Ferro Coke Production and Its Evaluation in Blast Furnace Utilization

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Abstract:

In recent years, the reduction of CO_2 emissions and the stable supply of raw materials are two major issues for the steel industry. Low reducing agent operation in the blast furnace is required to reduce CO_2 emissions in ironmaking. In order to achieve this with using low-grade raw materials, ferro coke characterized by high coke reactivity is considered to be useful.

In this paper, the effect of ore ratio on the reactivity and strength of Ferro Coke produced in the laboratory was investigated. The two-dimensional blast furnace model based on the reaction behavior of Ferro Coke and conventional coke were constructed, and the reaction behavior and strength change in the furnace were predicted. Based on these results, the ferro coke production process was established, and the reducing agent ratio was reduced by using ferro coke in the actual blast furnace.

1. Introduction

In the steel industry, a response to environmental problems, represented by global warming, is now essential, and among those efforts, reduction of CO_2, which is a greenhouse gas (GHG), has become a critical challenge. The CO_2 generated by the steel industry accounts for approximately 15 % of the total CO_2 generated in Japan[1], with the ironmaking process accounting for about 70 % of emissions in the steel industry. As one potential solution to these problems, production of innovative raw materials with high reactivity, which enable lower temperature operation of the blast furnace, and establishment of an innovative ironmaking processes utilizing in the blast furnace have been pro-posed. Ferro Coke [2–4] is one form of these innovative raw materials. Due to the catalytic effect of the iron content of Ferro Coke, reaction of the carbon material begins from a lower temperature in comparison with conventional coke, and as a result, a reducing agent ratio (RAR) reduction effect can be expected through reduction of the temperature of the thermal reserve zone when Ferro Coke is used as a new blast furnace burden material [5–13].

In this paper, a basic study of the effect of the iron ore blending ratio on the reactivity and strength of Ferro Coke produced at the laboratory scale was carried out,[14] and a two-dimensional blast furnace model based on the reaction behavior of Ferro Coke and conventional coke was constructed and used to predict the reaction behavior and strength changes in the furnace[15]. Based on these results, the Ferro Coke production process was established, and reduction of RAR was achieved by use of Ferro Coke in an actual blast furnace.

2. Concept and Features of Ferro Coke

The Ferro Coke used in this report is a new agglomerated raw material which is different from the sinter (sintered ore) and coke traditionally used as blast furnace burden. In particular, as a type of "Carbon Iron Composite (CIC)," its manufacturing and use methods have features that are intended to greatly improve performance in the blast furnace. **Figure 1** shows the concept of CIC. Composite blast furnace burden materials such as carbon composite, and partially reduced sinter, which contains metallic iron, have been proposed [16,17].

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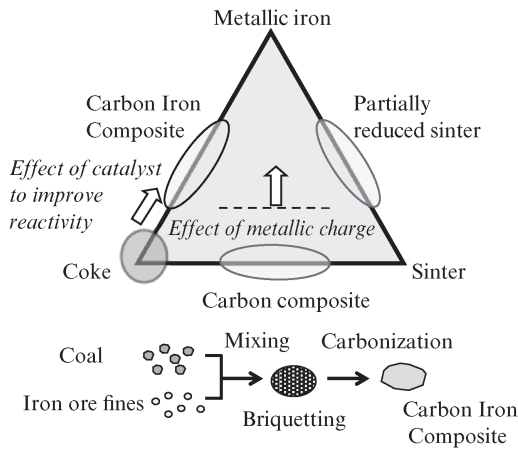Steel Res. Lab.,
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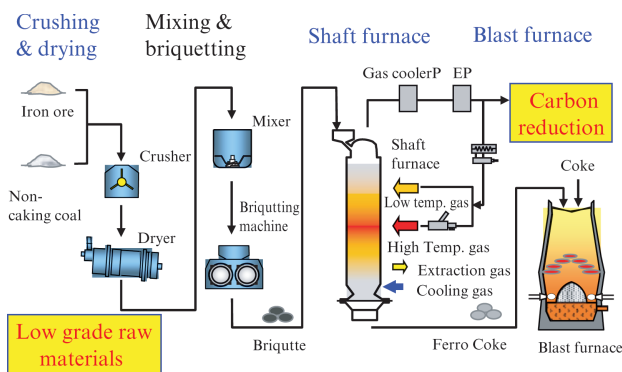Fig. 1　Conception of CIC compared with conventional burden

