Reduction Behavior of Carbon Composite Iron Ore Hot Briquette in Shaft Furnace and Scope on Blast Furnace Performance Reinforcement

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(Received on March 18, 2003; accepted in final form on July 16, 2003)

The reduction and melting behavior of carbon composite iron ore hot briquette in shaft furnace are discussed. As these agglomerates are made by the use of thermal plasticity of coal, the reduction rate by chain reactions in interface between ore and coal could be increased. The carbon composite iron ore hot briquettes achieve 95% reduction degree in about 10-min descent time to the 1 100°C heat reserve zone bottom end and the drop of molten iron temperature is kept to 20°C. As a result, it is expected that these new agglomerates could decrease the fuel rate and discharging amount of CO₂ as well as have a possibility of extension of furnace life. Finally the paper ends by shaping the future of blast furnace on environmental phases for the new century. Especially, it is expected that carbon composite iron ore hot briquette lowers temperature of heat reserve zone and shortens the length, suggesting the possibility of shortening of the reserve zone (inactivity zone), that is, shortening of the blast furnace height.

KEY WORDS: blast furnace; carbon composite iron ore briquette; hot briquetting; reaction rate; innovative ironmaking.

1. Introduction

In recent years, the carbon composite iron ore reduction method using agglomerates with solid reducing material such as coal, etc. incorporated inside iron ore has been realized, and smelting process utilizing high-speed reduction from low temperature has been investigated. For a method to incorporate solid reducing material inside iron ore, attention was placed on coal melting solidifying phenomenon in the heating process, and a possibility has been found to manufacture high-density and high-strength charging material (carbon composite iron ore hot briquette with superb heat conductivity by heating a mixture of iron ore and coal in the temperature range from 350 to 600°C, and pressure-forming (briquetting) with coal melted). Because in this method, molten coal is able to be used as a binder at the interface with iron ore, the use of binder is no longer required, and large economical effects combined with increased productivity are expected.

To date, many reports have been made on reduction behavior concerning carbon composite iron ore cold briquette from laboratory scale to blast-furnace application. Reduction of carbon composite iron ore hot briquette takes place by heating only, and is assumed to provide excellent reduction performance, but no report has been yet made on reducing and melting behaviors of carbon composite iron ore hot briquette of by heating in shaft furnace.

In this research, reducing and melting behavior of carbon composite iron ore hot briquette (hereinafter called “hot bonded briquette”) in a shaft furnace will be reported, and at the same time, the possibility of next-generation blast furnace will be discussed with a hope that this paper could be of further help for blast furnace production and operation flexibility.

2. Experiments and Method

2.1. Experiment Details

Hot bonded briquette was prepared by mixing 22% coal (maximum fluidity of 1.67) and 78% pulverized ore for iron ore pellets and pressurizing and forming the mixture in the hot condition heated to the temperature range from 350 to 600°C, and pressure-forming (briquetting) with coal melted). Because in this method, molten coal is able to be used as a binder at the interface with iron ore, the use of binder is no longer required, and large economical effects combined with increased productivity are expected.

Table 1 shows material compounding conditions of reducing and melting experiment in a shaft furnace.

In the experiment, low-reactivity coke for casting (50–60 mm) was used as charge coke to lower the reduction potential in the furnace and allow reduction of hot bonded briquette to take place primarily by heating only, thereby enabling us to positively seek for advantage of high-speed reduction of carbonaceous material inside iron ore. In particular, attention was focused on grasping changes of gasifi-
cation amount and gasification speed of carbon in hot bonded briquette when hot bonded briquette is used in a shaft furnace, as well as grasping changes of the internal state of furnace caused by endothermic reaction resulting from gasification reaction.

