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Ferroalloy Production by the Smelting–Reduction Process with a Coke Packed Bed

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A new smelting–reduction process with a coke packed bed has been developed to produce ferroalloys or pig iron by the use of low-grade coke and fine ores. The process is characterized by (1) a coke packed-bed shaft furnace, (2) two-stage tuyères, (3) direct use of fine ore without agglomeration, (4) gravitational powder transportation and injection through the upper tuyère, and (5) a fluidized-bed pre-reduction furnace for full utilization of the byproduct gas.

Bench-scale tests of smelting reduction, gravitational powder transportation, and fluidized bed pre-reduction were carried out independently to confirm the principles and effectiveness of the process. Pilot-plant tests for the production of ferrochromium were conducted successfully in 1986. Scale-up for the production of 100 t/d of ferrochromium was investigated, and the production cost of the process was shown to be lower than that for an electric-furnace process.

Introduction

Compared with the production of ferroalloys in an electric furnace or the production of iron in a blast furnace, smelting–reduction processes have many advantages from the viewpoint of raw materials, energy sources, investment costs, and the control of environmental problems. Although the features of the processes are not necessarily the same owing to local conditions and needs, various smelting–reduction processes have been under development, with the following expected advantages:

(1) simple process flow and low investment costs
(2) utilization of cheaper energy sources
(3) utilization of fine ores without agglomeration
(4) less environmental pollution.

Kawasaki Steel have developed a new smelting–reduction process with a coke packed bed (called the STAR process) for the production of ferroalloys, based on fundamental studies and shaft-furnace technologies[1-12]. The STAR process has the advantages listed and allows the direct use of low-grade coke and fine ores.

Experiments were conducted on laboratory-scale, bench-scale, and pilot-scale equipment. This paper describes the features of the STAR process, the experimental results, and economic aspects of the process.

Features of STAR Process

The concept of the STAR process is illustrated in Figure 1. The process is characterized by

(1) a coke packed-bed shaft furnace
(2) two-stage tuyères
(3) direct use of fine ore without agglomeration
(4) a gravitational powder-transportation system
(5) a fluidized-bed pre-reduction furnace.

In addition, the pre-reduction process can be dispensed with at plants where byproduct gas is fully utilized as fuel.

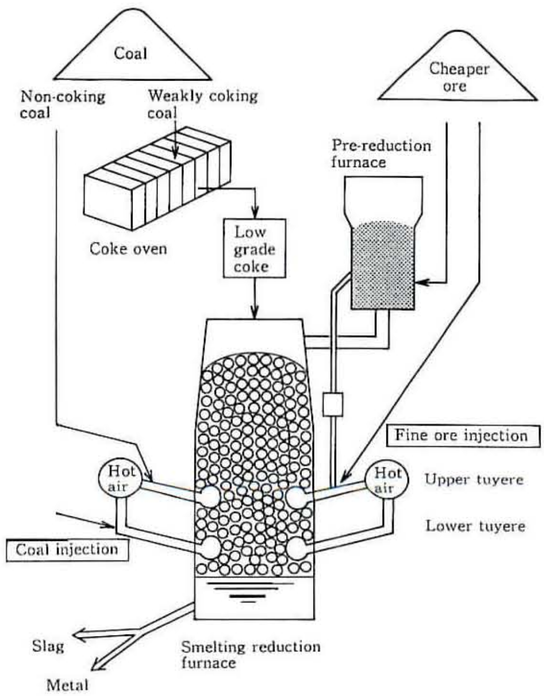

FIGURE 1. Details of the STAR process

Coke Packed-bed Shaft Furnace

The shaft furnace is filled with small-size coke. The temperature of the exhaust gas from the furnace is relatively low, since the heat of the gas generated in the raceway is transferred to the coke. The constitution of the lower part of the furnace is almost the same as that of the conventional blast furnace; hence, less corrosion of the lining and good separation of slag and metal are expected. These features are remarkable advantages compared with the molten-metal bath process. Another feature is the use of low-grade coke made from weakly coking coal, because the ore is injected through the upper tuyères and, consequently, the deterioration of coke under heavy burden loading or by solution-loss reaction in the shaft need not be considered. The injection of pulverized coal through the tuyères is, in principle, also possible as a means of decreasing the consumption of coke.

