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A new smelting reduction process with coke-packed bed (Kawasaki's STAR process) has been developed to produce ferroalloys or pig iron, by using low grade coke and fine ores. The process is characterized by (1) coke-packed bed shaft furnace, (2) installation of two-stage tuyeres, (3) direct use of fine one without agglomeration, (4) gravitational powder transportation and injection through the upper tuyere, and (5) fluidized bed pre-reduction furnace for full utilization of a by-product gas. Bench scale tests of smelting reduction, gravitational powder transportation and fluidized bed pre-reduction were carried out independently to confirm the principle and the effectiveness. Campaigns of the pilot plant test for the production of ferrochromium were successfully done in 1986. The scale-up for ferrochromium production of 100 t/d was investigated, and the production cost by the process was shown to be more economical than that by an electric furnace.

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1 Introduction

Compared with ferroalloy production by the electric furnace or iron production by the blast furnace, smelting reduction processes have many advantages from the viewpoint of raw materials, energy sources, investment cost, and control of environmental problems. Although the features of the processes are not necessarily the same due to local conditions and needs, various smelting reduction processes have been under development,[1~10] with the following advantages expected:

(1) Simple process flow and low investment cost
(2) Utilization of cheaper energy sources
(3) Utilization of the fine ores without agglomeration
(4) Less environmental pollution

Kawasaki Steel has developed a new smelting reduction process with a coke-packed bed (called the **STAR** process) for the production of ferroalloys, on the basis of fundamental studies and shaft furnace technologies.[11~22] The STAR process has the above advantages and allows direct use of low grade coke and fine ores.

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

2 History of Research and Development

Figure 1 shows the chronology of research and development in connection with the pre-reduction and smelting-reduction processes at Kawasaki Steel. Fluidized bed technologies were developed as a basic pre-reduction process for the direct use of fine ore. Fundamental studies of iron ore reduction by the fluidized bed method were begun in 1972. Both the circulating fluidized bed and the bubbling fluidized bed were developed on a bench scale, and the fundamental technology was established by 1979. The development of fluidized

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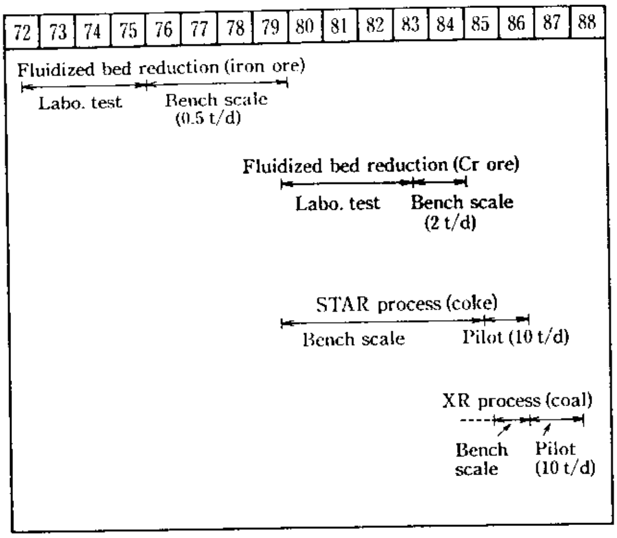

Fig. 1 History of R & D on the smelting reduction process at Kawasaki Steel Corp.