2.2. Details of the Equipment

Figure 1 shows the experimental equipment of hot bonded briquette in shaft furnace (300 mm in inside diameter by 3 m high). Burdens are charged by bucket conveyor from the furnace top with a level 2.5 m above the tuyere set as a stock line. The experiment was based on melting of cast iron at 200 kg/tm coke rate and 150 kg/h melting rate, and cast iron was reduced and melted with part of cast iron replaced with hot bonded briquette. Cast iron used had the components of 4.0 % C and 1.0 % Si, and cast iron weighing 5.0 kg was divided into two and used.

Based on the heat balance (furnace heat loss: 13.7 Mcal/hr and flame temperature: 1600°C) at the wind rate of 120 Nm³/h, the bed height was set to 2.5 m and bed coke height to 800 mm in order to enable the experiment to be carried out at blast temperature of 50°C without preheating and also maintain the CO gas utilization of CO₂/(CO + CO₂) less than 0.45. At each bed height, a thermometer, pressure gauge, and gas analyzer were installed, respectively, to measure temperature, pressure, and gas composition at each position, and at the same time, the in-furnace temperature was measured by vertical horizontal probes to investigate changes of internal state of the furnace.

3. Experimental Results and Discussion

3.1. Heat Balance and Material Balance

Figures 2 and 3 show in-furnace gas concentration distribution and in-furnace temperature distribution, respectively, when cast iron is melted and when hot bonded briquettes are blended. The furnace top temperature when cast iron is melted is 980°C but is deflected from Boudouard’s equilibrium, and the top gas CO₂ concentration is about 11 % and η_CO is around 40%. In addition, the heating rate is decelerated at 1200°C by the formation of oxide film on the surface of cast iron. Consequently, oxidizing atmosphere is formed, where hot bonded briquette reduction is advanced primarily by heating only. When hot bonded briquettes are blended, top gas temperature lowers, CO₂ concentration changes nearly constantly, and CO₂ concentration increases. This may be attributed to gasification (solution loss reaction) of carbon composite in hot bonded briquettes or direct reduction reaction of iron oxide, which takes place from the low-temperature region.

Table 2 shows carbon balance when cast iron is melted and when hot bonded briquettes are blended, respectively. When cast iron is melted, oxide film is formed by the oxidizing atmosphere at the upper shaft part, and when droplets of molten iron trickle down from film inside of cast iron in the vicinity of coke bed along coke clearances of coke bed, the droplets containing iron oxide is reduced,
and the gasified carbon rate used for smelt reduction is 56 kg/thm. When hot bonded briquettes are blended, the in-furnace gasified carbon rate increases by gasification of carbonaceous material inside iron ore.

Table 3 shows heat balance when cast iron is melted and when hot bonded briquettes are blended, respectively.

<table>
<thead>
<tr>
<th>Table 2. Carbon balance of carbon composite iron ore hot briquette in shaft furnace.</th>
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<tr>
<td><strong>Input Carbon</strong></td>
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<td></td>
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<tr>
<td>Total</td>
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<th>Table 3. Heat balance of carbon composite iron ore hot briquette in shaft furnace.</th>
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<tr>
<td><strong>Input</strong></td>
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<tr>
<td>Coke (C-O2→CO2)</td>
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<tr>
<td>Briquettes (C-O2→CO2)</td>
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<tr>
<td>Oxidation of Fe, Si, and Mn</td>
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<tr>
<td>Total</td>
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| Output | **Cast iron melting** | **With Briquettes of 277 kg/thm** | **711 kg/thm** |
|-----------------------------------------------|
| | | (a) | (b) | (c) |
| Hot metal temperature | 1488 °C | 315 | 313 | 2 | 1438 °C | 345 | 30 |
| Decomposition of CaO | 5 | 4 | 1 | 10 | 5 |
| Top gas temperature | 980 °C | 409 | 760 °C | 329 | 327 | 630 °C | 327 | 82 |
| Gasification of carbon | 56 kg | 180 | 82 kg | 262 | 82 | 207 kg | 661 | 481 |
| Heat loss | 574 | 750 | 176 | 1582 | 1008 |
| Total | 1483 | 1659 | 175 | 2325 | 1442 |
Blending hot bonded briquettes (277 kg/thm) increases the in-furnace gasified carbon rate by 26 kg/thm. And the increase of endothermic heat of 82 Mcal/thm resulting from this corresponds to the rate of drop of exhaust gas sensible heat of 80 Mcal/thm (drop of furnace temperature of 220°C). That is, the endothermic heat resulting from hot bonded briquette blending is compensated for by the furnace top gas sensible heat, and as a result, drop of hot metal temperature is kept to 15°C (converted calorie: 2 Mcal/thm). The carbon amount consumed by smelt reduction which is assumed from the drop of molten metal temperature is 1 kg-C/thm, and the reduction degree of hot bonded briquette on the coke bed is assumed to be 95%. The burden descending speed when hot bonded briquettes are blended is 4.7 m/h and it takes 20 min for the burden to descend to the coke bed, suggesting that reduction takes place at a high speed at the shaft part in hot bonded briquette and 95% reduction degree is achieved during the descending time of 20 min.

