Reduction Disintegration Behavior of Lump Ore in COREX Shaft Furnace

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The heavy disintegration of lump ores would produce plenty of small particles in COREX shaft furnace, which would decrease the gas permeability and productivity of the shaft furnace, thus the proportion of lump ores in the burden of COREX shaft furnace is limited to a low level. In this work, the reduction disintegration behavior of lump ore samples was studied by simulating the reduction process of COREX shaft furnace. The influence of temperature, reduction time and gas composition on the reduction disintegration index (RDI\(_{6.3}\)) of lump ore samples were also evaluated. The results showed that the disintegration behavior of lump ores in COREX shaft furnace could be generally divided into three steps and the disintegration mainly occurred in the second step, which was in the temperature zone from 450°C to 650°C with low reduction degree. Meanwhile, the RDI\(_{6.3}\) of lump ore samples all presented the tendency of “inverted V-shape” in the temperature range from 450°C to 650°C under different reduction time. However, the mutual promotion of reduction reaction and carbon deposition reaction (CDR) was attributed to the main reason for the heavy disintegration of lump ores in COREX shaft furnace. In addition, increasing H\(_2\) concentration in reducing gas and rapid reducing at higher temperature would decrease the disintegration degree of lump ores in COREX shaft furnace.

KEY WORDS: lump ore; disintegration behavior; COREX shaft furnace; reduction disintegration index; carbon deposition reaction.

1. Introduction

The COREX smelting reduction process is environmentally friendly with low energy consumption, which provides a new way for the sustainable development of the ironmaking and steelmaking industry.\(^1\) However, the severe disintegration behavior of lump ores limits its proportion in the burden of COREX shaft furnace, which would increase the cost of hot metal.\(^2\) Many studies have shown that the disintegration of iron ores would produce plenty of fines, which would decrease the gas permeability and production efficiency of the furnace.\(^3,5\) What is more, the stable furnace operation could be negatively affected when the disintegration of iron ores deteriorated.\(^3,5\)

The disintegration of iron ores mainly occurs during the reduction process from hematite to magnetite in the temperature zone of 400°C–700°C, and some researchers indicate that the main reason for the disintegration is the stress concentration caused by the volume expansion of magnetite.\(^6,10\) But these studies mainly focus on the disintegration behaviors of iron ores under the blast furnace conditions, especially for sinter mixes and pellets.\(^11,13\) However, compared with the blast furnace process, the residence time of iron ores in the low temperature zone of the COREX shaft furnace is much longer, and the CO and H\(_2\) proportion in reducing gas of COREX shaft furnace is also quite higher. All these factors have great influence on the disintegration behaviors of iron ores, leading the disintegration degree of lump ores much heavier in COREX shaft furnace.\(^9\)

In the present work, the reduction disintegration behavior of lump ore samples in COREX shaft furnace was studied. The RDI\(_{6.3}\) of lump ore samples under different temperature, gas composition, and reduction time were measured to study the influencing factors and disintegration mechanism of lump ores. Besides, measures to decrease the disintegration degree of lump ores in COREX shaft furnace were also discussed based on the above results.

2. Experimental

2.1. Samples

The lump ore samples used in this work were imported from South Africa and were in actual use for COREX shaft furnace in China. The chemical composition of the lump ore samples was shown in Table 1. The lump ore samples were crushed and sieved to grain sizes of 10–12.5 mm and 12.5–16 mm before use.

2.2. Experimental Procedures

All the experiments were conducted by the static loading reduction equipment. Figure 1 shows the schematic diagram
of the equipment. The total weight of lump ore samples for each test was 2 kg, half of the samples were with size of 10–12.5 mm and the other half was 12.5–16 mm.

As for the disintegration behavior tests, the lump ore samples were put into the reactor tube and heated from room temperature with a heating rate of 2.5 °C/min, the gas was pure N₂ with a flow rate of 5 L/min. The reducing gas was introduced to the samples when the temperature reached 250 °C. The reducing gas composition changed from 35% CO, 50% CO₂ and 15% H₂ to 72% CO, 8% CO₂ and 20% H₂ gradually during the next 240 min to simulate the reduction process of COREX shaft furnace. Particularly, the heating was interrupted when the temperature of lump ore samples reached 450 °C, 550 °C, 650 °C, 750 °C and 850 °C respectively, and the reducing gas was changed to N₂ again to cool down the samples to room temperature.

