Study on the kinetics of gas-solid based synergistic reduction of limonite carbon-containing pellets

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Abstract: The gas-solid-based synergistic reduction of pellets is an innovative and effective method for iron ore smelting. With the development and utilization of iron resources, ore reserves have been greatly depleted; therefore, as a lean mineral resource, the comprehensive utilization of limonite has become increasingly important. To study the reduction kinetics of pellets in depth, this study used coke and reducing gases (CO and H₂) to study the reduction characteristics and changes occurring in carbon-containing limonite pellets. The results showed that the total weight loss percentage of pellets gradually increased with the temperature. The C/O molar ratio had a greater effect on the total weight loss percentage of pellets in a N₂ atmosphere, but it had no significant effect in CO or H₂ atmospheres. The maximum reaction rate increased with increasing temperature. The reduction reaction was the most difficult to proceed in the N₂ atmosphere, and the reaction was most likely to occur in the CO atmosphere. The analysis of pellets by EPMA and XRD found that the pellets reduced in the N₂ atmosphere had the lowest porosity, and the pellets reduced in the H₂ atmosphere had the highest porosity, which is more conducive to gas diffusion. Some of the unreduced Si, Al, Mn, Ca, and Fe in the pellets reduced in the N₂ atmosphere precipitated in the form of oxides, but when a reducing gas (CO, H₂) was introduced, precipitation did not occur.

Keywords: Limonite; pellet; reduction

1. Introduction

Blast furnaces have been extensively studied due to their prevalence in the ironmaking industry [1]. When selecting iron ore, most processes use magnetite or hematite for blast furnace smelting, but China has a large amount of limonite resources. Due to their low grade and high water of crystallization contents, these iron ores are not used in many pellets [2]. During the dehydration process of limonite, FeOOH is completely converted into Fe₂O₃, which introduces nanopores and increases the specific surface area of limonite [3]. As a result, its reduction performance is improved [4]. Blast furnace smelting produces serious pollution, consumes large amounts of energy, and has high requirements for ore strength. These drawbacks affect the application of limonite in the ironmaking process, which ultimately affects the development of steel enterprises. Direct reduced iron produces much less environmental pollution and has a wide application range of raw materials, which solves the shortcomings of blast furnace smelting.

Direct reduction methods can be divided into gas-based direct reduction and coal-based direct reduction. Gas-based direct reduction ironmaking methods use a reducing gas to reduce iron ore, most commonly H₂ and CO [5]. Under a H₂ atmosphere, because H₂ has a lower molecular weight and more easily diffuses, the reduction performance of pellets is significantly higher than that under a CO atmosphere, and the reduced pellets have a higher reduction rate [6].

Coal-based direct reduction methods use coal as a reducing agent and fuel (which can be solid or processed into a reducing gas) is added to the granular material layer of the reduction reaction device to reduce iron-containing raw
materials to directly reduce iron at high temperatures. The most mature coal-based direct reduction method is the rotary kiln process of non-carbon-containing pellets, but it requires large and expensive equipment and has a slow reduction rate and low recovery rate. Carbon-containing pellets can be made from a wide range of raw materials, strong adaptability of raw material particle size, and produce low amounts of environmental pollution [7]. Some researchers have found that the reduction degree of carbon-containing pellets increases upon increasing the C/O molar ratio and temperature of the pellets [8-9]. Interfacial reactions are the limiting step during the reduction of carbon-containing pellets [10].

Although carbon-containing pellets have certain advantages, they still have several disadvantages such as high energy consumption, poor quality, poor equipment stability, high product energy consumption, and easy adhesion of pellets. If a small volume of reducing gas is introduced during the reduction of carbon-containing pellets, some shortcomings of the reduction process of carbon-containing pellets can be improved. In order to study the influence of the atmosphere, temperature, and C/O molar ratio on the reduction characteristics of pure limonite pellets, this paper uses a thermogravimetric method to calculate the reduction kinetics under different temperatures and different atmospheres, and uses EPMA and XRD to analyze the reduced pellets.