Figures 4 and 5 show changes of furnace wall pressure in the furnace height direction in the process from cast iron melting to hot bonded briquette blending. When hot bonded briquettes are blended (277 kg/thm) (Fig. 4), furnace wall pressure (P1) 0.5 m from tuyere slightly increases. This is assumed to be attributed to choking of in-furnace gas flow due to formation of cohesive zone by hot bonded briquette blending, which corresponds to a rise of heat loss in the heat balance (Table 3). Furthermore, when hot bonded briquettes are blended (711 kg/thm) (Fig. 5), hot bonded briquette blending not only increases furnace wall pressure (P1) but also increases furnace wall pressure (P3) 1.5 m from tuyere. In this furnace state, as the furnace wall pressure (P2) coincides to furnace wall pressure (P1), so gas flow is assumed to be channeling on furnace wall side. As a result, heat loss (Table 3) rapidly increases (1008 Mcal/thm) and by this increase of heat loss and increase of the above-mentioned in-furnace gasification endothermic heat (481 Mcal/thm), the heat input rate increases (1442 Mcal/thm). Now, in the case of hot bonded briquette blending (711 kg/thm), the furnace top temperature drops to 630°C only, and in terms of heat balance, the endothermic heat (481 Mcal/thm) of 151 kg/thm increase of in-furnace gasified carbon rate is not compensated for by the drop of exhaust gas sensible heat alone. This will be discussed in
Sec. 3.3.

Table 4 shows changes of slag and metal components when cast iron is melted and when briquettes are blended, respectively. As the hot bonded briquette blending increases, burden S increases, hot metal temperature lowers, and S in hot metal increases. Reduction degree of ore in hot bonded briquettes estimated from the lowering rate of hot metal temperature and FeO in slag by heat balance is assumed to be about 95%.

3.2. Gasification Reaction Rate

Since the reduction rate of hot bonded briquette on the coke bed is assumed to be 95%, in-furnace gasification reactions may fall into two broad general categories: direct reduction reaction of iron oxide by hot bonded briquette and gasification reaction by ascending CO₂ gas of carbonaceous material. Because the contribution ratio of these two reactions is unable to be referred to from the overall balance, next discussion will be made on the gasification reaction rate.

From the gas concentration distribution in furnace height and variation per unit height, the gasification reaction rate of carbon in hot bonded briquette in the furnace will be evaluated. Let the descending speed of burden be constant from furnace top to bed coke, and as is the case of Okabe et al.5) and let the variation \( D(\% \text{CO}_2/\% \text{CO}_2) \) per unit time \( Dq \) (h) be equal to the CO₂ amount which reacts with carbon during \( Dq \) and becomes CO; then, the gasification reaction rate \( R_s \) is defined by the following formula.