Fig. 2　Process flow the Ferro Coke production

While specific properties such as reactivity are strengthened in coke and sinter used as burden, these composite burden materials have a structure in which a carbon material and iron oxide coexist or the iron oxide partially contains metallic iron, which is expected to reduce the reduction load in the blast furnace by accelerating the reduction reaction. **Figure 2** shows the process flow of Ferro Coke production. Ferro Coke is a type of CIC, and is produced by crushing, mixing and briquetting (pelletizing) inexpensive iron ore and non-caking coal, which is then heated and carbonized in a shaft furnace. Since Ferro Coke is used as a blast furnace burden material, strength is also an important property, but Ferro Coke with the same strength as the
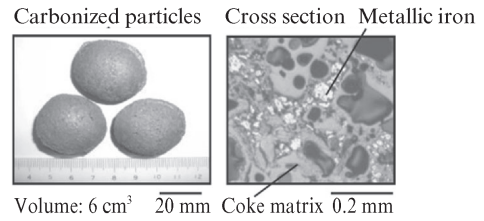

Fig. 3　Appearance of Ferro Coke

conventional coke can be produced, even when using low-grade raw materials, due to the effect of compaction in the briquetting process and comparatively precise temperature control by the shaft furnace. **Figure 3** shows the appearance of Ferro Coke. The iron ore contained in Ferro Coke is reduced almost to metallic iron by the carbonization process. As the method of using Ferro Coke in the blast furnace, mixing in ore layers consisting of sinter or lump ore is assumed. Differentiation of the functions of Ferro Coke and conventional coke is envisioned by using Ferro Coke to accelerate the ore reduction reaction and control the temperature of the thermal reserve zone, taking advantage of its high reactivity and lower solution loss reaction beginning temperature, while using conventional coke to maintain gas permeability and liquid permeability in the blast furnace.

3. Ferro Coke Strength and Reactivity Evaluation Tests

3.1 Ferro Coke Production Test

The Ferro Coke used in this experiment was produced using the coals A and B and iron ore shown in **Table 1** and **Table 2**, which were blended at the ratios shown in **Table 3** (in the tables and figures, Ferro Coke is denoted as FC). Soft pitch and asphalt pitch added in an amount of 5 to 7 mass% were used as binders. The coal was crushed to 3 mm or under and pelletized into egg-shaped briquettes with a volume of 6 cm^3 with a twin-roll molding machine at a molding pressure of 4 to 5 t/cm, using a mixed raw material containing iron

Table 1　Properties of coals

	Mean maximum reflectance in oil, Ro (%)	Gieseler lastometry maximum fluidity, MF (ddpm)	Volatile matter, VM (mass %) dry basis	Ash (mass %) dry basis
Coal A	0.72	307	36.1	8.4
Coal B	1.80	0	11.2	8.6

Table 2　Chemical composition of iron ores (mass %)

	T.Fe	FeO	CaO	SiO$_2$	Al$_2$O$_3$	MgO	P	S	Na	K
Ore	67.5	0.21	0.01	1.31	0.73	0.01	0.033	＜0.01	＜0.01	＜0.01

Table 3　Blending conditions of raw materials (mass %)

Sample	Blending ratio				Iron ore ratio
	Coal A	Coal B	Ore	Binder	
FC-1	66.5	28.5	—	5.0	0.0
FC-2	59.8	25.7	9.5	5.0	9.5
FC-3	46.5	20.0	28.5	5.0	28.5
FC-4	33.2	14.3	47.5	5.0	47.5
FC-5	45.6	19.5	27.9	7.0	27.9

Fig. 5　Gas composition of experimental condition

ore blended at the specified ratio. Approximately 3 kg of the briquettes was placed in coke breeze, which was then filled in a carbonizing drum (width 200×depth 200×height 245 mm) and carbonized at a furnace wall temperature of 1 000°C for 6 h to obtain Ferro Coke. Based on the results of measurements of the temperature in the center of the coal charge layer in coke making, these conditions are equivalent to holding for 3 h at 900°C. In order to compare the reactivity in the blast furnace and strength after reaction of conventional coke with those properties of Ferro Coke, coke produced by an actual coke oven was sampled and used after size adjustment to 20±1 mm.