Two-stage tuyères play an important role in this process, and are effective for the smelting–reduction of ores that are difficult to reduce, such as chromium ores. The ore injected through the upper tuyère is immediately fused in the raceway and reduced as it drips through the coke packed bed. Although a great amount of heat is consumed by the smelting–reduction, reduction conditions such as the heat supply and the area of the high-temperature region are easily controlled by proper distribution of the blast between the upper- and the lower-stage tuyères.

Gravitational Powder-transportation System

Two kinds of gravitational powder-transportation system can be installed; both are shown schematically in Figure 2. The power required for the transportation of the powder is supplied by gravity in both systems. Compared with the ordinary pneumatic powder-transportation system, these systems have advantages of low flowrate of the carrier gas and less abrasion of the transportation pipes and nozzles. In system (a), without pre-reduction, fine ore is discharged by a rotary feeder and injected into the furnace with a small amount of carrier gas through the upper tuyères. In system (b), with pre-reduction, hot pre-reduced ore must be injected against back pressure because the pre-reduction furnace operates at a lower pressure than the smelting furnace proper. This back pressure, however, can be blocked off by the ore in the transportation pipe. The injection rate of the pre-reduced ore is controlled by adjustment of the fluidizing gas from the small fluidized bed installed towards the bottom of the transportation pipe. This system ensures high reliability by the elimination of moving parts.

Pre-reduction Utilizing a Fluidized Bed

Less reducible ores such as those of chromium can be smelted without pre-reduction in the fluidized-bed process. However, pre-reduction is useful when the byproduct gas is not fully utilized in the works. Thermodynamically, chromium ore is difficult to reduce with ordinary reductants such as CO or H_2 at relatively low temperatures. Conventionally, it is pelletized and pre-reduced in a rotary kiln at temperatures as high as 1300 to 1400°C. In the STAR process, however, chromium ore is pre-reduced in a fluidized bed, and the reduction temperature can be lowered to about 1100°C by the use of hydrocarbons as the

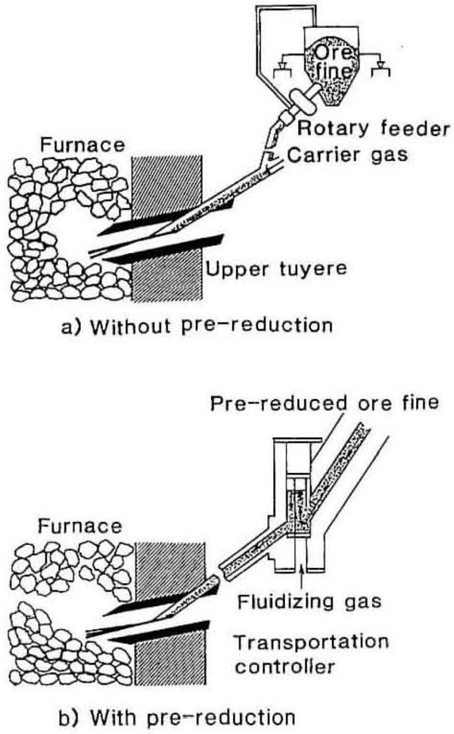

FIGURE 2. Schematic diagram of the gravitational powder-transportation system

reductant and exhaust gas from the smelting–reduction furnace as the heat source[1]. Fluidized-bed pre-reduction is advantageous in terms of the utilization of fine ore without agglomeration and the shorter reduction times required.

Fundamental Studies and Bench-scale Tests

Smelting–Reduction Behaviour

An understanding of the behaviour of chromium ore in a coke packed bed is very important in determining the flux composition, coke size, and distance between the upper and lower tuyères. As a first step in this study, the melting, reducing, foaming, and dripping behaviour of chromium ore with the addition of flux in a coke packed bed was examined in an experimental furnace using an X-ray fluoroscope[2-4]. A coke packed bed with an inner diameter of 40 mm and a height of 100 mm was maintained at an elevated temperature in an electric furnace, while pellets of 2 to 3 mm, which were made from chromium ore and fluxes of various compositions, were fed continuously into the furnace. The amount of dripped slag and metal was measured by a load cell. Marked changes in the smelting–reduction behaviour with changes in temperature, flux composition, and coke size were observed. The chromium ore and flux charged onto the coke packed bed melted within 2 minutes of the start of charging, began to boil, and were reduced during dripping in the coke packed bed. In the extreme case, when the flux composition was inappropriate, even the melting of the ore did not occur. Further, X-ray fluoroscope observation showed the importance of coke size. When the coke size was somewhat reduced, the permeability of the packed bed deteriorated, and dripping of the melt and the smelting reduction itself were terminated.