\[
R_s = k_s \cdot (\% \text{CO}_2 - \% \text{CO}_2) \cdot (12/22.4) \cdot (Vg/100) \cdot (\Delta Z/Vs) \tag{1}
\]

where,
- \( R_s \): Reaction rate (kg-C/h)
- \( k_s \): Gasification reaction rate (1/m)
- \( \% \text{CO}_2 \): CO₂ contents (%) 
- \( \% \text{CO}_2 \text{eq} \): CO₂ contents in equilibrium state of CO₂–CO–C system (%)
- \( Vg \): Gas volume (Nm³/h)
- \( \Delta Z \): Descending distance in \( Dq \) (h) time (m)
- \( Vs \): Descending speed (m/h)

Figure 6 shows the relationship between gasification re-

![Fig. 6. Relationship between reaction rate of carbon composite iron ore hot briquette in shaft furnace.](image-url)
ed, the 1 100°C heat reserve zone has been formed, direct reduction reaction by carbon composite iron ore hot briquette has been completed at 1 200°C. The descent time to the bottom end of 1 100°C heat reserve zone located 700 mm from the furnace top is about 10 min, which nearly coincides with the reduction time of hot bonded briquette found by Shimizu et al. in the 100% N₂ system.

Based on the foregoing, it is assumed that the increase of in-furnace gasified carbon rate when hot bonded briquettes are blended is primarily caused by the decrease of porosity and the increase of reaction area of iron oxide with carbonaceous material inside the hot bonded briquette. Consequently, it has been confirmed in the shaft furnace that hot bonded briquette provides outstanding reduction performance by direct reduction reaction of iron oxide by hot bonded briquette by heating which takes place with priority to the gasification reaction by CO₂ gas of carbonaceous material inside briquette.

3.3. Gasification Reaction Temperature

Heat supply is important to allow reduction of hot bonded briquette to take place by heating only as well as allow it to exhibit outstanding reduction performance. In the recent experiment, when hot bonded briquettes are blended (711 kg/thm), furnace top temperature lowers to 630°C only as hot bonded briquettes are blended, and in terms of heat balance, the increased calorie of in-furnace gasified carbon rate is unable to be compensated for by the drop of exhaust gas sensible heat alone.

Figure 7 shows changes of the CO gas content ratio in in-furnace gas on the Baur-Glaessner diagram when cast iron is melted and when hot bonded briquettes are blended. In the temperature region of 1 200°C or lower where reduction of ore in hot bonded briquettes is completed, in-furnace temperature lowers by the direct reduction of iron oxide by carbonaceous material incorporated in hot bonded briquettes and at the same time the CO gas content ratio increases, suggesting that it converges to the intersection (iron point) between Fe–FeO phase boundaries and Boudouard curve. Strictly speaking, there are differences between the CO gas content ratio and the iron point because of the effect of H₂–H₂O gas phase. At this temperature, because if carbon exists, FeO is reduced to Fe and gas is re-generates by carbon, in-furnace temperature is autonomously kept to this temperature until incorporated car-}

4. Scope on Blast Furnace Performance Reinforcement by Carbon Composite Iron Ore Hot Briquette

With respect to a process image of next-generation blast furnace, Ishii made investigation titled “Blast Furnace in Near Future on The View Point of Reaction Chemistry” in 1993, advocated that one of the defects of current blast furnace lies in excessively high furnace height, questioned the need of coke and sintering with strength and reaction properties that can stand the weight of burden, and presented a vision for a technique to shorten blast furnace height.

On the other hand, in the current blast furnace operation, efforts have been made to reduce fixed costs by extending the blast-furnace life in the long run for reduction of molten iron cost. Furthermore, in the medium run, after intensive pulverized coal (hereinafter called “PC”) injection for reduction of molten iron variable cost has taken root in all the companies, low-coke rate operation is intended in order to pursue further reduction of molten metal variable cost. Now, we would like to consider roles of the technique for using hot bonded briquette in these two medium and long-run problems and next-generation perspective we are now facing.

