly form the raw material basis for the production of chromium.

In order to demonstrate the possibilities and special characteristics of the reduction of chromium ore spinels, the phenomenology of chromium production will be explained in brief. Initially, i.e. during the heating up phase, the rate of reduction is determined by the rate of diffusion of the iron and chromium ions within the spinel. The formation of nodules starts at the corners and edges of the spinels. The diffusion along the grain boundaries is energetically preferred to grain diffusion so that the metal begins to grow from the grain boundary to the inside of the grain.

Fig. 5a shows a secondary electrode image from a microprobe of a partially reduced chromite particle from the core of an Indian chromium briquette which was reduced for 60 minutes at a temperature of 1450°C. Concentration diagrams through this particle are shown in Figures 5b to 5e, but should be evaluated only qualitatively.

A wide rim consisting of metallic chromium, iron and manganese is clearly recognisable. Moving towards the inside of the grain this is followed by a dark zone of reduced metal content but with a high content of Si, Al, Mg and Ca. Si and Ca must have diffused from the surrounding gangue since neither element can be found in the light-coloured core which is not yet reduced. Here, high levels of Cr, Fe, Mn, Al, Mg and O are found.

During further heating up, the reduction rate of the chromium spinel is increased by the fluxing reaction. The free standard energy for the reduction of magnesium-chromium spinels is reduced in particular by the presence of SiO_2.

In the presence of a liquid slag phase the chromium spinels are dissolved and reduction is faster and more complete.

By the addition of fluxes the temperature for the dissolution of the spinels in the slag can be reduced considerably.

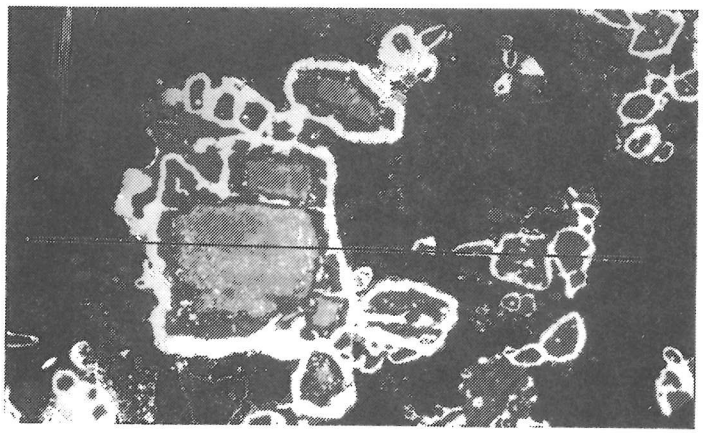

Fig. 5 a: Secondary electrode image from the microprobe of a partially reduced chromite particle. The cross-section for the determination of the elements is marked.