2. Materials and methods

2.1 Materials

The limonite samples used in this study were obtained from Honghe Iron and Steel Co., Ltd. It has a high porosity, strong water absorption, large wet capacity, and easily melts. Its chemical composition is shown in Table 1. The crystal phases in the sample were characterized by X-ray diffraction, and the XRD pattern of limonite is shown in Figure 1(a). The pattern shows that the main mineral form of limonite is FeOOH, which contains a large amount of crystal water. Coke was produced by Yunnan Fanya Electronic Commerce Co., Ltd. (Shizong), and its chemical composition is shown in Table 2. The XRD pattern of coke is shown in Figure 1(b). It can be seen from the figure that in addition to fixing C, the ash is mainly composed of SiO₂ and contains a small amount of Fe₂O₃. The particle size of limonite powder and coke powder used in the experiment both ranged from 0.075 mm~0.15 mm.

Table 1 Iron ore chemical composition

| w(T)  | w(FeO) | w(SiO₂) | w(MnO) | w(TiO₂) | w(LOI) |
|-------|--------|---------|--------|---------|--------|
| 54.6  | 0.29   | 4.04    | 0.0    | 3.47    | 14.82  |
| 7     | 48     | 09      | 18     | 5       | 82     |

Table 2 Chemical composition of coke breeze (wt%)

| Ash | S | H₂O | Volatile | C |
|-----|---|-----|----------|---|
| 14.29 | 0.59 | 0.46 | 1.64     | 83.60 |

Figure 1. XRD pattern of (a) Guisha limonite and (b) coke

2.2 Preparation of limonite-coke composite pellets
A disc pelletizer was used to prepare the limonite-coke powder composite pellets with a diameter of 10 ~ 12.5 mm. The prepared pellets were dried in a drying oven at 110 °C for 2 h to remove free water.

### Table 3 Compound pellet ratio (wt%)

| C/O   | 0.75 | 1   | 1.25 | 1.5  |
|-------|------|-----|------|------|
| Limonite wt% | 81.40 | 76.95 | 72.96 | 69.37 |
| Coke wt%   | 17.10 | 21.55 | 25.54 | 29.13 |
| Bentonite wt% | 1.50  | 1.50  | 1.50  | 1.50  |

#### 2.3 Thermodynamic analysis

Under a N₂ atmosphere, the main reactions of limonite pellets occurring during direct carbon reduction are the direct reduction of iron oxides, indirect reduction, and coke gasification, as shown in equations (1) ~ (8).

- **Crystal water desorption:** $n\text{Fe}_2\text{O}_3 \cdot m\text{H}_2\text{O} = n\text{Fe}_2\text{O}_3 + m\text{H}_2\text{O}$ (1)
- **Direct reduction:**
  - $\text{C} + 3\text{Fe}_2\text{O}_3 = \text{CO} + 2\text{Fe}_2\text{O}_4$ (2)
  - $\text{C} + \text{Fe}_2\text{O}_4 = 3\text{FeO} + \text{CO}$ (3)
  - $\text{C} + \text{FeO} = \text{CO} + \text{Fe}$ (4)
- **Indirect reduction:**
  - $3\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{Fe}_3\text{O}_4 + \text{CO}_2$ (5)
  - $\text{Fe}_2\text{O}_4 + \text{CO} = 3\text{FeO} + \text{CO}_2$ (6)
  - $\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$ (7)
- **Coke gasification:** $\text{C} + \text{CO}_2 = 2\text{CO}$ (8)

The main reactions occurring under a CO atmosphere are basically the same as under a N₂ atmosphere, but the direct reduction process of CO plays a dominant role. The reaction process occurs in a stepwise fashion, and the reaction process is shown in formulas (9) to (15).

- **$T > 843 \text{ K}$**
  - $n\text{Fe}_2\text{O}_3 \cdot m\text{H}_2\text{O} = n\text{Fe}_2\text{O}_3 + m\text{H}_2\text{O}$ (9)
  - $3\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{Fe}_3\text{O}_4 + \text{CO}_2$ (10)
  - $\text{Fe}_2\text{O}_4 + \text{CO} = 3\text{FeO} + \text{CO}_2$ (11)
  - $\text{FeO} + \text{CO} = \text{Fe} + \text{CO}_2$ (12)

- **$T < 843 \text{ K}$**
  - $n\text{Fe}_2\text{O}_3 \cdot m\text{H}_2\text{O} = n\text{Fe}_2\text{O}_3 + m\text{H}_2\text{O}$ (13)
  - $3\text{Fe}_2\text{O}_3 + \text{CO} = 2\text{Fe}_3\text{O}_4 + \text{CO}_2$ (14)
  - $\frac{1}{4}\text{Fe}_3\text{O}_4 + \text{CO} = \frac{3}{4}\text{Fe} + \text{CO}_2$ (15)

In addition to the reactions that take place in a N₂ atmosphere, the main reactions that take place in a H₂ atmosphere include the direct reduction of H₂, which plays a dominant role, as shown in equations (16) to (22).