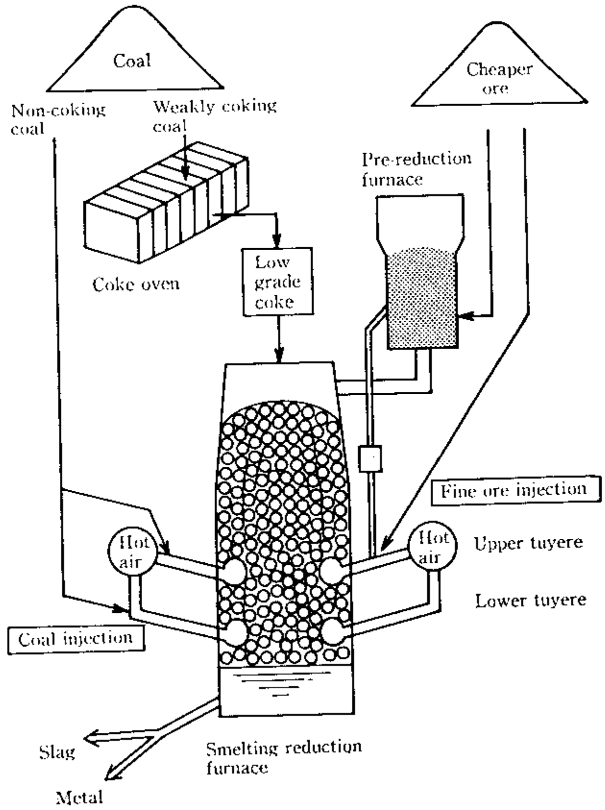

Fig. 2 Process image of STAR process

bed pre-reduction of chromium ore began in 1979, and bench scale tests of 2 t/day were completed in 1984. The STAR process using low grade coke and fine ore was developed in parallel with the pre-reduction process for chromium ore as a source of cheaper ferrochromium. The pilot plant tests of the STAR process were carried out successfully in 1986, and data for upscaling and operational know-how were obtained.

Kawasaki Steel is now developing the XR process, a more advanced smelting reduction process which permits direct use of fine ore and coal.

3 Features of STAR Process

The concept of the STAR process is shown in **Fig. 2**. The STAR process is characterized by

(1) A coke packed bed shaft furnace,
(2) Installation of two stage tuyeres,
(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 by-product gas is fully utilized as fuel.

3.1 Coke Packed Bed Shaft Furnace and Two-Stage Tuyeres

The shaft furnace is filled with small size coke. The temperature of the exhaust gas from the furnace is relatively low, as 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 tuyeres and consequently the deterioration of coke under heavy burden loading or by solution-loss reaction in the shaft need not be taken into consideration. Pulverized coal injection through the tuyeres is in principle also possible as a means of decreasing coke consumption.

Two-stage tuyeres play an important role in this process, and are effective for the smelting reduction of ores which are difficult to reduce such as chromium. The ore injected through the upper tuyere 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 heat supply and the area of the high temperature region are easily controlled by properly distributing the blast between the upper and lower stage tuyeres.

3.2 Gravitational Powder Transportation System

Two kinds of gravitational powder transportation system can be installed; both are shown schematically in **Fig. 3**. The power required for powder transportation is supplied by gravity in both systems. Compared with the ordinary pneumatic powder transportation system, these

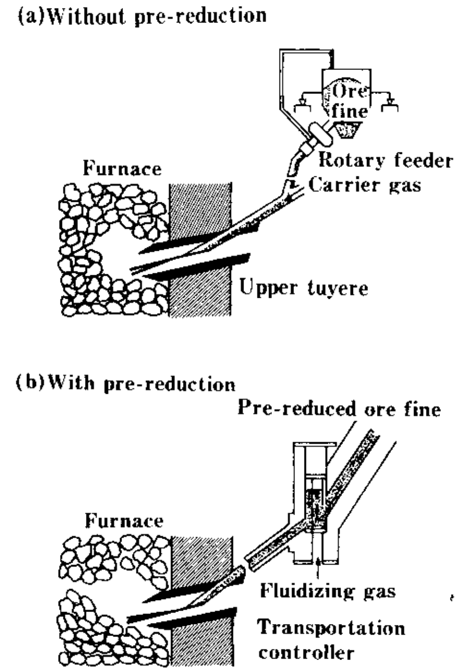

Fig. 3 Schematic diagram of gravitational powder transportation system

systems have advantages of low flow rate 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 tuyeres. In system (b), with pre-reduction, hot pre-reduced ore must be injected against back pressure because the pre-reduction furnace operates at 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 adjusting the fluidizing gas from the small fluidized bed installed toward the bottom of the transportation pipe. This system ensures high reliability by the elimination of moving parts.