As for the RDI-6.3 tests, the lump ore samples were heated from room temperature to the appointed temperature (450, 550 and 650 °C) under N₂ with a flow rate of 5 L/min, then reducing gas was injected to the tube and the samples were reduced for different time (30, 60 and 120 min). After the reduction, the gas was changed to N₂ again to cool down the samples to room temperature. Table 2 shows the temperature, reducing gas composition and reduction time for different reduction cases. In all cases, the total volume of the reducing gas was kept constant. In case 1 to 9, the concentration of CO, CO₂ and H₂ was 35%, 50% and 15% respectively. In case 10, the concentration of CO, CO₂ was exchanged with each other. While in case 11, the concentration of H₂ increased to 40.5% and the concentration of CO and CO₂ decreased, but the CO/CO₂ ratio was the same.

After the samples were cooled down to room temperature by N₂, the reduction degree was calculated from the change in weight before and after the reduction. Then the lump ore samples were tested by a tumbling drum at a rotation speed of 30 rpm for 30 min, the inner size of the drum was φ130 mm × 800 mm. The samples were sieved with 12.5 mm, 10 mm, 6.3 mm, 3.15 mm and 0.5 mm mesh respectively to determine the particle size distribution of the lump ore samples.

To compare the disintegration behavior of lump ore samples at different processes, the reduction disintegration behavior index (RDBI₆.₃) was calculated using the followed equation:

\[
RDBI_{6.3} = \frac{W_b}{W_a} \times 100 \% \quad (1)
\]

Where \( W_b \) was the weight of lump ore samples after the reduction at different process, \( W_a \) was the weight of particles smaller than 6.3 mm.

To study the influence of temperature, gas composition and reduction time on the disintegration of lump ore samples, the RDI₆.₃ was calculated using the followed equation:

\[
RDI_{6.3} = \frac{W_1}{W_0} \times 100 \% \quad (2)
\]

Where \( W_0 \) was the weight of lump ore samples after the reduction under different reduction conditions, \( W_1 \) was the weight of particles smaller than 6.3 mm.

In addition, the microstructures before and after reduction were also observed using the scanning electron microscope (SEM).

### 3. Results

#### 3.1. Disintegration Behavior of Lump Ore

Figure 2 shows the RDBI₆.₃ and reduction degree of lump ore samples under the five reduction processes in COREX shaft furnace. Generally speaking, with the increase of temperature, the RDBI₆.₃ of lump ore samples showed an upward tendency with the increase of reduction degree, but the increase rate of RDBI₆.₃ before reduction degree reached 10% was much larger. Taguchi et al. indicated that the increase rate of reduction disintegration degree would decrease when the reduction degree reached a certain value.⁴ While this value was considered to be around 11%, at which the hematite was totally reduced to magnetite.⁶

Figure 3 shows the particle size distribution of the lump ore samples.
ore samples under the five reduction processes after drum test. With the process of reduction, the weight ratio of particles of small size (< 6.3 mm) and middle size (6.3–10 mm) increased obviously, and the weight ratio of particles of large size (> 10 mm) decreased drastically, meaning the disintegration of lump ore samples became more and more serious. Particularly, the particle size distribution of lump ore samples under the 450°C, 550°C, and 650°C processes were quite different with each other, while the difference of particle size distribution of lump ore samples under the 750°C and 850°C processes were not obvious. Therefore, the disintegration behavior of lump ore samples was divided into three steps based on the reduction degree and RDBI-6.3 as follow: (1) the first step was in the temperature zone lower than 450°C; (2) the second step was in the temperature zone from 450°C to 650°C; (3) the third step was in the temperature zone from 650°C to 850°C. In the first step, the lump ore samples were reduced very slowly and the disintegration of lump ore samples was not obvious. The samples' average diameter (weighted average of particle size distribution) decreased from 12.75 mm to 11.71 mm. In the second step, the reduction degree of lump ore samples still decreased but the disintegration rate was much slower than the second step, while the reduction rate of the lump ore samples was very high in the third step. The average diameter of the lump ore samples decreased from 8.38 mm to 6.89 mm.