Figure 3 shows the effect of coke size on the static hold-up of molten ore and flux. When the coke particles are larger than 14 mm, the amount of metal hold-up is estimated to be about the same as in a cold model test. This observation suggested that the coke size should be larger than 14 mm.

Figure 4 shows the effect of the ore-charging rate on the average residence time. Average residence time is a function of ore-charging rate, coke size, heat supply, and bed height. Initially, the average residence time decreases with increased ore charging, but increases very sharply with a further increase in the charging rate because the heat supply becomes inadequate to maintain the endothermic reaction that characterizes smelting–reduction. This problem is easily solved by the use of two-stage tuyères in that the heat supply to the smelting–reduction zone can be controlled by proper distribution of the hot blast between the upper and lower tuyères, demonstrating one of the advantages of this system.

Smelting–Reduction

Bench-scale tests were carried out to confirm the principles of smelting–reduction in a coke packed bed and heat supply with two-stage tuyères[5]. The reactor of the coke packed bed with the two-stage tuyères is shown in Figure 5. The furnace proper had an inner diameter of 400 mm, an effective height of 2350 mm, and one upper tuyère and three lower tuyères. Coke, 10 to 15 mm in diameter, was used. After the furnace had been fully heated by coke combustion, chromium ore, preheated to 600°C, was fed with N_2 gas through the upper tuyère. The ore-injection rate was controlled by monitoring of the melting in the raceway, and coke was charged intermittently.

In this study, the effects of oxygen enrichment of the blast, pre-reduction of the chromium ore, and flux composition on the smelting reduction were examined. An example of the experimental results is shown in Figure 6. As the ore-injection rate was increased, the Cr_2O_3 concentration in the slag also tended to increase. When the oxygen concentration in the blast was increased, the Cr_2O_3 concentration tended to decrease. The actual result is determined by the adequacy of the heat input to the endothermic smelting–reduction reaction. The Cr_2O_3 content of the slag produced with a coke packed bed smelting–reduction furnace is lower than that of slag from an electric-arc furnace.