3.2 Ferro Coke Quality Evaluation Test

To evaluate the strength of Ferro Coke with different ore blending ratios, a drum strength test was carried out at the specified rotation speed using a I-type test machine (ϕ 130 mm×700 mm), and the remaining ratio of the specified particle size was evaluated. The percentage of the remaining on a 10 mm screen after 600 rotations to the tested weight of the sample was evaluated as the index I^{600}_{10}. For the above-mentioned Ferro Coke, reaction tests were conducted with the under-load reduction test system shown in **Fig. 4** using a gas composition simulating the conditions in a blast furnace, as shown in **Fig. 5**[14]. The Ferro Coke was crushed to 6 to 8 mm. The CO and CO_2 in the gas dur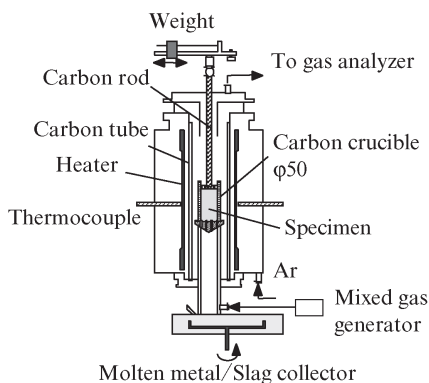ing the experiment and after reaction were analyzed using an infrared analyzer. The amount of the gasification reactions of the conventional coke and Ferro Coke by the carbon solution loss reaction was quantified from the carbon concentration of the exhaust gas and the oxygen balance. The gas rate in this experiment was 11.8 NL/min. The heating-up rate in the under-load reduction test was 9.0°C/min up to 900°C, 2.3°C/min from 900 to 1 100°C and 4.2°C/min above 1 100°C.

For Ferro Coke FC-5, the difference in reactivity with the conventional coke was evaluated using the above-mentioned under-load reduction test system. In this experiment, the Ferro Coke was used without crushing. In order to evaluate the strength after reaction, a reaction test was carried out in an atmosphere of CO 30 vol%-CO_2 30 vol%-N_2 40 vol% under a uniform temperature condition of 970 to 1 250°C, and the relationship between reactivity and strength after reaction was investigated. Strength was evaluated as I^{600}_{10} by the above-mentioned I-type test machine.

4. Experimental Results and Discussion

4.1 Effect of Ore Ratio on Ferro Coke Reaction Behavior

Figure 6 shows the relationship between the iron ore ratio and strength of Ferro Coke (FC-1 to FC-4) with different iron ore blending ratios. Although the same coal blend is used in FC-1 to FC-4, the strength of the

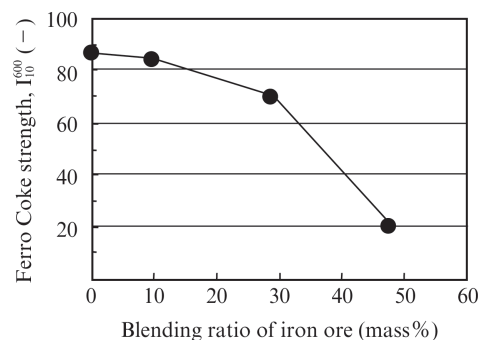Fig. 4　Schematic illustration of under-load reduction test system

Fig. 6　Effect of iron ore ratio on Ferro Coke strength

Ferro Coke after carbonization decreases as the ore blending ratio increases. Nomura et al. also reported that the strength of an iron-coke formed product after carbonization decreased as the amount of added fine ore increased[11]. In particular, I^{600}_{10} was remarkably low, at around 20, in FC-4 with 47.5 mass% addition of iron ore. The iron which is added as ore is almost all Fe_2O_3 before carbonization, but after carbonization, reduction had proceeded to a metallization ratio of approximately 80 %. Based on this, it is thought that strength of Ferro Coke decreased at higher iron ore contents in the raw material due to consumption of the carbon surrounding the ore by the reduction reaction, a decrease in the plasticity of the coal [18, 19] and a decrease in the ratio of carbon material, which manifests strength when coke is formed by carbonization, etc.