3.3 Pre-reduction by Fluidized Bed

Less reducible ores such as chromium can be smelted without pre-reduction using the fluidized bed process. However, pre-reduction is useful when by-product gas is not fully utilized in the works. Thermodynamically, chromium ore is difficult to reduce at relatively low temperatures with ordinary reductants such as CO or H_2. Conventionally, it is pelletized and pre-reduced by a rotary kiln at temperatures as high as 1300 to 1400°C. In this process, however, chromium ore is pre-reduced in a fluidized bed, and the reduction temperature can be lowered to about 1100°C by using hydrocarbons as the reductant and exhaust gas from the smelting reduction furnace as a heat source.[11] Fluidized bed pre-reduction is advantageous in terms of the utilization of the fine ore without agglomeration and shorter reduction time.

4 Fundamental Studies and Bench Scale Test

4.1 Smelting Reduction Behavior in a Coke-Packed Bed

An understanding of the behavior 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 tuyeres. As a first step in this study, the melting, reducing, foaming, and dripping behavior of chromium ore with the addition of flux in a coke-packed bed were examined in an experimental furnace using a X-ray fluoroscope.[12~14] A coke-packed bed with an inner diameter of 400 mmϕ and a height of 100 mm was maintained at an elevated temperature in an electric furnace, while sample pellets of 2~3 mmϕ, which were made from chromium ore and flux of various compositions, were continuously fed into the furnace. The amount of dripped slag and metal was measured with a load cell. Marked changes in the smelting reduction behavior 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 min from the start of charging, began to boil, and were reduced during dripping in the coke-packed bed. In an 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 stopped.

Figure 4 shows the effect of coke size on the static hold-up of molten ore and flux. Static hold-up is mainly

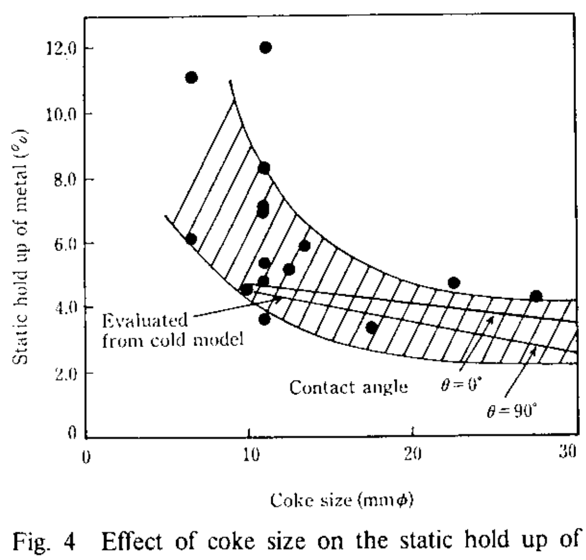

Fig. 4 Effect of coke size on the static hold up of metal

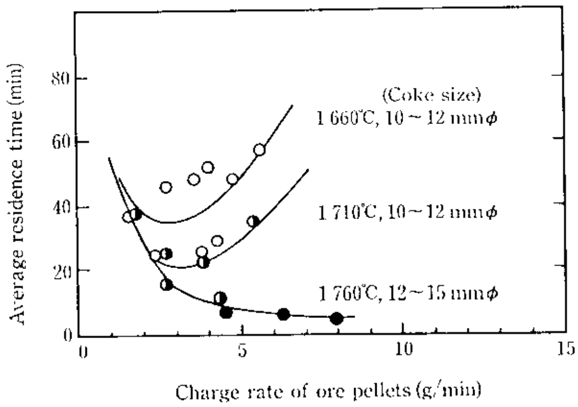

Fig. 5 Effect of the charging rate of ore on the average residence time in the coke-packed bed

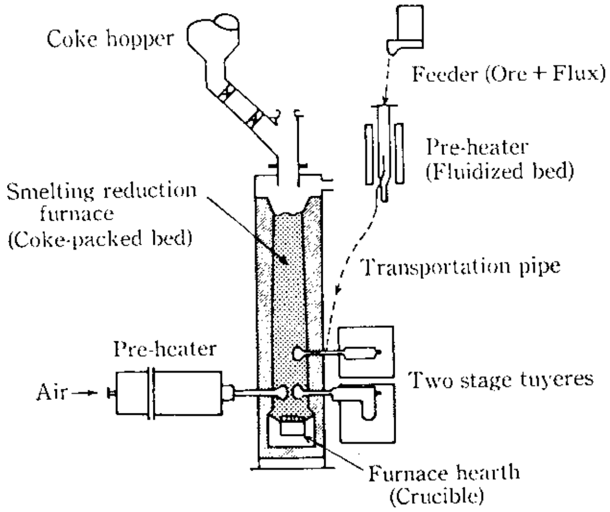

Fig. 6 Schematic diagram of the bench scale smelting reduction furnace

dependent on coke size. When the coke size is larger than 14 mm, the amount of metal hold-up is estimated to be almost the same as with a cold model test. This observation suggested that the coke size should be larger than 14 mm.