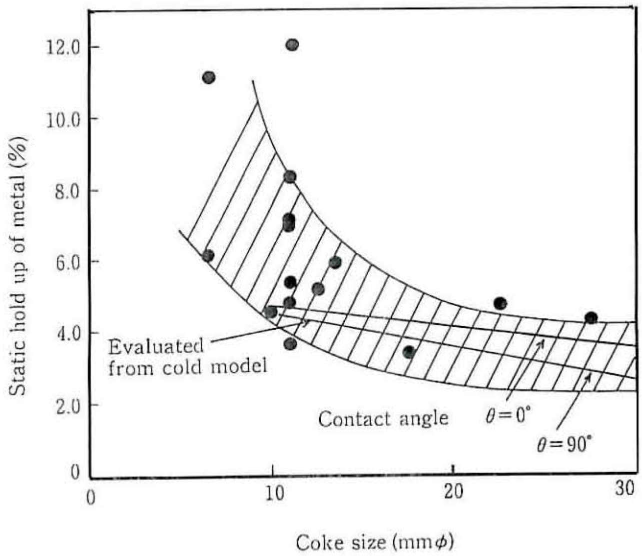

FIGURE 3. Effect of coke size on the static hold-up of metal

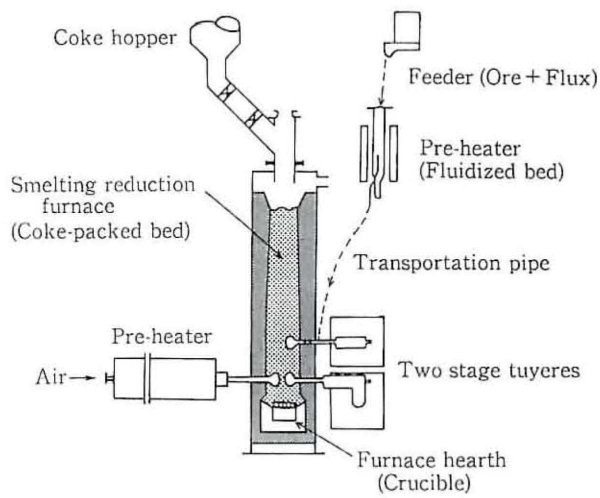

FIGURE 5. Schematic diagram of the bench-scale smelting–reduction furnace

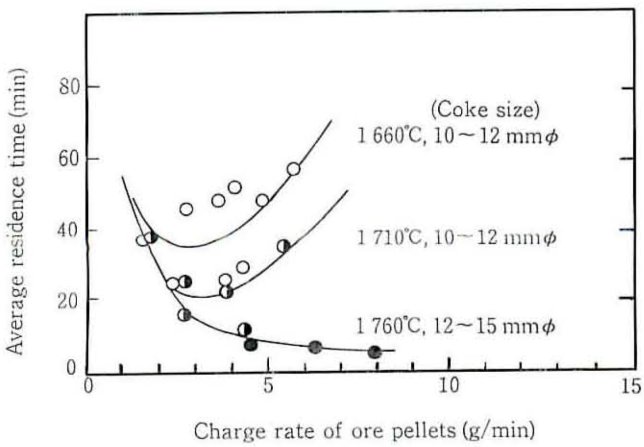

FIGURE 4. Effect of the charging rate of ore on the average residence time in the coke packed bed

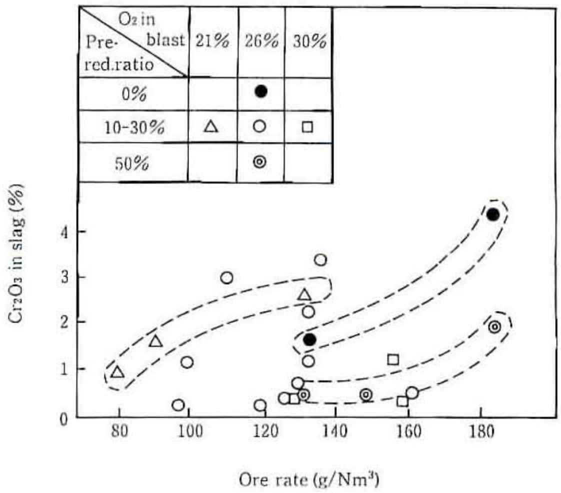

FIGURE 6. Effect of the ore-injection rate on the Cr_2O_3 content of the slag

Figure 7 shows the relationship between C and Si in the product metal. Depending on the experimental conditions, the Si varies from 1 to 10 per cent. The similarity of this relationship to that in the production of ferrochromium by electric furnace suggests that the coke packed-bed smelting–reduction furnace is similar to the electric furnace in smelting–reduction behaviour.

Reduction Behaviour between the Tuyères

The vertical distributions of temperature and degree of reduction of melts in the region between the upper and the lower tuyères are shown in Figures 8 and 9. The abscissa is the distance from the upper tuyère to the furnace bottom, and the distance between the two-stage tuyères is 0,5 m. From a distance of 0 to 0,2 m beneath the upper tuyère, the temperature of the melt decreases because the reduction of ore by coke proceeds at a high rate and the reaction is endothermic. The reduction of the ore is almost completed at a distance of 0,2 m beneath the upper tuyère. As a result, the temperature tends to increase again at distances lower than 0,2 m from the upper tuyère.

On the basis of these results, the two-dimensional distribution of temperature and degree of reduction of melts in the pilot plant were calculated from a mathematical model for certain operating conditions. Examples of the calculated results are shown in Figures 10 and 11. These diagrams show that, when oxygen is enriched up to 25 per cent in the blast, the temperature increases sufficiently and