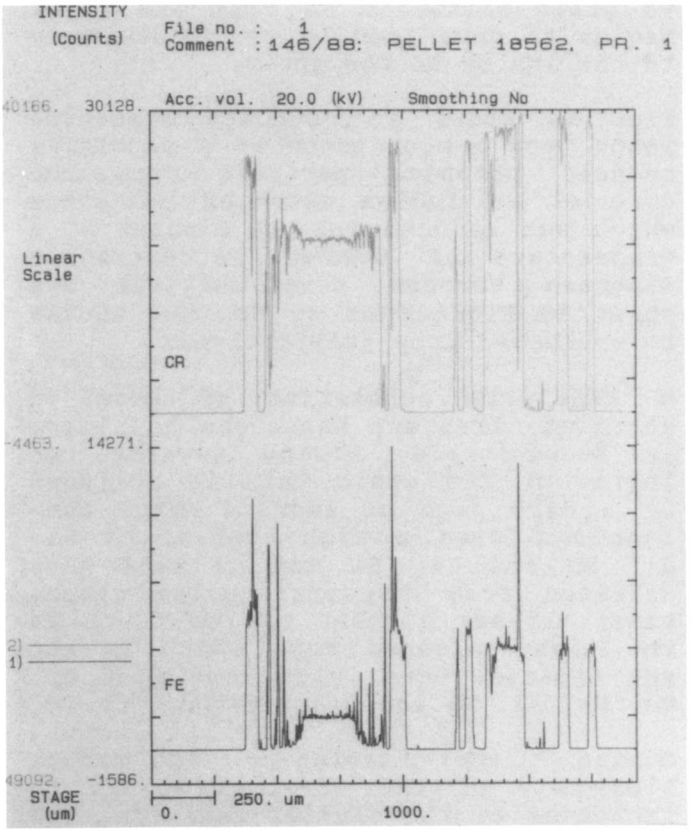

Fig. 5b: Distribution of Cr and Fe along the cross-section marked in Fig. 5a

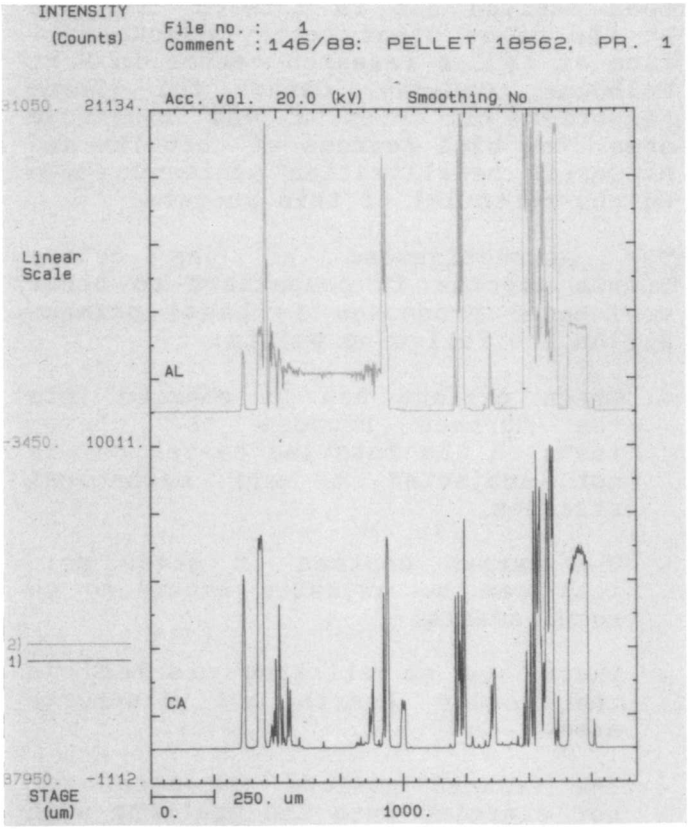

Fig. 5c: Distribution of Al and Ca along the cross-section marked in Fig. 5a

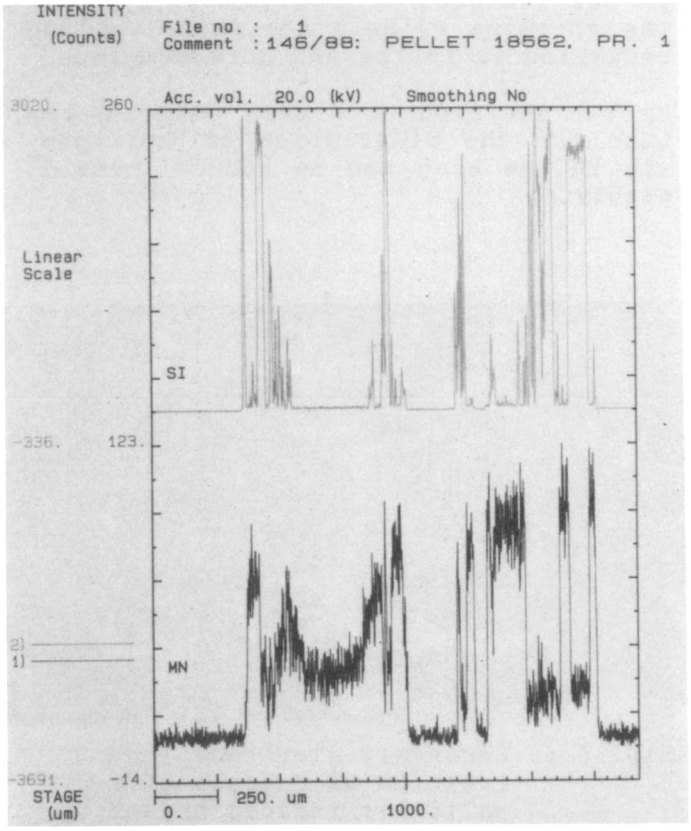

Fig. 5d: Distribution of Si and Mn along the cross-section marked in Fig. 5a

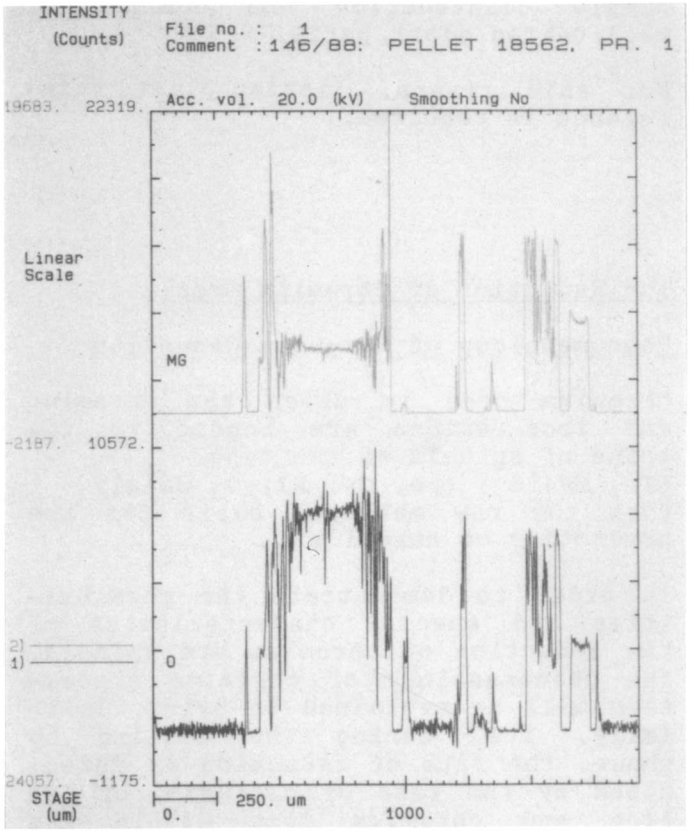

Fig. 5e: Distribution of Mg and O along the cross-section marked in Fig. 5a

In this case the transport of the Fe and Cr ions from the spinel/slag phase boundary to the carbon particle becomes the rate-controlling step. /9/

Russian investigations found that the degree of reduction for a given composition depends essentially on the reduction temperature. /10/

Our own investigations confirmed this result with high metallization always being related to the existence of liquid phases.