Figure 5 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, average residence time decreases with increased ore charging, but increases very sharply with further increases in the charging rate because the heat supply becomes inadequate to maintain the endothermic reaction which characterizes smelting reduction. This problem is easily solved with the two-stage tuyeres, as the heat supply to the smelting reduction zone can be controlled by properly distributing the hot blast between the upper and lower tuyeres, demonstrating one of the advantages of this system.

4.2 Bench Scale Tests of 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 tuyeres.[15] The reactor of the coke-packed bed with the two-stage tuyeres is shown in **Fig. 6**. The furnace proper had an inner diameter of 400 mm, an effective height of 2350 mm, and one upper tuyere and three lower tuyeres. Coke 10 to 15 mm in diameter was used. After the furnace was fully heated by coke combustion, chromium ore preheated to 600°C was fed with N_2 gas through the upper tuyere. The ore injection rate was controlled by monitoring 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 **Fig. 7**. As the ore injection rate is increased, Cr_2O_3 concentration in the slag also tends to increase. When the oxygen concentration in the blast is

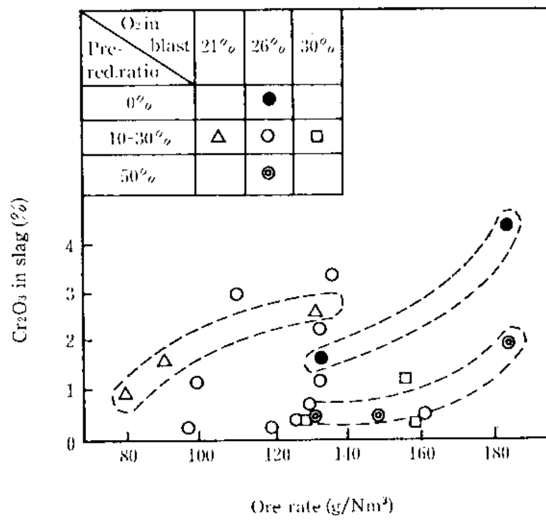

Fig. 7 Effect of the ore injection rate on Cr_2O_3 content in slag

increased, Cr_2O_3 concentration tends 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 the coke-packed bed type smelting reduction furnace, it may be noted, is lower than that of slag from the electric arc furnace.

Figure 8 shows the relationship between C and Si in the product metal. According to experimental conditions, Si varies from 1% to 10%. The similarity of this relationship to that in ferrochromium production by the electric furnace suggests that the coke-packed bed type smelting reduction furnace is similar in smelting reduction behavior to the electric furnace.

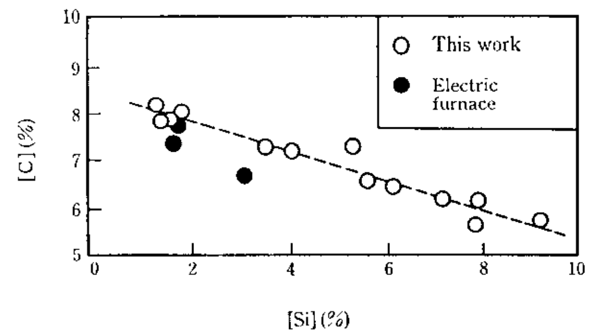

Fig. 8 Relation between C and Si content in metal

4.3 Gravitational Ore Transportation System

One of the fundamental features of the STAR process is the direct injection of fine ore into the smelting reduction furnace through the upper tuyeres. The abrasion of the transportation tubes and injection tubes is a serious problem with the conventional pneumatic powder transportation system, and may become even more serious when hot pre-reduced ore is used. Thus, the realization of a practical STAR process required development of a reliable powder injection system with less abrasion of the facilities.