Figure 4 shows the RDBI-6.3 and reduction degree distribution of the three steps. The vertical axis showed the ratio of RDBI-6.3 and reduction degree within different temperature intervals to that of the whole process (from 250°C to 850°C). As shown in the figure, the RDBI-6.3 ratio of the second step (450°C–650°C) was more than 60%, while the RDBI-6.3 ratio of the first step (250°C–450°C) and third step (650°C–850°C) were around 12% and 24%, respectively. However, the reduction degree ratio of the first step was less 5% and the second step was about 20%, while the reduction degree ratio of the third step was more than 75%.

In summary, it could be concluded that the lump ore samples mainly disintegrated in the second steps in the temperature zone from 450°C to 650°C despite that the reduction degree of the lump ore samples was relatively low.

3.2. Influence of Temperature on RDI sub 6.3 of Lump Ore

Figure 5 shows the reduction degree of lump ore samples under different temperatures and reduction times. There was no doubt that the reduction degree of lump ore samples increased with the increase of temperature and reduction time. However, the increasing extent of reduction degree from 450°C to 550°C was larger than that from 550°C to 650°C, especially at the reduction time of 30 min and 60 min. Meanwhile, the increasing extent of reduction degree from 60 min to 120 min was also much higher than that from 30 min to 60 min, especially at the temperature of 650°C.

Figure 6 shows the RDI sub 6.3 of lump ore samples under different temperature and reduction time. It can be seen from the results that the RDI sub 6.3 of lump ore samples under different reduction times all presented the tendency of "inverted V-shape" in the temperature range from 450°C to 650°C, which showed the same trend with former study.91
The RDI-6.3 at 550°C was highest and the RDI-6.3 at 650°C was also higher than that of 450°C. In addition, the influence of temperature on the RDI-6.3 of lump ore samples was variable under different reduction time, the longer the reduction time was, the smaller the difference of RDI-6.3 was. While the reason for the above phenomenon could be attributed to two sides. On one hand, the reduction rate of lump ore samples increased with the increase of temperature, which would increase the inner stress caused by the expansion of magnetite. On the other hand, the plasticity of lump ore samples increased with the increase of temperature, which could increase the ability of lump ore samples of bearing the stress concentration.

3.3. Influence of Gas Composition on RDI-6.3 of Lump Ore

Figure 7 shows the RDI-6.3 and reduction degree of lump ore samples reduced at 550°C for 60 min under different gas compositions. When the proportions of CO and CO2 were exchanged with each other as cases 5 and 10, there was no obvious difference between the reduction degree and RDI-6.3 under these two cases. However, when the H2 proportion in reducing gas increased to 40.5% as case 11, the RDI-6.3 of lump ore samples decreased obviously but the reduction degree decreased slightly. This result indicated that increasing H2 proportion would decrease the disintegration degree of lump ores, while former study showed that the disintegration degree of lump ore samples would increase when the H2 proportion in reducing gas increased from 5% to 10%. A probable explanation for this phenomenon was that the disintegration degree initially increased with increasing H2 proportion and then decreased to a value much lower.

It was also indicated that increasing H2 proportion would increase the proportion of larger grains. Then the particle size distribution of the disintegrated lump ore samples were measured and compared. Figure 8 shows the particle size distribution (< 6.3 mm) of lump ore samples after RDI-6.3 test at 550°C for 60 min. Case 5: 35%CO, 50%CO2, 15%H2; Case 10: 50%CO, 35%CO2, 15%H2; Case 11: 24.5%CO, 35%CO2, 40.5%H2.
as case 5 and 10, the weight ratio of smaller size (<3.15 mm) under higher CO content was much higher despite the RDI of lump ore samples under the two cases were almost the same. However, the weight ratio of fine particles smaller than 0.5 mm in size decreased obviously when the H2 proportion increased to 40.5% as case 11, the weight ratio of such fine particles under case 10 was about 1.5 times higher than that of case 11. Meanwhile, the weight ratio of larger particles size (3.15–6.3 mm) increased obviously in higher H2 concentration.

4. Discussion

4.1. Disintegration Mechanism of Lump Ore in COREX Shaft Furnace

Many researchers had studied the disintegration mechanism of sinter in blast furnace, and the main reason was attributed to the volume expansion produced in the reduction process from hematite to magnetite, especially by the skeletal hematite. However, the reduction conditions in blast furnace were very different with that of COREX shaft furnace, the physical properties and microstructures of lump ores were also different with sinter. All these factors would influence the disintegration behaviors of lump ores in COREX furnace.