The resulting chromium-iron crystal is nearly saturated in carbon. The micrograph of reduced chromium ores shows various forms of carbides, Fig. 6.

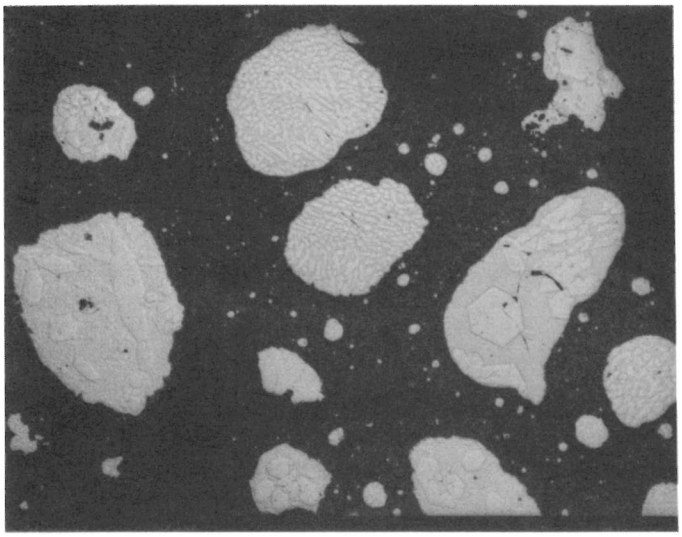

Fig. 6: Polished section of a reduced chromium ore pellet. In the metal (white) different types of carbides are visible.

Reduction Tests

Tests for the reduction of chromium have been carried out in the laboratory, on a pilot unit and on an industrial scale in the Ellwood City RHF since 1986.

The reduction of various chromium ores from different countries was examined using anthracite as well as coals high in volatiles and ash as a reductant. Table 1 gives a summary of the chemical compositions of the ores and Table 2 of the reductants used.

Iron and chromium were normally finely ground and then pelletised using bentonite as a binder. Very fine ores were pelletised without grinding or alternatively briquetted with the addition of molasses.