The experimental apparatus used in the cold model tests is shown schematically in **Fig. 9.**[16] The hopper and container were regarded as a pre-reduction furnace and smelting reduction furnace respectively. As the ore flow rate control device, a small fluidized bed was used, in which the flow rate of the ore was controlled by the amount of fluidizing gas. The effects of fluidizing gas volume, transport pipe angles θ_1, θ_2, the required powder height to seal off back pressure and others were studied.

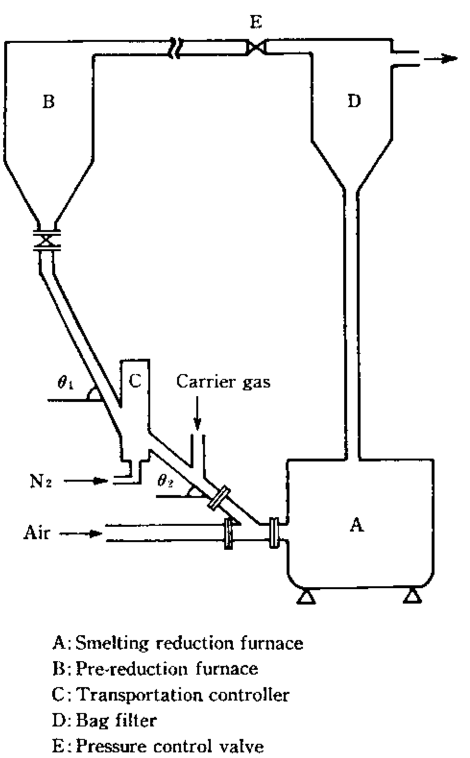

Fig. 9 Experimental apparatus for the gravitational powder transportation

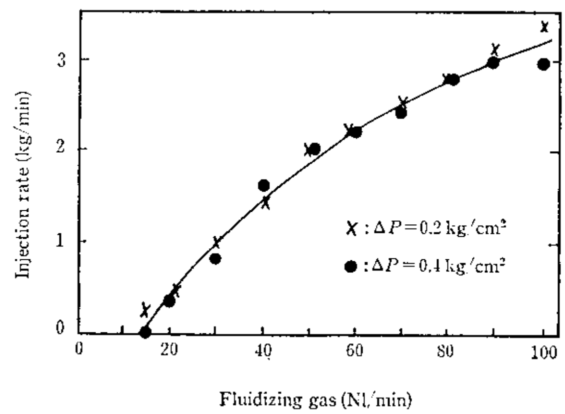

Fig. 10 Influence of the fluidizing gas amount on the ore injection rate

Stable injection was obtained in the range of θ_1 between 45 and 75° and in the range of θ_2 greater than 35°. Unstable descent of the ore occurred when the angle was too small, while, on contrary, slugging in the transportation pipe occurred at larger angles. In this system, a high solid ratio-to-carrier gas ratio ranging from 70 kg/m^3 to 150 kg/m^3 was obtained even at low carrier gas velocities of less than 10 m/s.

Figure 10 shows the relation between the injection rate and the fluidizing gas volume.[17] This result ensures that the flow rate can be controlled stably and accurately by adjusting the fluidizing gas volume even when pressure differences are great. Further, the application of this system to dust recycling is also suggested.

As is mentioned above, the gravitational ore transportation system has no moving parts and is applicable to the smelting reduction process. The advantages of this system have already been confirmed in the pilot plant test.

5 Pilot Plant Tests

Figure 11 and **Photo 1** show a schematic diagram of the pilot plant and an overview respectively. The hearth diameter of the furnace was 1.2 m. Three sets of two-stage tuyeres were installed at the furnace. The profile of the furnace, distance between the two-stage tuyeres, and operating conditions such as coke size, flux compositions, and oxygen enrichment were determined by fundamental studies. Five test campaigns were carried