There were several probable reactions in the temperature zone from 450°C to 650°C in the COREX shaft furnace, which could be the reason for the disintegration of lump ore samples. The three main reactions were listed as follow based on the thermodynamics theories.

\[
\begin{align*}
3\text{Fe}_2\text{O}_3 + \text{CO} &= 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \quad \text{(3)} \\
3\text{Fe}_2\text{O}_3 + \text{H}_2 &= 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \quad \text{(4)} \\
2\text{CO} &= \text{C} + \text{CO}_2 \quad \text{(5)}
\end{align*}
\]

Equations (3) and (4) were the reduction reactions from hematite to magnetite, which reacted easily in reducing atmosphere. Equation (5) was the CDR, which was related to gas concentration, system pressure and so on.

4.1.1. Comparison of CO and H2 Reduction Behaviors

As former studies indicated, the reduction from hematite to magnetite of pellets by CO tended to progress with topochemical reaction and cracks generated in concentric fashion. Similarly, Inazumi et al. reported that the reduction of sinter particles from hematite to magnetite by CO tended to proceed on the surface and the stress generated by the volumetric expansion of iron oxide causes crack formation. However, in the case of H2 reduction, Asada indicated that no cracks were formed in the magnetite phase, even the phase transformation from hematite to

![Fig. 9. SEM photos of lump ore samples under different temperature.](image-url)
magnetite completed, but many cracks were found in the multi-component calcium ferrite and volumetric expansion of magnetite phase was also observed. It had been reported that there was no obvious difference in the chemical reaction rate of the reduction from hematite to magnetite in a single particle ore between CO/CO₂ and H₂/H₂O atmosphere, but the interdiffusion coefficient De of H₂/H₂O gas was much higher than that of CO/CO₂. In addition, Murakami indicated that the reduction of hematite by H₂ mainly proceeded along the cracks in the iron ore samples.

Figure 9 shows the SEM photos of lump ore samples under different reduction temperatures. No pore or cracks were observed on the surface and internal of original lump ore samples as shown in the picture. However, when the samples were gradually reduced, fine cracks were generated inside the lump ore samples. According to these photos, the quantity and density of cracks at the cross section of the lump ore samples reduced at 550°C was higher than that of 450°C and 650°C, verifying the results that the disintegration degree of lump ore samples at 550°C was much higher than that of 450°C to 650°C. Particularly, most of the cracks were produced along the gangue phase such as SiO₂ and Al₂O₃, and few cracks were distributed in the hematite and magnetite phases. Vyver found that the gangue minerals could influence the direction and intensity of fractures and cracks often branched upon passing through gangue minerals. A probable explanation for this phenomenon was that the stress generated by the volume expansion of magnetite would concentrate at the zone where gangue existed.

Generally speaking, the reduction of lump ore samples by CO and H₂ could be summarized as follow. The CO reduction mainly occurred on the surface of the samples and particles of smaller size were generated due to the stress concentration. While, the H₂ reduction mainly occurred internal of the samples as the interdiffusion coefficient of H₂ was much higher, particles of larger size were generated by H₂ reduction. In addition, the cracks generated inside the samples were mainly along with the gangue phase.

4.1.2. Influence of Carbon Deposition Reaction

The CDR mainly occurred in the temperature zone from 400°C to 600°C according to the production experience of blast furnace. However, as the reducing gas pressure and CO concentration in COREX shaft furnace were much higher than that of blast furnace, the CDR would be much stronger in the COREX shaft furnace. Figure 10 shows the thermodynamics equilibrium component of CO–CO₂ system under different temperatures and pressures. The equilibrium ratio of CO/(CO+CO₂) was lower than 25% in temperature range from 400°C to 600°C. While the CO/(CO+CO₂) ratio of the COREX shaft furnace top gas was more than 50% according to the actual production data. Besides, the pressure of CO–CO₂ system in COREX shaft furnace was in the range from 252.0 to 315.2 kPa. All these factors indicated that the CDR occurred to large extant in COREX shaft furnace.

Figure 11 shows the total weight of carbon produced during the reduction process of lump ore samples at 550°C under different gas compositions. As for cases 5 and 10, the pressure of CO–CO₂ system was the same. But the CO content of case 10 was much higher and the carbon content in case 10 was also higher, indicating the increase CO concentration would increase the weight of carbon produced by CDR. However, as for case 5 and 11, the ratio of CO/(CO+CO₂) was the same, but the pressure of CO–CO₂ system in case 5 was much higher, resulting the carbon content in case 5 was about two times of that in case 11.