Laboratory Tests

The main aim of the laboratory tests was to determine the parameters for the RHF tests which followed. The tube furnace temperatures were around 1400 °C with a maximum temperature of 1480 °C. The gas atmosphere was in the range 70-80 % N_2, 10-20 % CO, 5-10 % CO_2 and corresponded to that measured in the RHF.

The results obtained were as follows:

- Chromium metallization between 80 and 90 % was achieved for all pellets.
- Initial tests with chromium ore briquettes yielded chromium metallization between 60 and 70 %.
- The addition of SiO_2 and special fluxes led to similar degrees of reduction at lower temperatures.
- The degree of reduction increases with the temperature under otherwise constant conditions. The minimum temperature for 70 % chromium metallization was 1350 °C in all cases. All samples which were examined metallographically showed molten silicate phases at these high reduction levels.
- An increase in retention time beyond 25 minutes does not result in higher reduction levels.
- Increasing the fine share (less than $75 \cdot 10^{-6}$ m) reduces the retention time required for reduction.
- An increase in carbon content above the stoichiometric carbon level had only a minor effect on the degree of reduction. The carbon content of the reduced pellet could, however, thus be varied between 3 and 15 %.

Rotary Hearth Tests

Rotary hearth tests were carried out on a semi-industrial scale and on an industrial scale at the INCO pilot unit and at the INMETCO production unit.

The furnaces have the following dimensions:

	Port Colborne RHF	INMETCO RHF
mean hearth dia.	3.05 m	11.0 m
hearth width	0.71 m	4.8 m
inside height	0.53 m	1.1 m

Table 1: Chemical Composition of Chrome Ores (wt.%)

	I	II	III	IV	V	VI
Fe	21	21	22	21	12-16	15-16
Cr	25	30	32	31	33-35	25-27
Al_2O_3	15	15	12	15	8-12	10-14
SiO_2	8	6	2	1	6-12	5-12
MgO	6	6	7	10	10-15	11-15
CaO	2	1	1	0.5	0.8-2.0	0.8-2.0

Table 2: Composition of Carbon Sources (wt.%)

Description	Proximate Analysis Fixed C	Ash	Volatiles
Anthracite Coal			
I	86	10	4
II	80	10	10
Coke			
III	87	12	1
High Volatile/ Bituminous Coal			
VI	57	10	33
V	45	20	35

The low inside height of the pilot rotary hearth furnace initially caused problems with the furnace atmosphere right above the bed. The flows induced by the existing oxy-fuel burners meant that oxidizing gas components were swept into the pellet layer leading to carbon burn-off and reoxidation.

This problem was solved by replacing these burners with especially designed low-momentum burners.

Pellets and briquettes made from different chromium ores corresponding to the laboratory blends were used in several tests series.

The tests were carried out using the different raw materials for approximately 10-16 h each to determine the reducibility of certain ore/coal mixtures. To ensure a fairly even heat transfer throughout the bed, the bed was only 1-2 pellet layers high which meant a productivity of 45-60 kg of product per m^2 and hour.

The results were as follows:

- Chromium reduction levels between 73 and 83 % for chromium pellets were achieved on the pilot as well as on the production unit.

- Total reduction was up to 90 % taking the virtually total reduction of iron into account.

- After refitting the oxy-fuel burners on the pilot unit, these results also proved to be constant and reproducible.

- The maximum furnace temperature could be limited to 1450 to 1480 °C by the addition of fluxes.

  Without these fluxes the furnace temperatures had to be 100 to 150 °C higher.

- The average retention time of the chromium pellets in the rotary hearth was 20-30 minutes.

- Compared to the laboratory tests, the slightly lower metallization was caused by the considerably wider size distribution of the green pellets caused by transporting these pellets over long distances.
  An analysis of grain fractions showed that either the fine fraction was almost fully metallized and the remainder not yet sufficiently reduced or that the larger pellets were highly metallized with the fines showing considerable reoxidation.

- A first batch test using Indian chromium briquettes achieved over 50 % chromium metallization.

- The "green" briquettes remained intact due to the low mechanical stresses.

Fig. 7 shows some reduced chromium/anthracite pellets with a roughly ground surface which demonstrate the potential of the RHF process for chromium reduction.

The pellets consist of an almost entirely reduced metallic zone and an outer shell, which is essentially originally partly molten gangue rich in chromium oxide.
The degree of chromium reduction is about 90 % as can be determined from the micrographs by an evaluation using microscopy (Fig. 8).