In order to investigate the effect of the iron ore blending ratio on the gasification reaction beginning temperature, an under-load reduction test was conducted up to a temperature of 1 200°C using the above-mentioned Ferro Coke (FC-1 to FC-4) with different ore blending ratios. **Figure 7** shows the relationship of the gasification reaction rate of Ferro Coke and temperature. Since the highest gasification reaction temperature occurred in FC-1, which contains 0.0 % iron ore, while the gasification reaction was detected from lower temperatures in the order of increasing iron ore ratios in FC-2 (ore ratio: 9.5 %), FC-3 (28.5 %), FC-4 (47.5 %), it can be concluded that the gasification reaction occurs from lower temperatures as the ore ratio increases. The gasification reaction beginning temperature was quantified from the gasification reaction rates shown in Fig. 7. Under the conditions of this test, a reaction rate of around $10^{-5}s^{-1}$ is considered to be the limit of detection due to the resolution of the analyzer, but because there were variations in the measurement results at low temperatures, the temperature where the reaction rate becomes $2 \times 10^{-5}s^{-1}$ was assumed
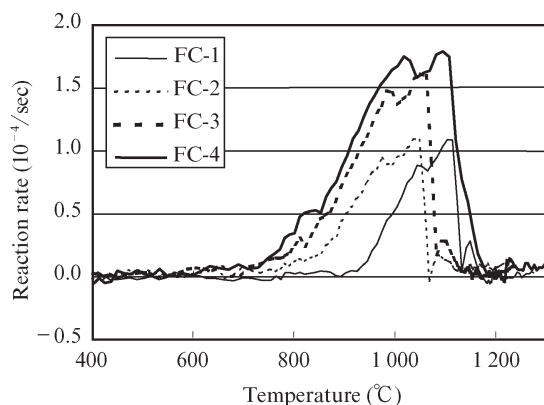
as the reaction beginning temperature. **Figure 8** shows the relationship of the iron ore blending ratio in the raw material and the reaction beginning temperature. Although the reaction beginning temperature is lower in the case of higher ore blending ratios, that relationship was not linear, and the slope in Fig. 8 tended to become smaller as the blending ratio of the ore increased. Nomura et al. also reported that the reaction beginning temperature decreases as the blending ratio in coke increases[11]. The reaction beginning temperature of FC-1 (ore ratio: 0.0 mass%) was 950°C, but decreased by approximately 150°C in FC-3 (ore ratio: 28.5 mass%). When a reaction test was conducted under the same conditions as the under-load reduction test and the weight loss of the conventional coke and Ferro Coke was measured, the temperature at which the weight loss of the samples reached 0.1 mass% was 970°C for the conventional coke but decreased by 140°C, to 830°C, in FC-3 (ore ratio: 28.5 mass%). Although the reactivities of the conventional coke and Ferro Coke with 0.0 mass% iron ore (FC-1) were slightly different, it was found that the gasification reaction began at a temperature 140 to 150°C lower in FC-3 (ore ratio: 28.5 mass%) compared to that of the conventional coke and Ferro Coke, which did not contain iron ore in the raw material. From the relationship of the reaction beginning temperature in the under-load reduction test and the iron ore blending ratio, it was found that the reaction beginning temperature can be decreased with a higher ore blending ratio. However, when considering use in the blast furnace, strength after carbonization is also important. Because FC-4 with 47.5 mass% added iron ore showed a remarkably low I^{600}_{10} of around 20 in comparison with the value of conventional coke, which is 80 or more, use of FC-4 in the blast furnace is considered difficult. If both of these requirements are taken into account, among the Ferro Coke used in this test, the product with the iron ore blending ratio of 28 to 29 mass% is considered appropriate, and in the following, the evaluation of the

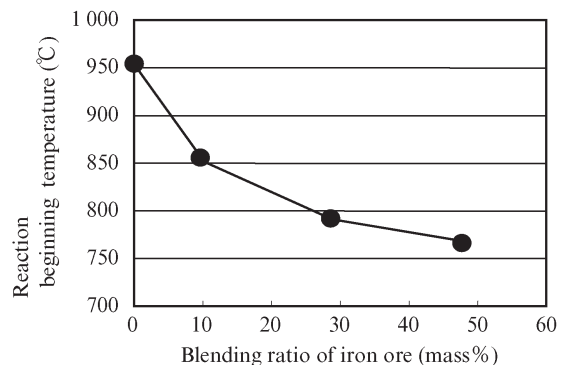Fig. 7   Effect of iron ore ratio ore on reaction rate of Ferro Coke

Fig. 8   Effect of iron ore ratio on reaction beginning temperature of Ferro Coke

blast furnace when using Ferro Coke was carried out under this condition.

4.2 Results of Reactivity Measurement of Ferro Coke and Conventional Coke

Figure 9 shows the results of an under-load reduction test simulating the gas and temperature conditions in a blast furnace, which was conducted using FC-5 (ore ratio: 27.9 mass%) and simple conventional coke in order to measure the reaction beginning temperatures of Ferro Coke and conventional coke. With both samples, the percentage of the gasification reaction (ΔC%) measured with an infrared gas analyzer increased as the temperature rose. When the results were arranged with the temperature at which 0.1 mass% of the charged coke had reacted as the reaction beginning temperature, the reaction beginning temperature of FC-5 was 824°C while that of the conventional coke was 973°C, confirming that Ferro Coke has higher reactivity than conventional coke.