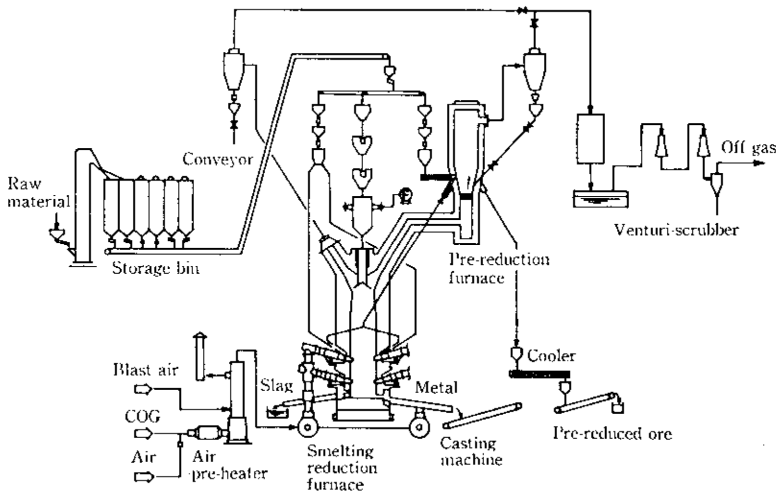

Fig. 11 Schematic diagram of the pilot plant

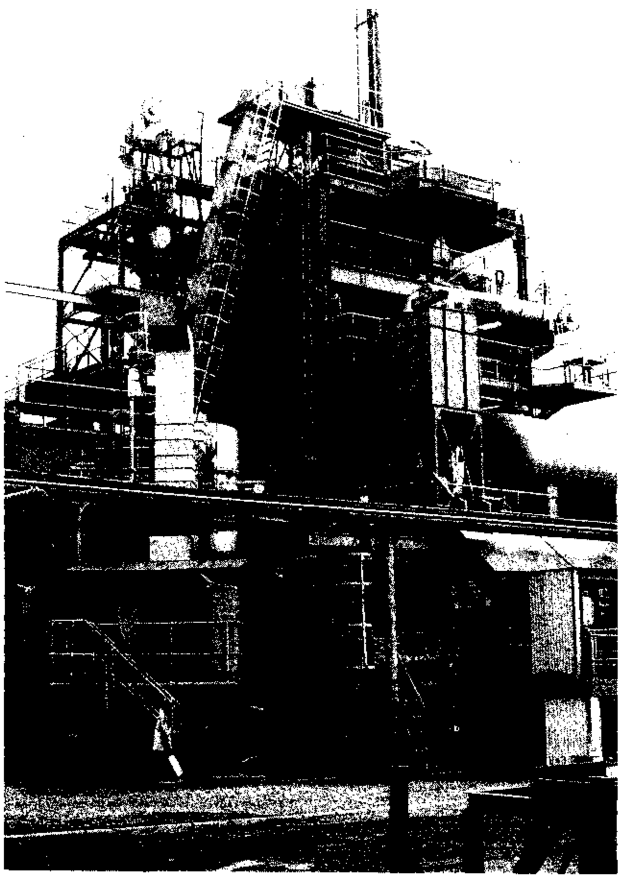

Photo 1 External view of the pilot plant

out in 1986, as shown in **Table 1**.

Several kinds of metal such as iron and ferrochromium were produced using low grade coke and fine ores.[18~20] Operating conditions were adjusted according to the metal produced. Good fluidity of the slag is very important to maintaining stable continuous operation.

Table 1 Operation tests of pilot plant

Test campaign	Date (1986)	Period (day)	Produced metal
1 st	April	10	Pig iron
2 nd	June	14	Pig iron Cr-pig iron
3 rd	July-Aug.	14	Pig iron Cr-pig iron Ferrochromium
4 th	Sept.-Oct.	14	Pig iron Cr-pig iron Ferrochromium
5 th	Nov.-Dec.	12	Ferronickel Cr-Ni-pig iron

On the basis of the fundamental studies, the SiO_2, Al_2O_3, CaO and MgO content of the slag were adjusted to obtain the optimal fluidity and melting poinf, and smooth operation was attained. These campaigns were carried out without pre-reduction on the premise that a commercial unit would be constructed in a location where by-product gas is fully utilized. The major results are described below.

Chromium content in the metal can be controlled easily and rapidly by changing the ratio of iron ore, chromium ore and flux. **Fig. 12** shows the relation between the Si content of the metal and Cr content of the slag. The Cr content of the slag increased with decreased Si content, which reflected thermal conditions. Compared with FeCr production by the electric furnace, the yield of chromium is higher.