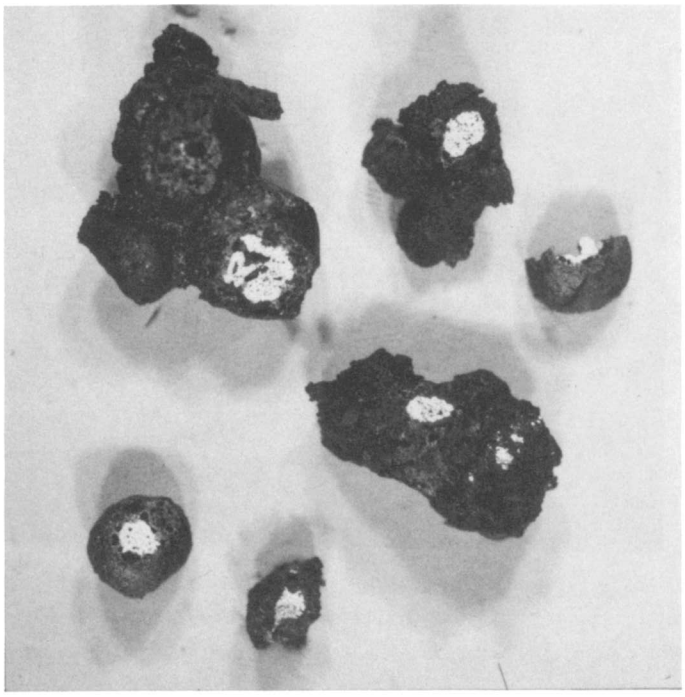

Fig. 7: Rough-Cut pellets. Metal (white-silver), slag (black)

To obtain these high reduction levels, the RHF process has to be controlled in a way which avoids premature high-carbon burn-off as well as the reoxidation of the sponge chromium.

Highly metallized sponge chromium is extremely sensitive to reoxidation.

The pellet bed which, however, is only 1 to 2 pellet layers high tends to be protected from the furnace atmosphere by the carbon monoxide developed in the reduction process. Towards the end of the reduction process this gas flow

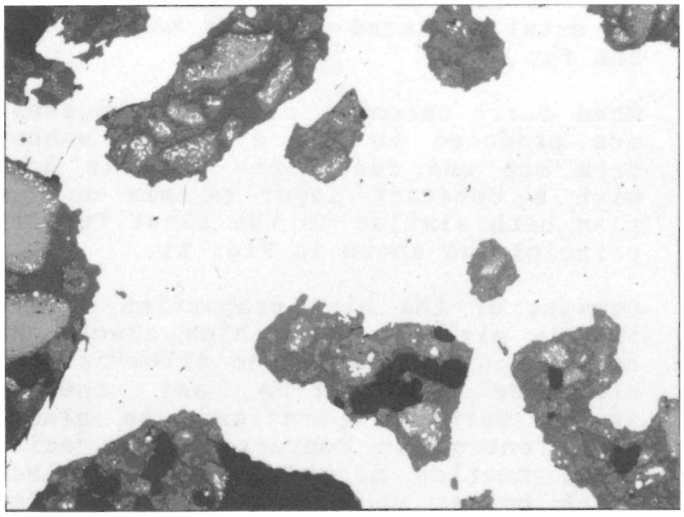

Fig. 8: Polished section of a chromium pellet shown in Fig. 7, metal (white), chromite (light grey), gangue (dark grey), plastic mass (black)

is no longer strong enough to prevent the penetration of the pellet bed by the furnace gas. Covering the bed with highly volatile coal in the last section of the furnace reduces reoxidation considerably. Furthermore reoxidation can be kept down by ensuring a narrow size distribution of the green pellets which facilities fairly equal conditions for all green pellets.

The chromium ore reduction tests demonstrated that reduction in the RHF is particularly easy to handle when the reduction temperature of the chromium spinel meets with the temperature at which the reductant becomes reactive.

Chromites and low reactivity anthracite proved to be a particularly good combination when the reaction temperature of the chromites was reduced by the addition of fluxes.

In cases of great difference between the reaction temperature and the temperature at which the coal becomes reactive, appropriate measures like high heating-up rates, which cover this temperature difference in a short time, can be used to limit carbon burn-off.