- **$T > 843 \text{ K}$**
  - $n\text{Fe}_2\text{O}_3 \cdot m\text{H}_2\text{O} = n\text{Fe}_2\text{O}_3 + m\text{H}_2\text{O}$ (16)
  - $3\text{Fe}_2\text{O}_3 + \text{H}_2 = 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$ (17)
  - $\text{Fe}_2\text{O}_4 + \text{H}_2 = 3\text{FeO} + \text{H}_2\text{O}$ (18)
  - $\text{FeO} + \text{H}_2 = \text{Fe} + \text{H}_2\text{O}$ (19)

- **$T < 843 \text{ K}$**
  - $n\text{Fe}_2\text{O}_3 \cdot m\text{H}_2\text{O} = n\text{Fe}_2\text{O}_3 + m\text{H}_2\text{O}$ (20)
  - $3\text{Fe}_2\text{O}_3 + \text{H}_2 = 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O}$ (21)
  - $\frac{1}{4}\text{Fe}_3\text{O}_4 + \text{H}_2 = \frac{3}{4}\text{Fe} + \text{H}_2\text{O}$ (22)

#### 2.4 Kinetics analysis

The reduction of iron oxides is a complex process, and the thermal weight loss method is
commonly used to study the reduction reaction kinetics. In order to reasonably study the reduction process of oxidized pellets, previous researchers have established many different methods to investigate the mechanism. Previous studies have shown that under a N\textsubscript{2} atmosphere, coke acts as the only reducing agent, and the reaction involves nucleation and growth. The process can be described by the Avrami-Erofeev model [11]. Under H\textsubscript{2} and CO atmospheres, the reducing gas plays a leading role in the reduction process. At this time, the reduction reaction is controlled by interfacial chemical reactions, which can be modeled using the shrinking core model [7]. Table 4 lists the kinetic models used to describe the above reactions.

| Response model           | Equation                                      | Rate control procedure              |
|-------------------------|-----------------------------------------------|-------------------------------------|
| Avrami-Erofeev Model    | \[ -\ln(1 - x)^{2/3} = kt \]                  | Nucleation and growth control       |
| Shrink Nuclear Model    | \[ 1 - (1 - x)^{1/3} = kt \]                  | Interface chemical reaction control |

2.5 Experimental method

A schematic diagram of the limonite pellet reduction experiment device is shown in Figure 2. The test system mainly includes a vertical tube furnace, flowmeter, balance, electric furnace control system, and data processing computer. The computer is connected with the balance to realize real-time data recording.

The tube furnace was heated to the reduction temperature and then purged with N\textsubscript{2} gas with a purity of 99.99%. After the furnace was filled with N\textsubscript{2} gas, the prepared limonite-coke composite pellet particles were suspended in a hanging basket, suspended under the balance by an iron-chromium-aluminum wire, and the reducing gas was simultaneously introduced (gas velocity = 0.382 m/min). The mass of the pellets was automatically recorded by a computer.

Figure 2 Test device schematic diagram

The limonite-coke powder composite pellet particles lose oxygen during the reduction process, and the coke content in the particles also decreases as reduction proceeds. The formula for calculating the total weight loss percentage (w) is shown in formula (23) [12-13]:

\[
w = \frac{w_0 - w_t}{w_0} \times 100\%
\]

(23)
where $w_0$ is the initial mass of a pellet, $w_t$ is the mass of a pellet at time $t$, $w_{Fe}$ is the maximum weight loss of limonite, and $w_C$ is the maximum weight loss of coke.

Therefore, the formula for calculating the reaction rate $v$ of limonite-coke powder composite pellets is shown in equation (24):

$$v = \frac{dw}{dt} = \frac{\Delta w}{\Delta t}$$

where $\Delta w$ is the increase in the total weight loss percentage at each time interval $\Delta t$.