Though the CDR occurs to a large extent in the COREX shaft furnace, the carbon deposition behavior was greatly influenced by the H₂ content. It was estimated that the CDR mainly occurred near the surface of lump ore samples when the samples were reduced by CO without H₂. Meanwhile, cracks were produced internal of the lump ore samples when H₂ was added to the reducing gas. These cracks would provide “channels” for the CO to diffuse into the samples, leading the CDR occurred along the cracks internal of the samples. This assumption explained the phenomena why the disintegration degree of lump ore samples would initially increase with increasing H₂ concentration.

To verify the influence of CDR on the disintegration behavior of lump ore samples, two parallel tests were conducted. One is that the lump ore samples were reduced at...
550°C until the weight of samples no longer changes, the other one is that the lump ore samples continued reduced for 30 min at 550°C after the weight no longer changes. The reducing gas is 40% CO and 60% CO$_2$ with a flow rate of 13.3 L/min. Under this reduction conditions, the lump ore samples could be only reduced to magnetite, and no FeO or Fe would be produced during the reduction progress based on the thermodynamics theory.\textsuperscript{22) The reduction degree of the two tests were 10.95% and 11.14% respectively, and no doubt the RDI$_{6.3}$ of the latter was much higher than the former, 43.78% and 54.75% respectively. After the tests, the carbon content of lump ore samples were tests, the samples were water-washed to wipe off the carbon that adhere to the surface of the lump ore samples. Figure 12 shows the photos of reduced lump ore samples after water-washed under the two conditions. The cracks of the latter test were more and larger than the former. The weight ratios of carbon deposition inside the samples and the lump ore samples were 0.048% and 0.061% respectively. This result verified the opinion that the carbon deposition inside iron ores could promote the formation of cracks and reduce the intensity of iron ores.\textsuperscript{23}

In conclusion, the reason for disintegration of lump ores in COREX shaft furnace could be attributed to two parts, one part was the volume expansion caused by the reduction from hematite to magnetite, and the other part was the stress caused by the carbon powder produced by the CDR. The disintegration mechanism could be conducted as follows. Firstly, the lump ore samples were reduced by CO near the surface as the reduction ability of CO was higher than H$_2$ under 810°C, and the COD occurred near the surface, producing small particles and generating fine cracks near the surface of lump ore samples. Secondly, the reduction by H$_2$ occurred along the fine cracks produced by CO reduction as H$_2$ was easy to diffuse into the inside of lump ore samples, and internal cracks were produced near the gangue phase due to the volume expansion of magnetite reduced from hematite by H$_2$. Meanwhile, the internal cracks produced by H$_2$ reduction provide “channels” for CO to diffuse into the inside of lump ores and the CDR occurred at the internal cracks, the carbon produced by the CDR would enlarge the cracks again. Therefore, it was the mutual promotion of reduction reaction and carbon deposition reaction that causes the heavy disintegration of lump ores in COREX shaft furnace.

4.2. Measures to Decrease Disintegration Degree

As the stress concentration caused by the volume expansion of magnetite and carbon deposition was the main reason for the disintegration of lump ores, how to decrease the stress seemed to be the key to decrease the disintegration degree of lump ores.

As shown in Figs. 7 and 8, increasing H$_2$ proportion in reducing gas would decrease disintegration degree of lump ores. Because the stress level in the magnetite crystals produced by H$_2$ reduction was lower than that produced by CO reduction,\textsuperscript{10} and the CDR would be limited as the pressure and the proportion of CO–CO$_2$ system decreased.

Figure 13 shows the carbon weight, reduction degree and RDI$_{6.3}$ of lump ore samples under different gas composition at 550°C. When the proportion of CO and CO$_2$ were changed with each other as case 5 and 10, the weight of carbon deposition increased from 15.08 g to 24.39 g, while the RDI$_{6.3}$ under higher CO content was 1.5% higher than that of lower CO content, but the weight ratio of smaller size (0–3.15 mm) under higher CO content was much higher (as shown in Fig. 8), meaning more carbon deposition would produce much more fine particles. On the other hand, when the H$_2$ proportion in reducing gas increased to 40.5% as case 11, the carbon deposition sharply decreased to 6.78 g, but the reduction degree decreased slightly. In addition, the RDI$_{6.3}$ dropped from 55.44% to 47.60%, meaning that controlling carbon deposition by increasing H$_2$ proportion could decrease the disintegration degree of lump ore samples. However, the efficiency of increasing H$_2$ proportion was limited as H$_2$ reduction would also produce small particles and cause disintegration of lump ores.