Although the temperature range used for high levels of prereduction meant that the gangue and metal carbides were at least in a doughy state, the bed did not bake together and sintering was limited to 5-6 pellets at most. The reason for this is that the pellets with a maximum of 2 layers hardly touch each other and that the rotary hearth with its large number of burners affords accurate temperature control avoiding local superheating.

Manganese Reduction Tests

After laboratory tests had shown that carbon-containing manganese pellets could be reduced to a level of manganese metallization of approximately 70 %, manganese pellets were fed to the pilot RHF for 5 hrs as a first test.

Table III shows the chemical composition of the manganese ore, Table IV the proximate analysis of the reductant. Carbon addition was stoichiometric with regard to the oxygen content of the metal oxides.

Since there is no reliable analysing method of distinguishing between Mn metal and Mn oxide if both are present

in a sample, the degree of reduction can only be assessed using metallographic methods.

Table III: Chemical Composition of Manganese Ore (wt.%)

MnO_2	75
Fe	3
Al_2O_3	6
SiO_2	3
H_2O	0.8
Na_2O	0.05

Table IV: Proximate Analysis of Anthracite Coal (wt.%)

Fixed carbon	86
Ash	10
Volatiles	4

The manganese pellets were fed at a rate of 200 kg/h and had a residence time between 22 and 30 minutes. The off-gas temperature was 1300 °C and the maximum furnace temperature close to the discharge was set to 1500 °C.

Metallographic examinations showed a degree of metallization between 50 and 65 % for the larger pellet fraction. The fine fraction was virtually entirely metallized so that the overall metallization was markedly above 60 %.

The pellet temperature, at 1320 - 1350 °C, was clearly above the melting temperature of metallic Mn.

The micrograph (Fig. 9) thus shows spherical white metal particles which had been molten. At the bottom of the larger pellets these metal spheres would bead out or drip to the hearth when the time until discharge was long enough. These metal beads formed the virtualy entirely metallized fine fraction (Fig. 10).

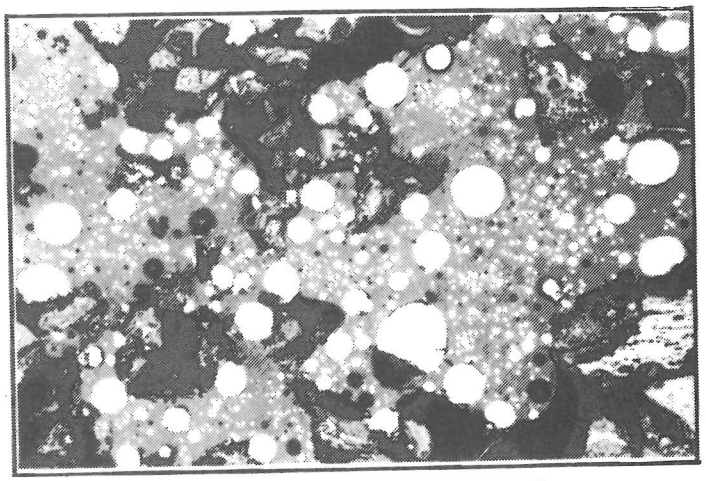

Fig. 9: Polished micro-section of highly metallized manganese pellets

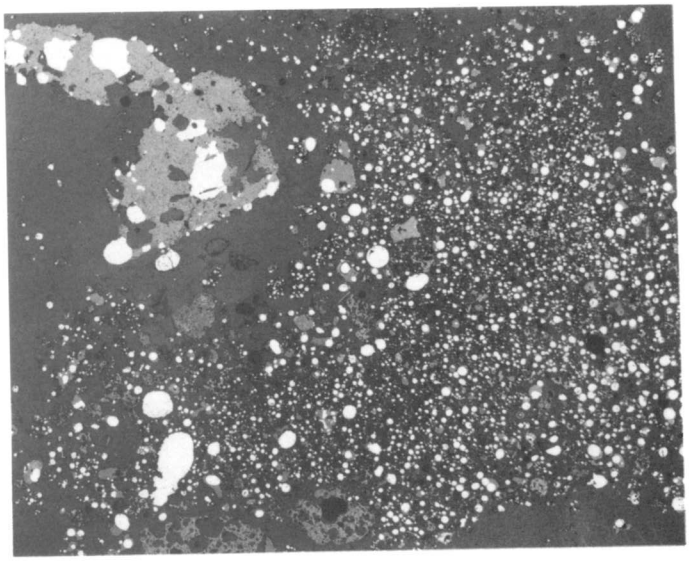

Fig. 10: Polished macro-section of a reduced manganese ore sample

The metallization of iron was nearly 100 %.