4.3 Results of Measurement of Strength after Reaction

As a quality evaluation of coke in the blast furnace, coke strength after reaction (CSR) is evaluated by drum strength from the viewpoint of suppressing powder generation. To evaluate strength after reaction, a reaction test was carried out under a uniform temperature condition using FC-5 and conventional coke. In this test, the reaction ratio was changed by changing the reaction time under the respective conditions, and the relationship between the reaction ratio and strength after reaction was investigated. **Figure 10** shows the experimental results. With both the Ferro Coke and the conventional coke, strength after reaction decreased as the reaction ratio increased. However, it can be understood that the decrease in strength with respect to the increase of the reaction ratio of 1 %, which is indicated by the slope of the lines in Fig. 10, differed depending on the sample and the reaction temperature.
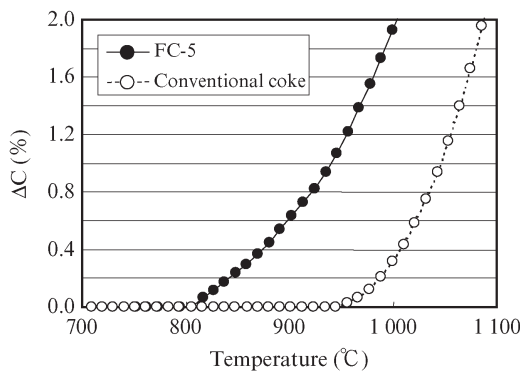

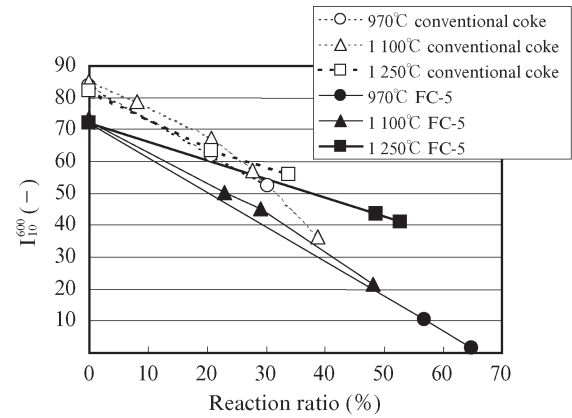Fig. 9 Comparison of reaction beginning temperature between Ferro Coke and conventional coke

Fig. 10 Relationship between reaction ratio and strength after reaction

5. Study of Ferro Coke Reaction Behavior in the Blast Furnace

The condition in a blast furnace was estimated by using a 2-dimensional blast furnace model[20] premised on the use of FC-5 at a unit rate of 101 kg/t-pig, on the assumption that the gasification beginning temperature is 150°C lower than the "Base" condition, based on the results of the experiment described above. The calculation conditions and results are shown in **Table 4**. Here, the reducing agent rate (RAR) shown for "Case" in Table 4 is a value which includes Ferro Coke with an ore blending ratio equivalent to that of FC-5. Assuming a gasification beginning temperature of 1 050°C as the Base condition, the Case calculation was performed assuming a condition in which this temperature is 900°C. The hot metal temperature increased, as shown in Table 4. **Figure 11** shows the temperature distribution in the blast furnace height direction and the reaction rate distributions of the coke solution loss reaction ($C+CO_2=2CO$) and the smelting reduction reaction ($FeO+C=Fe+CO$) at the nondimensional radial position r/R=0.75. the temperature of the region where the temperature gradient in the height direction becomes

Table 4 Calculation conditions and results with 2-dimensional blast furnace model

Calculation conditions		Base	Case
Coke rate	(kg/t-pig)	368	266
Pulerized coal rate	(kg/t-pig)	126	126
Ferro Coke rate	(kg/t-pig)	0	101
Reducing agent rate	(kg/t-pig)	494	493
Thermal reserve zone temp.	(°C)	1 050	900
Results		Base	Case
Hot metal temp.	(°C)	1 502	1 511
Production	(t/day)	12 250	12 340
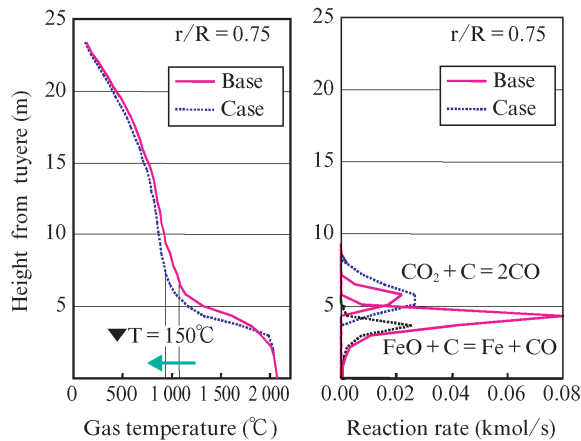
Fig. 11 Changes in gas temperature and reaction rates with Ferro Coke charging

