Kinetics of Reduction in Stages of Pellets Prepared from the Bayan Obo Iron Ore Concentrate

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ABSTRACT: To explore the reduction swelling process of pellets prepared from the Bayan Obo iron ore concentrate, based on the iron oxide reduction theory of pellets, the reduction of pellets prepared from the Bayan Obo iron ore concentrate was analyzed by thermogravimetric experiments and kinetic calculations in three stages. The reason for the abnormal swelling of pellets prepared from the Bayan Obo iron ore concentrate was analyzed from the perspective of kinetics. The research results showed that carbon deposition occurred in the first stage of reduction. The second stage of reduction was controlled by an interfacial chemical reaction, and the activation energy of the reaction was 117.99 kJ/mol. The reaction energy barrier was higher and the reaction rate was slower, and therefore, the reduction swelling rate of pellets was lower at this stage. The third stage of reduction was controlled by internal diffusion, and the reaction activation energy was 15.9 kJ/mol. The reduction reaction of pellets occurs violently, and the reduction swelling behavior was remarkable at this stage.

1. INTRODUCTION

Sinter is still the main raw material for ironmaking in China. In other countries, such as Sweden’s SSAB blast furnace, 100% pellet smelting has been achieved. However, at present, the average proportion of pellets in the Chinese blast furnace charge structure is less than 40%. Compared with sinter, pellets have the advantages of uniform particle size, high strength, high iron grade, and low energy consumption in the process. Wang et al. completed the production test of blast furnace smelting with a high proportion of pellets, and the results showed that in the blast furnace smelting process, increasing the proportion of pellets resulted in stable production and great environmental benefits. Its SO₂, NOₓ, PM, and CO₂ emissions are far lower than that in the blast furnace smelted with a high proportion of sinter. Increasing the proportion of pellets in the charge structure of the blast furnace is one of the development directions of ironmaking technology in China. The Chinese government attaches great importance to the issue of climate change, has proactively made emission reduction commitments and put forward the development goal of “striving to reach peak carbon-dioxide emissions by 2030 and striving to achieve carbon neutrality before 2060.” The price of imported iron ore has remained high recently. Significantly increasing the use of self-produced ore is the main way for inland steel companies to reduce production costs and increase economic benefits. As the only self-produced iron-containing raw material of Baotou Iron and Steel Company (hereinafter referred to as Baotou Steel), the Bayan Obo iron concentrate contains harmful elements such as K, Na, and F that have a significant impact on the reduction swelling of pellets, which limits the high-proportion application of the Bayan Obo iron concentrate in the pellet preparation process. At present, the proportion of pellets in the charge structure of the blast furnace in Baotou Steel is less than 30%, and the proportion of the Bayan Obo iron concentrate in the raw materials for pellet production is 47%, which severely restricts the production capacity of pellets and the reduction of ironmaking costs in Baotou Steel. Studying the relationship between the kinetic behavior and the reduction swelling rate in the reduction process of pellets prepared from the Bayan Obo iron ore concentrate is helpful to clarify the reduction swelling mechanism of pellets prepared from the Bayan Obo iron ore concentrate. It provides guidance for optimizing the ratio of raw materials and regulating the preparation process so that the Bayan Obo ore can be applied to the production of pellets in a large proportion.

The blast furnace smelting process is always accompanied by the occurrence of a gas–solid reaction, and there are many common models, such as the contracting volume(CV) model, Jander model, Ginstling–Brounshtein(G–B) model, and others.

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model,25,26 Chou model,27−33 Johnson−Mehl Avrami−Kolomogorov (JMAK) models,34−42 and nucleation index-incorporated JMAK (NI-JMAK) model.38,42 The reduction of pellets in a blast furnace is a typical gas−solid reaction. Many scholars have studied the reduction kinetics of pellets. Chen et al. studied the isothermal reduction kinetics of carbon-containing pellets of high-phosphorus iron ore using a mechanism function model to fit the reaction process.45 Zhao et al. used the thermogravimetric method to carry out hydrogen-rich reduction experiments on the Bayan Obo iron ore concentrate, investigated the influence of the ratio of H2 to CO on the reduction rate, and calculated the reaction activation energy according to different rate formulas.46 Wu et al. proposed a reaction kinetics model for the reduction of pellets after mixing H2 and CO and indicated that the resistance and reaction rate change with the temperature and the degree of reduction during the reduction process.47 Jiang et al. analyzed the reduction kinetics of zinc-containing pellets with internal carbon.46 They summarized the influence of temperature on the reduction of pellets and the main limiting factors in the early, middle, and late stages of the reduction reaction of zinc-containing pellets. Chen et al. proposed the reaction model of SrSO4 in carbon-containing pellets during the reduction process by fitting the kinetic parameters of the reduction process of SrSO4 carbon-containing pellets and calculating the apparent activation energy.47 Zhu et al. established a kinetic model for zinc-containing pellets to remove zinc through direct reduction and clarified the existence of zinc in pellets and the mechanism of zinc removal during the direct reduction process.48 Yuan et al. studied the isothermal reduction kinetics of composite pellets with different compositions at 900−1200 °C and calculated the apparent activation energy of gasification diffusion using the Arrhenius formula.49 Zhong et al. studied the reduction behavior of low-grade iron ore-coal composite pellets at 850−1000 °C and discussed the influence of sodium salt addition on the reduction behavior of pellets.50