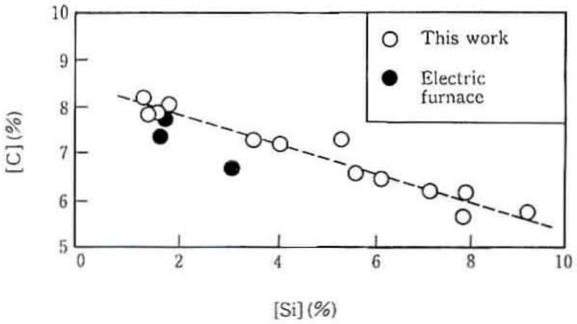

FIGURE 7. Relation between C and Si in the metal

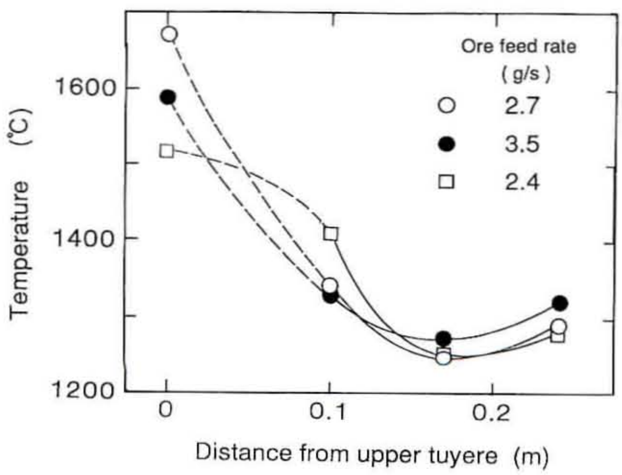

FIGURE 8. Longitudinal temperature distribution in the bench-scale furnace

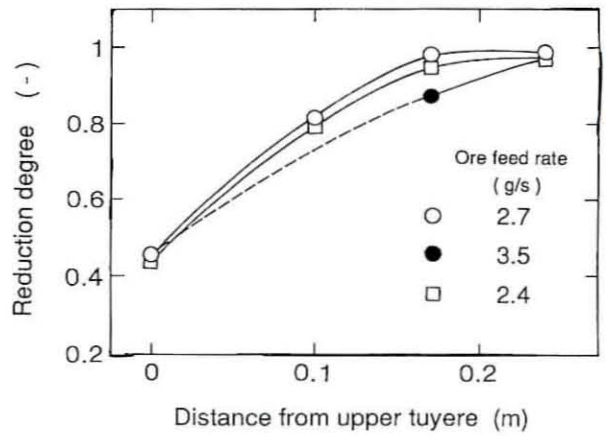

FIGURE 9. Longitudinal distribution of the degree of reduction of melts in the bench-scale furnace

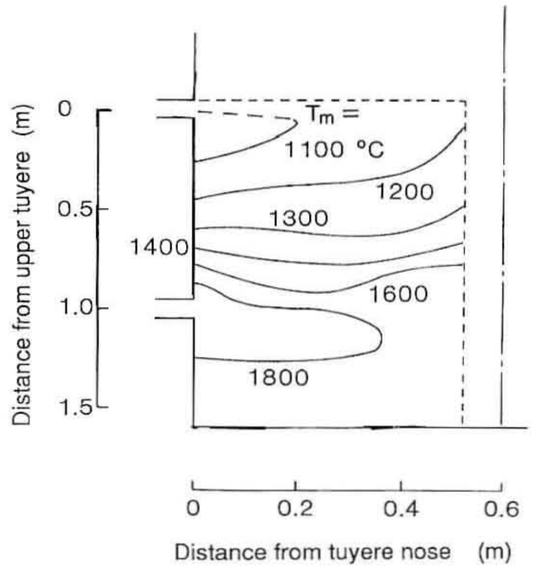

FIGURE 10. Isothermal contours estimated for the pilot-plant furnace from a mathematical model with 25 per cent oxygen enrichment

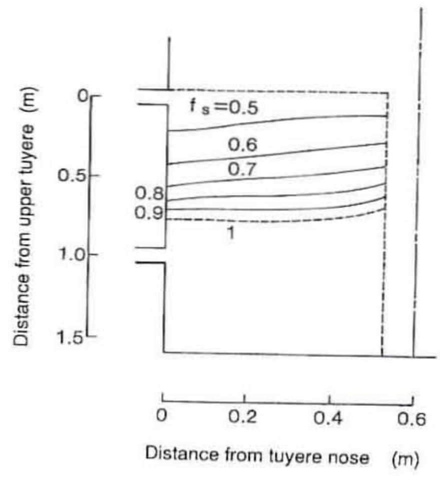

FIGURE 11. Iso-reduction degree curves estimated for the pilot-plant furnace from a mathematical model with 25 per cent oxygen enrichment (f_s is the fractional degree of reduction)

the reduction is completed in the zone between the upper and the lower tuyères. The optimum hearth diameter and the distance between the two-stage tuyères were determined from these simulations.