Fig. 12 Changes in reaction ratio and estimated coke strength with Ferro Coke charging

small, i.e., the temperature of the thermal reserve zone, decreased by approximately 150°C when Ferro Coke was used. Although the solution loss reaction increases as a result of the lower gasification beginning temperature of the coke, the smelting reduction reaction with FeO decreases because the reduction reaction of the iron ore also proceeds from a lower temperature and the ore reduction rate at 1 400°C is equivalent to the lower edge of the cohesive zone. As a result, the indirect reduction rate increased, and the hot metal temperature rose, as shown in Table 4. Next, the reaction ratios of Ferro Coke and conventional coke in the blast furnace height direction were studied based on the calculation results. On the assumption that Ferro Coke reacts preferentially to conventional coke in the blast furnace [11, 12], the reaction rate of the Ferro Coke at the lower edge of the cohesive zone was assumed to be 52 % from the results of the under-load reduction test. It was also assumed that contact with molten FeO is rate-controlling for smelting reduction reaction, and the reaction velocities of the Ferro Coke and the conventional coke were the same. Based on these assumptions, the average reaction ratios of the Ferro Coke and the conventional coke in the blast furnace height direction were obtained. The results of the comparison with the Base condition are shown in **Fig. 12**. As described above, although the solution loss reaction increased, the smelting reduction reaction decreased, and the equilibrium reaction ratio combining the Ferro Coke and the conventional coke decreased in comparison with the Base case due to lowering of the reaction beginning temperature. Based on the temperatures at the various positions and the change of the respective reaction ratios of the Ferro Coke and the conventional coke, the strength decrease was estimated from Fig. 10. However, with both Ferro Coke and conventional coke, the decrease in strength against the increase in the reaction ratio was uniform at temperatures of 970°C and
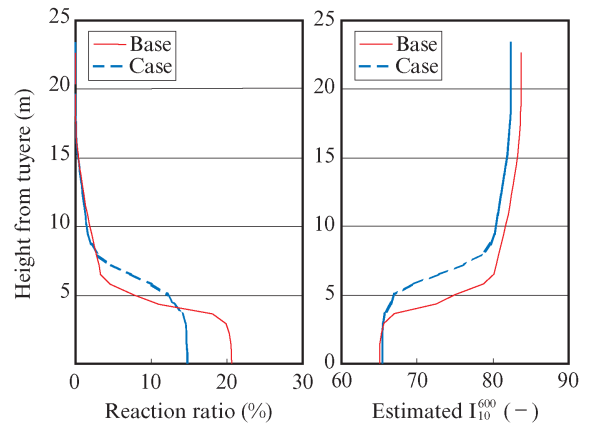
less and 1 250°C and more. Figure 12 shows the estimated transition of the average strength of the Ferro Coke and the conventional coke in the blast furnace height direction. Because the reaction position of the solution loss reaction shifts upward accompanying the lower gasification beginning temperature of the coke, the position where the strength decrease occurs also shifts upward. Moreover, focusing on the consumption of carbon in Fig. 11, because the amount of the solution loss reaction increases in comparison with the Base condition, the decrease in strength due to the solution loss reactions of the Ferro Coke and the conventional coke becomes larger in comparison with the Base condition, but because the amount of reaction by smelting reduction decreases greatly in comparison with the Base condition, the strength decrease is smaller when the combined effect of these two reactions is considered. On the other hand, since it has also been reported that the decrease in coke strength is smaller in the smelting reduction reaction than in the solution loss reaction [21], a detailed investigation of the strength decrease due to the smelting reduction reaction will be necessary in the future.