3 Results and discussion
3.1 Reduction kinetics analysis
3.1.1 Percentage analysis of total weight loss

The experiment was carried out at 973–1373 K, with either a N$_2$, CO, or H$_2$ atmosphere, and 0.75–1.5 C/O molar ratios. The total weight loss percentage of limonite pellets was calculated using equation (23). Figure 3 shows the relationship between the total weight loss percentage and reaction time.
Figure 3. The effect of reaction conditions on the total weight loss percentage of limonite pellets: (a) C/O molar ratio is 1, N\textsubscript{2} atmosphere; (b) C/O molar ratio is 1, CO atmosphere; (c) C/O molar ratio is 1, H\textsubscript{2} atmosphere; (d) reaction temperature is 1375 K, N\textsubscript{2} atmosphere; (e) reaction temperature is 1373 K, CO atmosphere; (f) reaction temperature is 1373 K, H\textsubscript{2} atmosphere.

Figure 3 shows that the reduction temperature, reducing atmosphere, and C/O molar ratio significantly affected the total weight loss percentage of limonite pellets. As shown in Figures 3(a), (b), and (c), under a given C/O molar ratio and reducing atmosphere, a higher temperature increased the total weight loss and shortened the reaction time. As shown in Figure 3(b), using a C/O molar ratio of 1 and a CO atmosphere as an example, the total weight loss of limonite increased from 57.26% to 82.20% as the temperature increases. From 973 K to 1373 K, the reduction time decreased from 62 min to 30 min. This increase occurred because increasing the temperature promoted the endothermic reduction reaction between the iron oxide and reducing agent.

As shown in Figure 3 (d), (e), and (f), at 1375 K, when the C/O molar ratio increased from 0.75 to 1.5. Under an N\textsubscript{2} atmosphere, the total weight loss of limonite pellets increased from 53.28% to 66.67%, which was proportional to the C/O molar ratio. Under CO and H\textsubscript{2} atmospheres, the total weight loss percentage of limonite pellets was the same. It can be seen that under a N\textsubscript{2} atmosphere, increasing the C/O molar ratio increased the reduction rate of limonite pellets. The C/O molar ratio in CO and H\textsubscript{2} atmospheres did not affect the total weight loss percentage of the pellets.

3.1.2 Response rate analysis

By substituting the total weight loss percentage and reaction time into equation (24), the reaction rate of the limonite pellets was calculated. Figure 4 shows the relationship between reaction rate and time under different reducing temperatures, reducing atmospheres, and C/O molar ratios.
Figure 4. The influence of experimental conditions on the reaction rate of limonite pellets: (a) C/O molar ratio is 1, N₂ atmosphere; (b) C/O molar ratio is 1, CO atmosphere; (c) C/O molar ratio is 1, H₂ atmosphere; (d) reaction temperature is 1375 K, N₂ atmosphere; (e) reaction temperature is 1373 K, CO atmosphere; (f) reaction temperature is 1373 K, H₂ atmosphere.

As shown in Figure 4, the reduction temperature, reducing atmosphere, and C/O molar ratio have a significant effect on the reaction rate. From Figure 4 (a), (b), and (c), when the atmosphere and the C/O molar ratio are the same, the maximum reaction rate increases with the temperature. For example, as shown in Figure 4(b), in a CO atmosphere with a C/O molar ratio of 1, the temperature increases from 973 K to 1373 K, and the maximum limonite reaction rate increases from 6.510521 s⁻¹ to 14.47173 s⁻¹. The results show that a higher temperature promoted the reduction of limonite. Figure 4(d), (e), and (f) show that in N₂ and H₂ atmospheres, upon increasing the C/O molar ratio, the maximum reaction rate first increased and then decreased because coke was added with N₂ as a reducing agent. When the amount of coke increases, its reducibility rapidly increases. When the coke reaches a certain amount, unreacted coke prevents the generated CO from contacting the limonite, which decreases the reaction rate. Under the H₂ and H₂ atmospheres, increasing the amount of coke provides more reducing agent to generate more CO gas, which accelerates the reaction. When the amount of coke exceeds a certain ratio, it affects the inward diffusion rate of H₂, and unreacted carbon also reduces the specific surface area of the ore. As a result, the reaction rate is reduced. In a CO atmosphere, the reaction rate gradually increases upon increasing the C/O molar ratio, which shows that adding the proper amount of coke increases the maximum reaction rate. In N₂ and H₂ atmospheres, the optimal C/O molar ratio was between 0.72 and 1.5. In a CO atmosphere, the optimal C/O molar ratio is greater than or equal to 1.5.