4.1. Reducing Fuel Rate and Extending Life of Blast Furnace

It has been confirmed that reduction of hot bonded briquette provides outstanding reduction performance in the high-temperature region by allowing direct reduction reaction of iron oxide to preferentially take place by heating only by carbonaceous material incorporated in hot bonded briquette. Excessively improving reducibility in the FeO stage causes the constraint point of reduction to become the FeO/Fe₃O₄ equilibrium point newly, and in the chemical reserve zone temperature in such event lowers to 670°C and coke rate to 375 kg/thm. The recent coal rate of hot bonded briquette alone is 360 kg-C/t-Fe, and the heat absorption rate of direct reduction is compensated for by top gas sensible heat, and the drop of molten metal temperature is held to 20°C. It is assumed that determination of reduction limit and optimization of calorie supply would be the problems.

Because the furnace hearth is unable to be repaired, it is the greatest problem to prevent abnormal erosion of corners of furnace bottom side walls, and it is critical to control the molten iron flow of unsaturated carbon that trickles to the
furnace hearth.\textsuperscript{12} To meet this, subject to stabilization of molten iron temperature to prevent changes of carbon solubility and slips, deadman coke behavior and properties (particle size, porosity) that define the molten iron flow in the hearth will increase importance.

Figure 8(a) shows the relationship between solution loss reaction load (hereinafter called the “coke reaction load”) calculated per unit coke in 250 kg/thm PC rate test operation and coke fine generation in deadman.\textsuperscript{13} Good correlation is observed between coke reaction load and coke fine generation in deadman. This indicates that reaction degradation of coke that forms the deadman can be suppressed by coke center charging but fines derived from reacted coke intermediate and peripheral regions in the furnace radial direction flow into the deadman from the deadman surface layer by percolation.\textsuperscript{14}

Figure 8(b) shows the estimated reaction load when the coke rate is reduced in high PC operation. In this case, it is presumed that unburned PC is consumed by solution loss reaction with priority to coke. When the PC rate is constant, the coke reaction load increases as the coke rate lowers and coke fine generation in deadman increases (Fig. 8(a)). Consequently, when further low coke rate operation is intended in the future, flow of unsaturated carbon molten iron that trickles is assumed to be hindered by the increase of fine generation in the deadman, and securing of gas and liquid permeability in the deadman increases still greater importance.

In the reduction process of hot bonded briquette in the shaft furnace in the recent experiment, it is assumed that hot bonded briquette reaches 95% reduction rate in about 10-min descent time to the bottom end of the 1100°C heat reserve zone, and it can be expected that hot bonded briquette subtly responds to rapid temperature rise, that is, abnormal descent such as slips, etc. and self-completes the reduction. Consequently, hot bonded briquette has a possibility of contributing to reduction of coke rate for preventing degraded coke from flowing in the deadman that defines the molten iron flow in the hearth as well as to stabilization of furnace operating condition and further to extension of blast furnace life.

4.2. Increasing Compactness (Reducing Height) of Blast Furnace

With respect to the increased compactness of blast furnace, a joint research project titled “Research concerning Innovative Smelting Reactions of Blast Furnace intended for Reducing Energy by Half and Minimum Environmental Load”\textsuperscript{15} funded by Special Coordination Funds for Promoting Science and Technology by Ministry of Education, Culture, Sports, Science and Technology was started in 1999. In the reduction test using a heat-insulating type blast furnace inside reaction simulator\textsuperscript{16} by Naito et al., temperature of heat reserve zone lowers and the length is shortened\textsuperscript{17} when hot bonded briquette is reduced as compared to sinters, suggesting the possibility of shortening of the reserve zone (inactivity zone) which is about one half the distance from furnace top to cohesive zone top end, that is, shortening of the blast furnace height.

Figure 9 shows a scope on blast furnace performance reinforcement based on reduction behavior of hot bonded briquette in blast furnace. In order to pursue the production capacity of current blast furnace to the utmost limit, it is essential to reduce the height of blast furnace with the current stockline diameter maintained. It is expected to increase compactness of blast furnace by achieving the high hot metal production, that is, high-accuracy charging technique for high-speed charging,\textsuperscript{18} high oxygen enriched blast technique for alleviating channeling limit,\textsuperscript{19,20} two-stage tuyere blast for maintaining smelting capability,\textsuperscript{21} and other hearth heat-retaining techniques, and systematization of blast furnace techniques of these material properties, charging distribution control, and blast techniques.