6. Demonstration Test

6.1 Production of Ferro Coke on 30 t/d Scale and Use in Blast Furnace

A Ferro Coke production plant with a scale of 30 t/d was constructed at JFE Steel's East Japan Works (Keihin District), and a demonstration test of the production capacity of 30 t/d and a Ferro Coke use test in a large-scale blast furnace were conducted. Approximately 2 100 t of Ferro Coke was prepared, and a use test in an actual blast furnace was carried out over a 5-day period. **Figure 13** shows changes in the pulverized coal rate, coke rate, the permeability index F2 [22] cor-
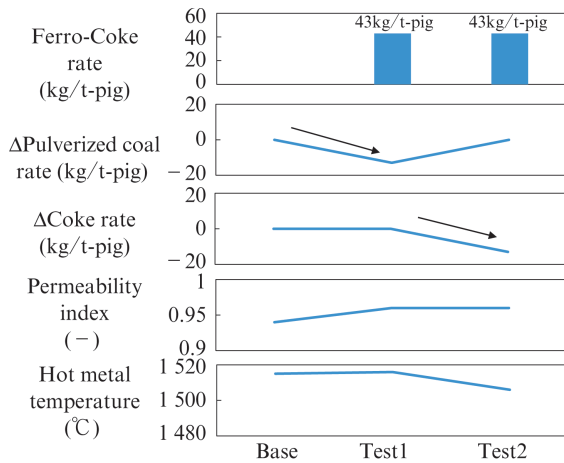
Fig. 13 Operation results of charging Ferro Coke in blast furnace

rected for the blast furnace profile and temperature and pressure, and the average hot metal temperature for the Base period before use of the Ferro Coke and test periods 1 and 2 during use of the Ferro Coke. In test period 1, pulverized coal was replaced with Ferro Coke, and in test period 2, coke was replaced with Ferro Coke. As the results of these tests, there was no deterioration in the permeability resistance of the blast furnace, and reduced RAR operation was realized in an actual blast furnace by using Ferro Coke.

6.2 Production of Ferro Coke on 300 t/d Scale and Use in Blast Furnace

The NEDO commissioned project "Technological development of ironmaking process utilizing Ferro Coke" was started in 2017. As part of this project, a 300 t/d scale Ferro Coke plant with an expanded production scale has been constructed at West Japan Works (Fukuyama District), and the Ferro Coke production technology will be established and the effects of continuous, long-term charging of Ferro Coke in a blast furnace on the reducing agent rate (RAR) and operational stability of the blast furnace will be confirmed.

7. Conclusion

Using Ferro Coke produced at the laboratory scale, reaction and strength tests were conducted under various conditions, the reaction behavior in the blast furnace was estimated using a 2-dimensional blast furnace model, and the effect on the reducing agent rate (RAR) when Ferro Coke is used in actual operation was investigated. As a result, the following knowledge was obtained.

(1) The gasification reaction begins from a lower temperature when Ferro Coke with a high blending ratio of iron ore is used. In comparison with samples containing no iron ore, the reaction began from a temperature approximately 150°C lower when Ferro Coke with an ore ratio of 28.5 mass% was used.

(2) The behavior in a blast furnace when Ferro Coke is used was estimated with a 2-dimensional blast furnace model, confirming that Ferro Coke has the effect of reducing the temperature of the thermal reserve zone accompanying lowering of the gasification beginning temperature, and the effect of increasing the indirect reduction ratio by increasing the solution loss reaction and decreasing the smelting reduction reaction. In addition, as the result of an estimation of the coke strength after reaction, it was found that the strength after reaction when using 101 kg/t-pig of Ferro Coke was substantially the same as that when using only conventional coke.

(3) A Ferro Coke production plant was constructed, Ferro Coke was produced and a use test was carried with a large-scale blast furnace, confirming that RAR can be reduced by using Ferro Coke. Development of a production process with a scale of 300 t/d began in 2017, and in the future, the effects of long-term charging of Ferro Coke on blast furnace operation will be confirmed.

Acknowledgement

References

1) Center for Global Environmental Research, National Institute for Environmental Studies, Japan. National Greenhouse Gas Inventory Report of JAPAN. 2012–04
2) Kobayashi, K.; Okuhara, T. Preparation and properties of formed iron coke as materials for smelting reduction of iron ore. CAMP-ISIJ. 1991, vol. 4, no. 4, p. 1123.
3) Fukada, K.; Shimoyama, I.; Asanuma, M.; Anyashiki, T.; Ariyama, T.; Hanaoka, K. Development of carbon composite iron process. CAMP-ISIJ. 2004, vol. 17, no. 4, p. 842.
4) Nomura, S.; Terashima, H.; Sato, E.; Naito, M. Some Fundamental Aspects of Highly Reactive Iron Coke Production. Tetsu-to-Hagane. 2006, vol. 92, no. 12, p. 849–856.
5) Naito, M.; Okamoto, A.; Yamaguchi, K.; Yamaguchi, T.; Inoue, Y. Improvement of Blast Furnace Reaction Efficiency by Use of High Reactivity Coke. Tetsu-to-Hagane. 2001, vol. 87, no. 5, p. 357–364.
6) Ujisawa, Y.; Nakano, K.; Matsukura, Y.; Sunahara, K.; Komatsu, S.; Yamamoto, T. Subjects for Achievement of Blast

Furnace Operation with Low Reducing Agent Rate. ISIJ Int. 2005, vol. 45, no. 10, p. 1379–1385.