According to the gas-phase equilibrium diagram of CO reduced from iron oxides, the reduction of iron oxide follows the principle of gradual transformation. However, the current research on the kinetics of the reduction process of pellets prepared from the Bayan Obo iron ore Concentrate is directly from the process of Fe2O3 → Fe and there are relatively few studies on the kinetics of the reaction of iron oxides in the intermediate stage. Therefore, based on the iron oxide reduction theory of pellets,51 from the perspective of thermodynamics, the reduction process of pellets prepared from the Bayan Obo iron ore concentrate is divided into three stages (Fe2O3 → FeO, FeO → Fe, and FeO → Fe), and the temperature and gas ratio of the three stages are determined by the gas-phase equilibrium diagram of CO reduced from iron oxides. The reduction process of pellets prepared from the Bayan Obo iron ore concentrate was studied in stages by isothermal kinetics.

The reduction degree of iron oxide is calculated according to the mass change before and after the reaction of the sample, and the calculation method is shown in eq 1

\[ D = \frac{\Delta m}{\sum m} \times 100\% = \frac{m_0 - m_t}{m_0 - m_r} \]  

In the formula, \( D \) is the reduction degree, \( \% \); \( \Delta m \) is the variation of the weight at time \( t \), \( g_i \); \( \sum m \) is the total weight change of pellets, \( g_i \); \( m_r \) is the initial weight, \( g_i \); \( m_t \) is the weight after the reaction, \( g_i \).

The unreacted core model can be used to determine the reduction reaction process of pellets prepared from the Bayan Obo iron ore concentrate.

(1) When the reduction process is controlled by an interfacial chemical reaction, the kinetic equation can be expressed by the Mckewan equation.52

\[ 1 - (1 - D)^{1/3} = kt \]  

(2) When the reduction process is controlled by internal diffusion, the kinetic equation can be expressed by the Ginstling−Brounshtein equation.53

\[ 1 - 2D/3 - (1 - D)^{2/3} = kt \]  

(3) When the reduction process is controlled by external diffusion, the kinetic equation can be expressed by the Jander equation.54

\[ [1 - (1 - D)^{1/3}]^2 = kt \]  

\( D \) in eqs 2–4 is the reduction rate calculated using eq 1.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Experimental Raw Materials. The main raw materials are the Bayan Obo iron ore concentrate and bentonite of Baotou Steel. Table 1 shows the chemical composition of the Bayan Obo iron ore concentrate.56 The TFe content of the iron concentrate is 65.06%, the content of CaO and SiO2 is 1.95 and 2.78% respectively, and the alkali metals K, Na, and F are also present. Table 2 shows the chemical composition of bentonite added to pellets.56

| chemical composition | MgO | CaO | SiO2 | Al2O3 | ignition loss |
|----------------------|-----|-----|------|-------|--------------|
| percentage contents  | 2.57 | 2.64 | 64.76 | 12.02 | 10.59        |

\( ^{\text{a}} \)This table is referenced with permission from Taylor & Francis, Ironmaking & Steelmaking, 2021.

2.2. Experimental Instruments. A KTF-1700-VT high-temperature tube furnace produced by Anhui Kemi Machinery Technology Co., Ltd., was used to roast pellets, and a TFD-1100-70-RZ02 thermogravimetric vertical furnace produced by the same company was used to perform thermogravimetric experiments and record the weight change of pellets. Figure 1 shows the structure diagram of the thermogravimetric vertical furnace. The visual high-temperature deformation analyzer was used to record the projected area change of the pellets at each reduction stage, in which the principle is to characterize the reduction swelling index (RSI) of the pellets according to the
changes in the projected area of the pellets during the reduction process. The schematic diagram of the experimental equipment is shown in Figure 2. The projected area of a pellet is shown in Figure 3.

\[
\text{RSI} = \frac{\Delta S}{S_0} \times 100\% = \frac{S_t - S_0}{S_0} \times 100\%
\]

In the formula, \(\Delta S\) is the variation of the area at time \(t\), cm\(^2\); \(S_0\) is the initial projected area, cm\(^2\); and \(S_t\) is the projected area at a certain time \(t\), cm\(^2\).