When secondary combustion by two-stage tuyere blast is taken into account, the following equation is deduced from simultaneously considering direct reduction and indirect reduction for reduction of iron oxide expressed by $\text{FeO}$$\text{C}_x$$\text{C}_y$$\text{CO}_z$.

\[
\text{FeO}_x + \text{X}_1\text{C} + \text{X}_2\text{CO} + \text{X}_3\text{CO}_2 = \text{Fe} + x\text{CO} + y\text{CO}_2, \quad \text{......(2)}
\]

In order to intuitively see changes of the required carbon rate, the required carbon rate \(X_1 + X_2 + X_3 (\text{kmol-C/kmol-Fe})\) is found by the following equation newly deduced in the recent experiment by defining three operating factors, namely, direct reduction degree \(\text{D.R.}\), CO gas utilization rate \(\eta_{\text{CO}}\) at the furnace top, and secondary combustion rate \(\eta_{\text{pc}}\) by two-
Equation (3) takes into account the mass balance only of substances involved in reactions, but this equation enables us to intuitively see changes of the fuel rate of blast furnace in the future resulting from changes of operation. Now, in the case where the secondary combustion rate \( \eta_{pc}=0 \), the required carbon rate \( X_1+X_2 = n(1 - \eta_{pc})X_1/\eta_{pc} \) converges at \( X_1+X_2 = n(1 - \eta_{pc})/\eta_{pc} \) presented by Nakatani et al. in 1963.22)

Figure 10 shows the scope on decreasing carbon rate on compact furnace based on reduction behavior of carbon composite iron ore hot briquette.

5. Conclusion

A smelting method using high-speed reduction from low temperature by carbon composite iron ore hot briquette with solid reducing material such as coal, etc. incorporated inside iron ore is being investigated for increased productivity and economic effects. Analysis of reduction reactions in a shaft furnace is carried out for purpose of positively pursuing advantages of high-speed reduction of carbon composite iron ore hot briquette produced by pressure-forming (briquetting) with carbonaceous material melted, and the results of the work carried out allow us to draw the following conclusions.

(1) Pressure-forming briquettes with coal melted lowers the porosity and increases the reaction area. And by this lowered porosity and increased reaction area, the briquette reaction rate becomes faster than the reaction rate of coke-ore composite cold pellet. As a result, briquettes achieve 95% reduction degree in about 10-min descent time to the 1100°C heat reserve zone bottom end and the drop of
molten iron temperature is kept to 20°C.

(2) As the in-furnace temperature is lowered by direct reduction of iron oxide by carbonaceous material in briquette, the CO gas content ratio increases, converges at the intersection (iron point) between Fe–FeO phase boundaries and Boudouard curve, and is autonomously kept to form the temperature reserve zone.

(3) It is expected that carbon composite iron ore hot briquette lowers temperature of heat reserve zone and shortens the length, suggesting the possibility of shortening of the reserve zone (inactivity zone) which is about one half the distance from furnace top to cohesive zone top end, that is, shortening of the blast furnace height.

In years to come, innovation of blast furnace operation is required by systematizing blast-furnace techniques for material properties, burden distribution control, and blast techniques, in order to allow long-term extension of blast furnace life and medium-term low coke rate operation to coexist for the purpose of reduction of molten iron cost.

In conclusion, the authors wish to acknowledge the very substantial contribution of Mr. Hideo Futagawa, Mr. Nobuyuki Kudo, and Hiroyuki Nagashima of Keihan Co., Ltd. in their generous assistance and advice in fabricating briquettes and Mr. Hirotoshi Murata of Naniwa roki Co., Ltd. for his excellent assistance and advice in carrying forward this research.

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