A small part of the metallic Mn evaporated, reoxidized in the gas phase and was deposited as a green powder. Some pellets partially had a green coating as a consequence of surface reoxidation.

During the test no problems with sintering or sticking arose.

Smelting of highly metallized manganese and chromium pellets

Ferro-chromium and ferro-manganese are usually produced in submerged arc furnaces. The economical continuous operation and the large amount of slag varying from 0.7 to 1.3 tonnes per ton of metal produced are the major reasons for this.

When ferro-chromium or ferro-manganese are produced in the classical manner from ore and reductants this is done with a constant layer of mix on the slag bath similar to the blast furnace principle as shown in Fig. 11.

Because of the high proportion of ore in the mix, there is high electrical resistance in the system allowing good electrode penetration and thereby stable furnace operation. The electrical energy is converted into resistance heating mainly via a coke bed which builds up around the electrodes and only partially through the resistance of the slag and metal.

When highly metallized ferro-chrome or ferro-manganese pellets are charged,

the electrical parameters in the system change significantly:

- The resistance of the mix becomes lower due to the high proportion of metallic components in the charge,
- The carbon bed around the electrodes necessary for heat transfer is reduced to a minimum or disappears completely.

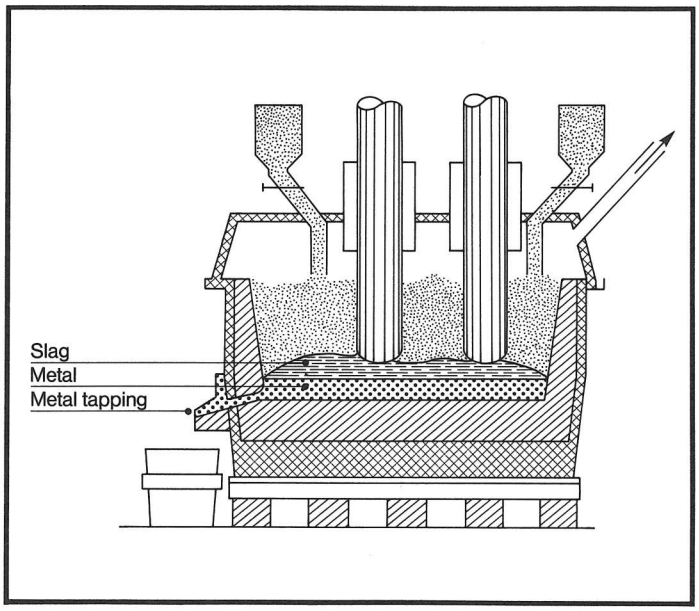

Fig. 11: Schematic diagram of a submerged arc furnace for the production of pig iron

Due to the lack of carbon in the charge, heat transfer occurs only in the slag. Therefore, the slag must be raised to a certain minimum level sufficient for the heat conversion required.

The higher electrical conductivity of the mix no longer allows a mix layer above the slag. The furnace has to be operated with the slag bath open to the furnace atmosphere. /11-12/

The mix will be charged batchwise to the open slag bath and melts within the slag.

Beside the different energy transfer there are some other process characteristics such as the following /13/:

- The furnace is stationary, closed, and gas-tight.
- The energy required for smelting is supplied continuously through the electrodes to slag and metal.
- Raw materials are charged continuously to the furnace through feed pipes.
- Slag and metal are tapped separately, the slag from a higher taphole than that for the metal, ensuring a more or less constant layer of slag in the furnace.
- The process gas generated is continuously drawn, unburnt from the furnace
- Self-baking low-cost Soederberg electrodes can be used as well as prebaked electrodes.

The submerged arc furnace for processing highly metallized manganese and chromium ore will be the same as those which are in operation for the processing of sponge iron. Fig. 12 shows a schematic diagram of a submerged arc furnace operating with open slag bath.