### Kinetics analysis

The apparent reaction rate and correlation coefficient under different conditions were calculated by the kinetics models in Table 4 and the results are shown in Table 5. The correlation coefficients in Table 5 are all above 0.95, indicating that the response model has a good linear relationship. The results further confirmed the correctness of the response model. Table 5 also shows that the apparent reaction rate of limonite pellets increases as the reduction temperature increases. At the same reduction temperature, the apparent reaction rate constant in the H₂ atmosphere is the largest, and the apparent reaction rate constant in the N₂ atmosphere is the smallest.

| Atmosphere | T (K) | Response model | K (min⁻¹) | R²    |
|------------|-------|----------------|-----------|-------|
| N₂         | 973   | \([−\ln(1−x)]^{2/3}\) = kt | 0.00427   | 0.96973 |
|            | 1073  | = kt           | 0.00513   | 0.99039 |
|            | 1173  |                | 0.00711   | 0.97605 |
|            | 1273  |                | 0.01665   | 0.98125 |
According to the Arrhenius equation, the relationship between reaction ($T$) and reaction rate constant ($k$) can be obtained, as shown in equation (3) [15]. In equation (3), $E$ is the activation energy (kJ/mol), and $k_0$ is the frequency factor.

$$k = k_0 \exp\left(-\frac{E}{RT}\right)$$

(25)

Combine with equation (3), and take the logarithms of both sides of the equation, as shown in equation (4):

$$\ln k = -\frac{E}{RT} + \ln k_0$$

(26)

The linear fit between $\ln k$ and $1000/RT$ is shown in Figure 4, and the fitted kinetic parameters are listed in Table 6.

![Figure 5 The fitting curve of \(\ln k\) and 1000/RT under different conditions](image)

Table 6 Kinetics parameters of the reduction of limonite particles

| Atmosphere | \(E\) (kJ/mol) | \(\ln k\) (min\(^{-1}\)) |
|------------|----------------|-------------------------|
| \(N_2\)    | 49.42836       | 0.43608                 |
| \(CO\)     | 25.31582       | -1.21843                |
| \(H_2\)    | 33.31605       | 0.23853                 |

Table 6 shows that the reaction was the most difficult in the \(N_2\) atmosphere, and the reaction is most likely to occur in the CO atmosphere.

3.2 Microstructure changes of reduced particles

Using EPMA and XRD, taking C/O = 1.5 as an example (reduction time = 120 min), the microstructures of the particles reduced in \(N_2\), CO, and \(H_2\) atmospheres were studied and analyzed. The results are shown in Figure 5.
Figure 6 EPMA Images and XRD patterns of limonite pellets reduced at 1373 K under different conditions: (a) C/O = 1.5, N\textsubscript{2} atmosphere, (b) C/O = 1.5, CO atmosphere, (c) C/O = 1.5, H\textsubscript{2} atmosphere.

First, the EPMA image in Figure 6 shows that the porosity of the pellets reduced in the N\textsubscript{2} atmosphere was the lowest, while the porosity of the pellets reduced in the H\textsubscript{2} atmosphere was the highest. The porosity of the pellets reduced in the CO atmosphere was between the two. This indicates that during the reduction of carbon-containing pellets, the introduction of a reducing gas increases the porosity of the pellets, which improves the diffusion of coke after gasification. The reducing gas will also directly reduce the pellets, which promotes the reaction progress [17]. The XRD pattern in Fig. 5 shows that the pellets had the same composition after the reaction, and all were composed of Fe, SiO\textsubscript{2}, and Fe\textsubscript{3}O\textsubscript{4}.