Concerning the sulfur partition between metal and slag, good desulfurization was achieved in spite of the relatively low basicity, ranging from 1.0 to 1.2. Even in commercial operation, S in metal should not be a problem as the slag volume in FeCr production is larger than that in pig iron production.

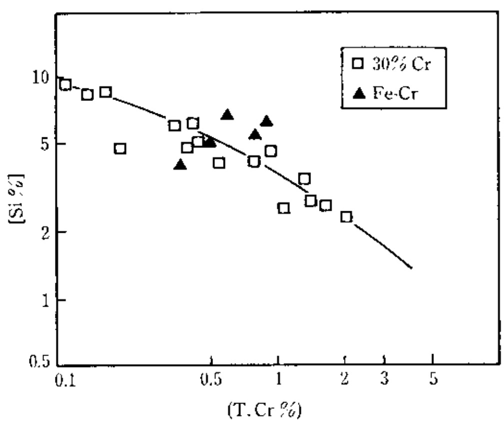

Fig. 12 Relation between Si content in metal and T.Cr in slag

Top gas temperature varied in the range from 700°C to 1000°C, and was mainly dependent on the coke ratio regardless of the chromium content of the metal. The coke ratio was very large in the pilot plant operation as heat loss from the furnace was large. However, heat loss is generally reduced as the scale of the furnace is increased, so coke consumption and top gas temperature should decrease greatly in the commercial plant.

It is evident from the above-mentioned results of the pilot plant tests that the STAR process is preferable to conventional methods of producing ferroalloys such as ferrochomium.

6 Upscaling 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 conditions on this relationship, must be clarified as a basis for upscaling the smelting reduction furnace. Further, the makeup of the smelting reduction region must be taken into account in upscaling the process.

The smelting reduction furnace is divided into three zones, as shown in **Fig. 13**. The ratio of heat consumed in the smelting reduction to supplied heat, E_f, is based on the partial heat balance of zone II.[21] The heat utilization rate E_f is defined as follows.

$$E_f = Q_M / Q_2$$

where, Q_M is the heat required for the smelting reduction and Q_2 is the effective heat supplied to zone II. E_f indicates the substantial utilization of supplied heat be-

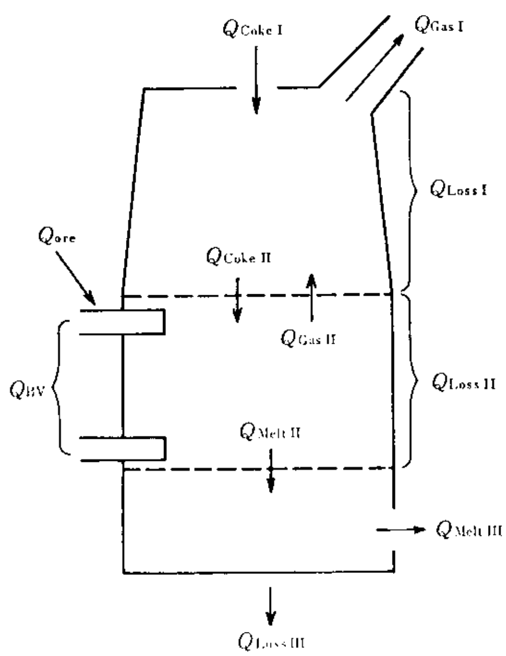

Fig. 13 Outline of the heat balance model

Table 2 An example of heat balance and parameter E_f of the pilot plant test

	Zone I		Zone II		Zone III	
Input	4 890 kcal/h		[A] 8 930 kcal/h		980 kcal/h	
Out put	Q_{Gas}	3 060	Q_R	[C] 3 230	Q_{Melt}	940
	Q_{Loss}	320	Q_{Loss}	[B] 810	Q_{Loss}	40
	Q_{Coke}	1 510	Q_{Gas}	4 890	—	—
	Total	4 890	Total	8 930	Total	980

$$E_f = \frac{\boxed{C}}{\boxed{A} - \boxed{B}} = 0.40$$

tween the upper and lower tuyeres, and is an important factor in determining the productivity of the furnace. An example of the heat balance of each zone in the pilot plant test and the calculation of E_f is shown in **Table 2**.