Pilot-plant Test

Figure 12 is a schematic diagram of the pilot plant and also shows an overview of the layout. The hearth diameter of the experimental furnace was 1,2 m. Three sets of two-stage tuyères were installed in the furnace. The profile of the furnace, the distance between the two-stage tuyères, and the operating conditions such as coke size, flux compositions, and oxygen enrichment were determined from fundamental studies. Five test campaigns were carried out in 1986, as shown in Table I.

Several products, such as iron and ferrochromium, were produced from low-grade coke and fine ores[8-10], and the operating conditions were adjusted according to the product requirements. These campaigns were carried out without pre-reduction on the premise that a commercial unit would be constructed in a location where byproduct gas is fully utilized (and is therefore not available for pre-reduction). The most important results are as follows.

The chromium content in the metal was controlled easily and changes were effected by variation of the mixing ratio of iron ore, chromium ore, and flux. The chemical compositions of metal and slag obtained in these experiments are summarized in Table II. Good fluidity of the slag is very important for the maintenance of continuous operation. On the basis of the fundamental studies, the slag compositions were adjusted in the ranges shown in Table II and smooth operation was attained.

Figure 13 shows the relation between the silicon content of the metal and the chromium content of the slag. Compared with the production of ferrochromium by electric furnace, the yield of chromium is higher.

TABLE I
OPERATION OF THE PILOT PLANT

Test campaign	Period (1986)	Period days	Produced metal
1st	April	10	Pig iron
2nd	June	14	Pig iron Cr-pig iron
3rd	July–August	14	Pig iron Cr-pig iron Ferrochromium
4th	September–October	14	Pig iron Cr-pig iron Ferrochromium
5th	November–December	12	Ferronickel Cr–Ni-pig iron

TABLE II
METAL AND SLAG COMPOSITIONS

	Metal composition, %				Slag composition, %			
	Cr	Si	C	S	SiO_2	CaO	Al_2O_3	MgO
Pig iron	–	1	1	0,003	38	47	7	1,0
	–	9	5	0,020	42	50	9	1,5
30% Cr	28	2	4	0,002	31	36	13	6
	35	10	7	0,020	34	38	15	8
Fe–Cr	45	3	6	0,003	31	35	16	6
	52	8	7	0,015	34	37	18	8