According to Fig. 6, consolidated products precipitated in the pellets reduced in the N\textsubscript{2} atmosphere, but no crystalline products precipitated when reduced in CO and H\textsubscript{2} atmospheres. The spectrum of the consolidated products was detected, and the results are shown in Figure 7 and Table 7.
Figure 7 Spectrum detection results

Table 7 Element ratio

|    | O   | Al | Si  | Ca  | Mn  | Fe  |
|----|-----|----|-----|-----|-----|-----|
|    | 41.77 | 6.19 | 26.97 | 3.42 | 14.84 | 6.81 |

As shown in Figure 7, the analysis of the results of the test shows that when reduced in an N₂ atmosphere, some unreduced Si, Al, Mn, Ca, and Fe precipitated in the form of oxides. When a reducing gas (CO, H₂) was used, no precipitation occurred.

4 Conclusion

(1) In pellets reduced with a C/O molar ratio of 1 under the same reducing atmosphere, increasing the temperature increased the total weight loss percentage and shortened the reduction time.

(2) In pellets reduced at 1373 K under a N₂ atmosphere, increasing the C/O molar ratio promoted the reduction rate of limonite pellets. In CO and H₂ atmospheres the C/O ratio did not affect the total weight loss percentage of the pellets.

(3) In N₂ and H₂ atmospheres, the optimal C/O molar ratio was between 0.72 and 1.5. In a CO atmosphere, the optimal C/O molar ratio was ≥ 1.5.

(4) In pellets reduced with a C/O molar ratio of 1 at 1373 K, the $E$ values in N₂, CO, and H₂ atmosphere were 49.42836 kJ/mol, 25.31582 kJ/mol, and 33.31605 kJ/mol, respectively, and the ln$k$ values were 0.43608 min⁻¹, -1.21843 min⁻¹, and 0.23853 min⁻¹, respectively.

(5) In pellets reduced with a C/O molar ratio of 1 at 1373 K, the porosity of pellets reduced in a N₂ atmosphere was the smallest, the porosity of pellets reduced in a H₂ atmosphere was the largest, and the porosity of pellets reduced in CO atmosphere was somewhere in between. The composition of the pellets after reduction was the same.

(6) In pellets reduced with a C/O molar ratio of 1 at 1373 K under a N₂ atmosphere, some unreduced Si, Al, Mn, Ca, and Fe precipitated in the form of oxides. When a reducing gas (CO, H₂) was introduced, no precipitation occurred.

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References

[1] T.J. Chun, G.T. Mu, Q.M. Meng, H.M. Long, P. Wang, C.G. Bi, J. Min. Metall. Sect. B-Metall., 55(2)(2019)167 – 175.
[2] G.F. Gao, X.L. Zhou, Z. Shi, L.P. Liu, J. Materials Transaction., 61(3)(2020)1805-1812.
[3] K. Abe, A. Kurniawan, T. Nomura, T. Akiyama, J. Journal of Energy Chemistry., 27(5)(2018)1489-1495.
[4] R. Sah, S. K. Dutta, J. Trans Indian Inst Met., 64(6)(2011)583-591.
[5] L.Y. Yi, Z.C. Huang, H. Peng, T. Jiang, J. Journal of Central South University., 19(2012)2291-2296.
[6] R.Z. Longbottom, L. Kolbeinsen, C. Proceedings of the 4th Ulcos seminar-New Direct Reduction (DR)., (2018)10-11.
[7] Y. Man, D. University of Science and Technology Beijing., (2015)52-53.
[8] P. Gao, G.F. Li, X.T. Gu, Y.X. Man, J. Mineral Processing and Extractive Metallurgy Review., 41(3)(2020)162-170.
[9] S. Mishra, G.G. Roy, J. Ironmaking&Steelmaking., 45(5)(2018)426-433.
[10] Y. Man, J. Feng, J. Powder Technology., 301(2016)674-678.
[11] P. Gao, G.F. Li, X.T. Gu, J. Mineral Processing and Extractive Metallurgy Review, 41(3)(2020)162-170.
[12] Y.M. Wang, Z.F. Yuan, Z.C. Guo, Q.Q. Tan, Z.Y. Li, W.Z. Jiang, J, Trans. Nonferrous Met. Soc. China, 18(2008)962-968.
[13] R.F. Johnston, H.T. Nguyen, J. Minerals Engineering, 9(7)(1996)765-773.
[14] J.W. Chen, W.B. Chen, L. Mi, J. Metals., 9(95)(2019)1-13.
[15] L. Yi, Z. Huang, H. Peng, J. Cent South Univ., 19(2012)2291-2296.