A parameter P, defined as follows, can thus be introduced in order to evaluate the effects of operating and equipment conditions on E_f.

$$P = f(L/G, n, D_r, a, H, A)$$

where n: number of sets of two stage-tuyeres
D_r: depth of raceway (m)
a: effective specific surface area of coke bed (m^2)
H: distance of two stage tuyere (m)
A: area of hearth (m^2)
L: amount of molten material (m^3/h)
G: amount of gas (Nm^3/h)

Here, L/G is a ratio of liquid to gas and is similar to the thermal flow ratio in blast furnace operation. Parameter P is a function related to operating and equipment conditions. The relation between E_f and P obtained from the experimental results in the bench scale tests and pilot plant test is shown in **Fig. 14**. It is clear that E_f can be estimated from the parameter P regardless of the size of the furnace and the metal produced. The furnace profile and operating conditions can be designed on the basis of this relationship.

An example of a commercial plant furnace for ferrochromium production at an output of 100 t/day designed on basis of the above-mentioned method of upscaling is shown in **Fig. 15**.[22] The furnace volume is about 150 m^3. It is considered from this figure that a conventional blast furnace can be converted to a smelting reduction furnace without problem. Further, the energy balance estimated by the simulation model based on the heat and mass balance shows that coke consumption in a commercial plant can be expected to decrease to half that in the pilot plant test. The direct cost of ferrochromium production should therefore be reduced by 25 to 50% when the by-product gas credit is taken into account.

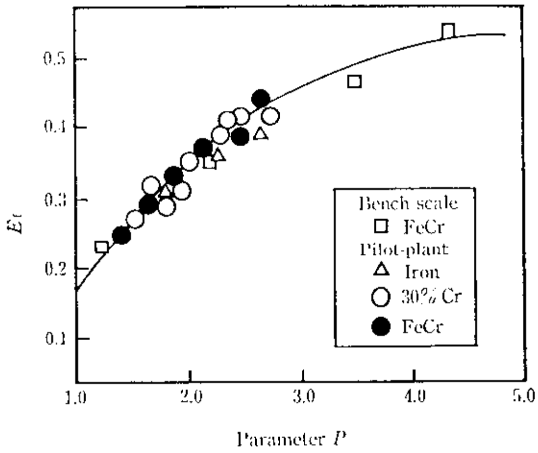

Fig. 14 Relation between E_f and parameter P

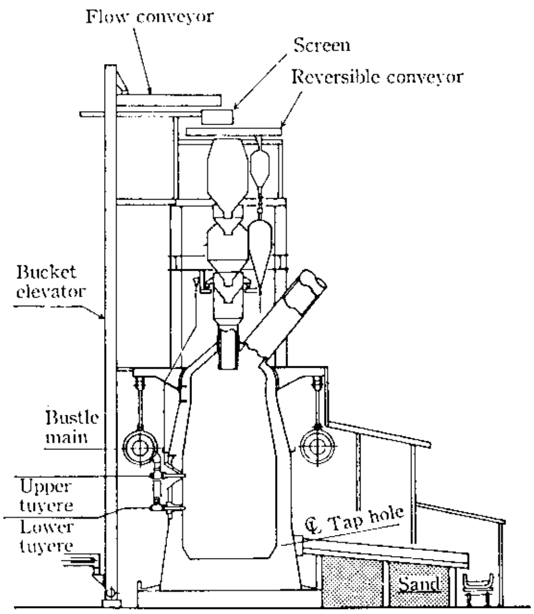

Fig. 15 An example of the smelting reduction furnace designed for the 100 t/d production of ferrochromium

7 Conclusions

Based on fundamental studies and pilot plant tests Kawasaki Steel Corp. has developed a new 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) For stable operation, it is important to control the fluidity and melting point of slag by the adjustment of slag composition.
(2) A gravitational powder transportation system was developed to feed fine ore to the smelting reduction furnace.
(3) Operating and equipment conditions for upscaling the process can be estimated from the heat utilization parameter.
(4) The production cost of ferrochromium on a commercial scale was estimated at 25 to 50% less than with the conventional process.

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