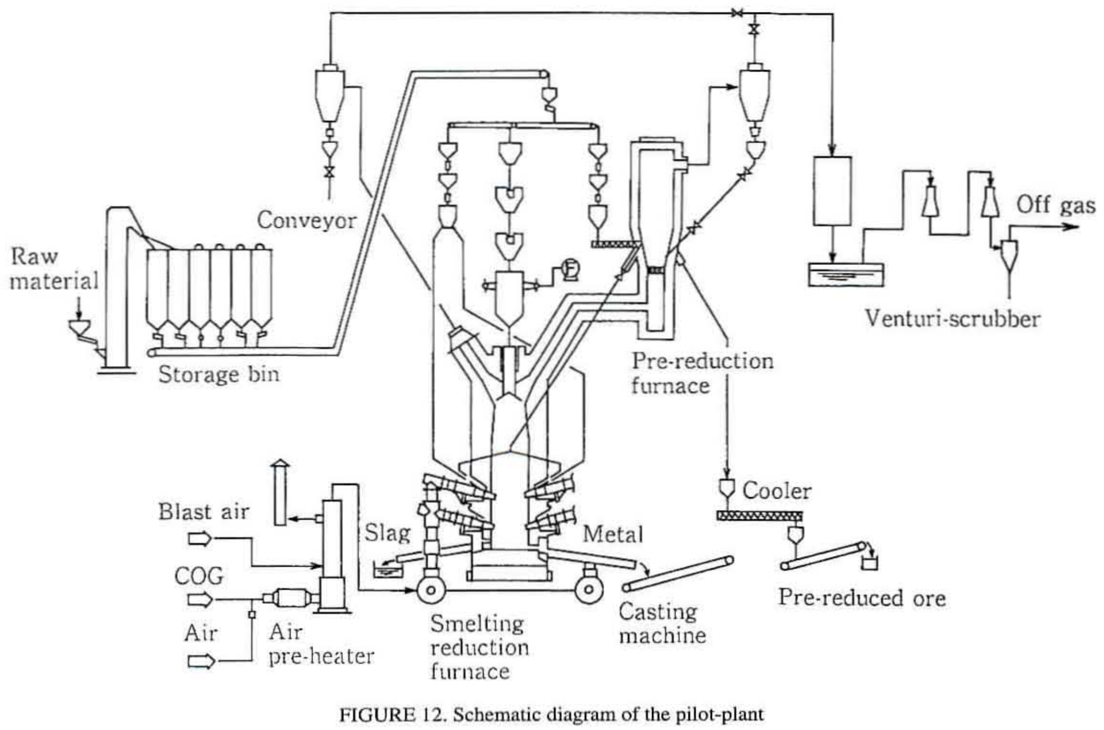

FIGURE 12. Schematic diagram of the pilot-plant

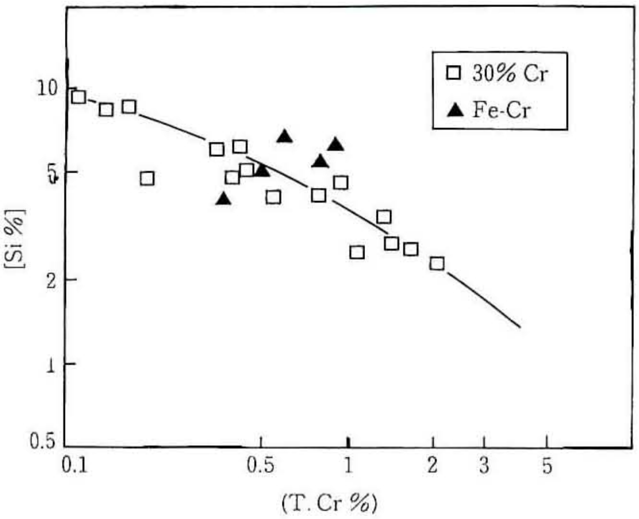

FIGURE 13. Relation between silicon content in the metal and total chromium in the slag

Concerning the sulphur partition between metal and slag, good desulphurization (ranging from 1,0 to 1,2) was achieved in spite of the relatively low basicity. Even in commercial operation, sulphur in the metal should not be a problem because the slag volume in the production of ferrochromium is larger than that in the production of pig iron.

The top-gas temperature was influenced by the coke ratio, regardless of the chromium content of the metal. The coke ratio was very high in the pilot-plant operation because the heat losses from the furnace were high. However, the heat losses are generally reduced as the scale of the furnace is increased, so that the coke consumption and the top-gas temperature should decrease greatly in a commercial plant.

The results of the pilot-plant tests have shown that the STAR process offers many technological and technical advantages, and is even preferable to the conventional method for the production of ferroalloys like ferrochromium.

Scaling-up and Economic Evaluation

The relation between the heat required for the smelting reduction and the heat supply, and also the effect of operating conditions and equipment on this relationship, must be clarified as a basis for the scaling up the smelting–reduction furnace. Furthermore, the makeup of the smelting–reduction region must be taken into account in the scale-up of the process.

An example of a commercial furnace for ferrochromium production at an output of 100 t/d was designed on the basis of the above-mentioned mathematical model and also a scaled-up model[12]. The furnace volume is about 150 m^3 and it was assumed that a conventional blast furnace can be converted to a smelting–reduction furnace without any major problems. The energy consumption was estimated by the use of the simulation model on the basis of a heat and mass balance. The coke consumption in a commercial plant is expected to decrease to about half that of the pilot plant. The direct cost of ferrochromium production should therefore be reduced by 25 to 50 per cent when the credit for byproduct gas is taken into account.

Conclusion

Based on fundamental studies and pilot-plant tests, Kawasaki Steel Corporation has developed a smelting reduction process (the STAR process) in which a coke packed bed is used to produce ferroalloys from fine ore and low-grade coke. The following results were obtained.

(1) The chromium content in the metal can be controlled easily and rapidly by variations in the ratio of the iron ore, chromium ore, and flux.

(2) For stable operation, it is important to control the fluidity and melting point of the slag by adjustment of the slag composition.

(3) Operating conditions and equipment requirements for scaling up the process can be estimated from the data obtained in this study.

(4) The production cost of ferrochromium on a commercial scale by the STAR process was estimated to be 25 to 50 per cent less than by the conventional process.

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