7) Ariyama, T.; Sato, M. ;Sato, T.; Watakabe, S.; Murai, R. Desirable Coke Properties for Blast Furnace in Future. Tetsu-to-Hagane. 2006, vol. 92, no. 3, p. 114–121.

8) Nomura, S.; Higuchi, K.; Kunimoto, K.; Naito, M. Strength and reactivity of iron-coke.   CAMP-ISIJ. 2008, vol. 21, no. 2, p. 894.

9) Higuchi, K.; Nomura, S.; Kunitomo, K.; Naito, M. Lowering the temperature of thermal reserve zone by using iron-coke. CAMP-ISIJ. 2008, vol. 21, no. 2, p. 895.

10) Sato, T.; Yamamoto, T.; Fujimoto, H.; Anyashiki, T.; Tato, M.; Takeda, K. Reduction of reducing agent rate with carbon iron composite. CAMP-ISIJ. 2009, vol. 22, no. 1, p. 5.

11) Nomura, S.; Higuchi, K.; Kunitomo, K.; Naito, M. Effect of decreasing thermal reserve zone temperature by innovative carbon iron agglomerates in blast furnace. CAMP-ISIJ. 2009, vol. 22, no. 2, p. 746.

12) Nomura, S.; Higuchi, K.; Kumitomo, K.; Naito, M. Reaction Behavior of Formed Iron Coke and Its Effect of Decreasing Thermal Reserve Zone Temperature in Blast Furnace. Tetsu-to-Hagane. 2009, vol. 95, no. 12, p. 813–820.

13) Nogami, H.; Yamamoto, T.; Miyagawa, K. Effect of Coke Reactivity on Blast Furnace Operation and Coke Reaction Behavior. Tetsu-to-Hagane. 2010, vol. 96, no. 5, p. 319–327.

14) Yamamoto, T.; Sato, T.; Fujimoto, H.; Anyashiki, T.; Sato, M.; Takeda, K. Effect of Raw Materials on Reaction Behavior of Carbon Iron Composite. Tetsu-to-Hagane. 2010, vol. 96, no. 12, p. 683–690.

15) Yamamoto, T.; Sato, T.; Fujimoto, H.; Anyashiki, T.; Fukada, K.; Sato, M.; Takeda, K.; Ariyama T. Reaction Behavior of Ferro Coke and Its Evaluation in Blast Furnace. Tetsu-to-Hagane. 2011, vol. 97, no. 10, p. 501–509.

16) Kasai, A.; Naito, M.; Natsui, Y.; Yamagata, Y. Reduction and Carburization of Carbon Composite Iron Ore Hot Briquet on Condition of Increasing in Temperature. Tetsu-to-Hagane. 2003, vol. 89, no. 12, p. 1212–1219.

17) Sato, H.; Machida, S.; Nushiro, K.; Ichikawa, K.; Sato, M.; Ariyama, T.; Takeda, K. Development of Production Process for Pre-reduced Agglomerates and Evaluation of Its Quality. Tetsu-to-Hagane. 2006, vol. 92, no. 12, p. 815–824.

18) Kannari, N.; Takakusagi K.; Ozaki, J.; Harada, Y.; Anraku, D.; Fujimoto, H.; Influence of Fe_2O_3 and $CaCO_3$ Addition on the Coking of Gooneylla Coal. Tetsu-to-Hagane. 2010, vol. 96, no. 5, p. 249–257.

19) Nomura, S.; Terashima, H.; Sato, E.; Naito, M.; Some Fundamental Aspects of Highly Reactive Iron Coke Production. Tetsu-to-Hagane. 2006, vol. 92, no. 12, p. 849–856.

20) Sato, T.; Nouchi, T.; Kiguchi, M. Development of a Blast Furnace Operation Simulator and its Application for Reduction of Si Content in Pig Iron. Kawasaki Steel Technical Report. 1998, no. 38, p. 24–31.

21) Kasai, A.; Kiguchi, J.; Kamijo, T.; Shimizu, M. Degradation of Coke by Molten Iron Oxide in the Cohesive Zone and Dripping Zone of a Blast Furnace. Tetsu-to-Hagane. 1998, no. 10, p. 697–701.

22) Kokubu, H.; Sasaki. A.; Taguchi, S.; Tsuchiya, N. Effect of Humidified Blast on Blast Furnace Operation from the Viewpoint of Softening and Melting Process of Ore Burdens. Tetsu-to-Hagane. 1982, vol. 68, no. 15, p. 2338–2345.