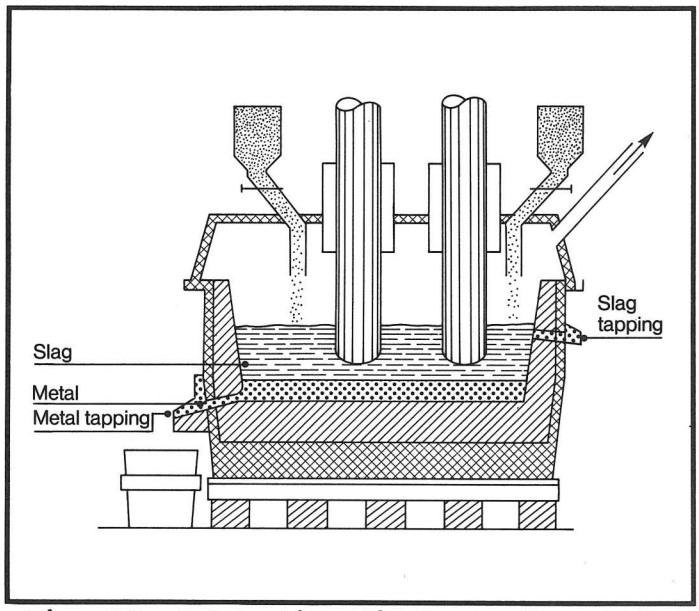

Fig. 12: Schematic diagram of a submerged arc furnace for the production of pig iron and steel with an open slag bath

As an example, Fig. 13 shows the energy consumption of a SAF charged with prereduced hot Indian chromium sponge. Starting out from an energy consumption of approximately 3750 kWh/t FeCr when smelting cold unreduced ore in the SAF, this could be decreased to approximately 1640 kWh/t FeCr charging hot prereduced sponge.

These figures are based on a chromium--metallization figure of 70 % and iron metallization of 90 %.

Producing FeMn with manganese pellets which have a manganese metallization of 70 % and iron metallization of 95 %, the following electrical energy consumption figures can be achieved:

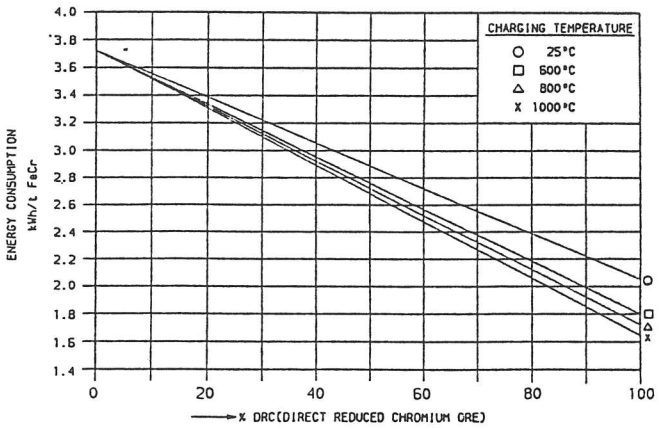

Fig. 13: Energy consumption as a function of chromium sponge in the charge of a SAF

manganese ore charge:
approx. 3,000 KWh/ton FeMn
metallized pellets cold:
approx. 1,600 KWh/ton FeMn
metallized pellets hot:
approx. 1,000 KWh/ton FeMn

Apart from these figures, the specific electrode consumption figures will also drop significantly (higher production per hour and no free oxygen from the dissociation of MnO_2).

Chromium and manganese recovery will increase. The improved kinetic reduction conditions with the fine distribution of carbon through the pellets results in a lower Cr_2O_3 and MnO content in the slag compared with the ore-based operation.

Finally, a lower carbon content in the FeCr and FeMn produced was achieved.

Conclusions

The rotary hearth process is well suited for reducing different kinds of oxidic materials into highly metallized pellets. Its performance has been proven for producing sponge iron from iron ore and wastes. Its application for the production of highly metallized chromium and manganese pellets has also been demonstrated.

The use of green pellets resting on the hearth together with only a short temperature treatment of less than 30 minutes produces a process technology which is easy to master.

Together with the appropriate smelting technology, the result is a highly-efficient combined process for the production of iron, steel and ferro-alloys.

The possibility of hot charging of the highly metallized pellets to the smelting process ensures reliable operational control and low overall energy consumption.

Apart from savings in electric power the use of a pre-reduction unit for ferro-alloy production can lead to the following improvements of the overall process:

- Increased smelting furnace throughput rate
- Increased chromium recovery
- Improved carbon control
- Substitution of metallurgical coke by non-coking coals.

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