As shown in Figs. 5 and 6, the reduction temperature had great influence on the disintegration and reduction degree of lump ore samples. Moving the reduction process from hematite to magnetite to lower or higher temperature was helpful to decrease the disintegration degree of lump ore samples. Figure 14 shows the comparison of reduction degree and RDI$_{6.3}$ of lump ore samples under case 3, 5 and 7. Case 5 indicated that the samples were reduced normally (550°C for 60 min), case 3 represented the situation that the samples were slowly reduced at lower temperature (450°C for 120 min) and case 7 represented the situation that the
Fig. 13. Carbon weight, reduction degree and RDI_{6.3} of lump ore samples under different gas composition at 550°C. Case 5: 35%CO, 50%CO₂, 15%H₂; Case 10: 50%CO, 35%CO₂, 15%H₂; Case 11: 24.5%CO, 35%CO₂, 40.5%H₂.

Fig. 14. Comparison of reduction degree and RDI_{6.3} of lump ore samples under different cases. Case 3: 450°C, 120 min, 35%CO, 50%CO₂, 15%H₂; Case 5: 550°C, 60 min, 35%CO, 50%CO₂, 15%H₂; Case 7: 650°C, 30 min, 35%CO, 50%CO₂, 15%H₂.

Fig. 15. Comparison of reduction rate and ratio of (RDI_{6.3}/Reduction degree) of lump ore samples under different cases. Case 3: 450°C, 120 min, 35%CO, 50%CO₂, 15%H₂; Case 5: 550°C, 60 min, 35%CO, 50%CO₂, 15%H₂; Case 7: 650°C, 30 min, 35%CO, 50%CO₂, 15%H₂.
samples were rapidly reduced at higher temperature (650°C for 30 min). As shown in the figure, both the two measures could decrease the RDI of lump ore samples, but the effect of rapid reducing at higher temperature was stronger.

However, both the two measures could decrease the reduction degree of lump ore samples. To further compare these measures, the reduction rate and the ratio of (RDI/RD) under different cases were conducted and the results were shown in Fig. 15. The reduction rate of case 3 was lowest in the three cases and the ratio of (RDI/RD) was highest, meaning more small particles would be produced at the same reduction degree under the condition that lump ores were slowly reduced at lower temperature. However, the reduction rate of case 7 was highest and the ratio of (RDI/RD) was lowest, indicating that rapid reducing at higher temperature produced few small particles at the same reduction degree.

In conclusion, increasing H2 concentration in reducing gas and rapid reducing at higher temperature would help decrease the disintegration degree of lump ores in COREX shaft furnace. While, combined with the actual production, increasing the flow rate would move the temperature field in COREX shaft furnace toward to the top of the furnace, which would decrease the low temperature zone in the shaft furnace.

5. Conclusions

The reduction disintegration behavior of lump ore samples in COREX shaft furnace was studied, the RDI and reduction degree of lump ore samples under different temperature, reduction time and reducing gas compositions were measured. Besides, the disintegration mechanism of lump ores in COREX shaft furnace and measures to decrease disintegration degree of lump ores were discussed. Following conclusions were obtained from the above results.

(1) The disintegration and reduction behaviors of lump ore samples in COREX shaft furnace could be generally divided into three steps and the disintegration of lump ores mainly occurred in the second step in the temperature zone form 450°C to 650°C, though the reduction degree was very low.

(2) The RDI of lump ore samples under different reduction times all presented the tendency of “inverted V-shape” in the temperature range from 450°C to 650°C, the RDI at 550°C was highest and the RDI at 650°C was also higher than 450°C.

(3) The heavy disintegration of lump ores was attributed to the mutual promotion of reduction reaction and carbon deposition reaction, as the stress concentration caused by the volume expansion of magnetite and carbon deposition was the main reason for the cracks produced in the lump ores samples in COREX shaft furnace.

(4) Increasing H2 proportion in reducing gas and rapid reducing at higher temperature would decrease the disintegration degree of lump ores in COREX shaft furnace.

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