A JSM-6510 scanning electron microscope (SEM) and energy-dispersive spectrometer (EDS) produced by JEOL were used to observe the microscopic morphology and analyze the element contents and distribution of the pellet.

2.3. Experimental Scheme. 2.3.1. Preparation of Raw Materials. The Bayan Obo iron ore concentrate and bentonite are ground below 0.074 mm, respectively, and put into a WGL-30B electric thermostatic drying oven at 473.15 K for 90 min. Then, the dried mineral powder and bentonite are put into a mixing tank at a ratio of 97:3 and mixed for 60 min. After the raw materials are mixed, the electric thermostatic drying oven
was again used to dry at 473.15 K for 30 min, and they were taken out for later use.

2.3.2. Preparation of the Sample. The dried raw materials are put into the disc pelletizing machine with a diameter of 1000 mm to pelletize. This process requires strict control of the amount of water sprayed to obtain qualified green pellets. A pelletizing system is that in which a raw pellet is generated for 3 min, grown for 8 min, and reinforced for 10 min. Qualified green pellets should meet the following conditions: the diameter is 10–12 mm, drop strength is 6–8 times/0.5 m, and compressive strength is not less than 10 N/P.

2.3.3. Experimental Scheme of Roasting. Qualified green pellets were selected and put in a high-temperature tube furnace for roasting. The roasting system is as follows: drying at 437.15 K for 30 min, preheating at 1173.15 K for 30 min, and roasting at 1523.15 K for 30 min. The heating rate was always maintained at 10 K/min, and then cooled with the furnace, and taken out when the temperature dropped below 100 °C. Pellets without cracks were selected for the staged reduction experiment of kinetics. The compressive strength of the pellets was above 2000 N, and the weight was kept at about 2 g.

2.3.4. Experimental Scheme of Reduction Swelling and Process Kinetics. From the gas-phase equilibrium diagram of CO-reduced iron oxide (Figure 4), it can be seen that the three equilibrium curves divide the diagram into stable existence areas of Fe₃O₄, FeO, and Fe. A point is selected from each of the three stable existence areas, and the abscissa and ordinate values of these points are used as the parameters of the temperature and CO content in this reduction stage. Finally, the reduction parameters of each stage (Table 3) are obtained. Limited by the experimental equipment, the temperature parameters of the reduction kinetics experiment are groped out according to the specific experimental conditions, and the CO content parameters are consistent with Table 3. Since the maximum gas flow allowed by the thermogravimetric vertical furnace is 500 mL/min, the maximum gas flow in Tables 3 and 4 is 500 mL/min.

### Table 3. Reduction Swelling Experimental Parameters of the Three Stages

| Reduction phase | T/K   | CO content (%) | t (min) | Gas flow (mL/min) |
|-----------------|-------|----------------|--------|-------------------|
| Fe₂O₃ → Fe₃O₄   | 1173.15 | 60            | 60     | 500               |
| Fe₃O₄ → FeO     | 1273.15 | 100           | 60     | 500               |
| FeO → Fe        | 1073.15 | 60            | 60     | 500               |

### Table 4. Reduction Kinetics Experimental Parameters of the Three Stages

| Reduction phase | T/K   | CO content (%) | t (min) | Gas flow (mL/min) |
|-----------------|-------|----------------|--------|-------------------|
| Fe₂O₃ → Fe₃O₄   | 873.15 | 20             | 60     | 300               |
| Fe₃O₄ → FeO     | 1123.15 | 60           | 60     | 500               |
| FeO → Fe        | 1173.15 | 100           | 60     | 500               |

3. RESULTS AND DISCUSSION

3.1. Reduction Swelling Results of Pellets. Figure 5 shows the X-ray diffraction (XRD) diagram of the main products in each stage of pellet reduction. (This table is referenced with permission from Taylor & Francis, Ironmaking & Steelmaking, 2021.)

![Figure 5](https://example.com/figure5.png)

**Figure 5.** XRD diagram of the main products in each stage of pellet reduction. It can be seen from the figure that the reduction products of each stage are consistent with the theoretical products set in the experiment, which shows that the parameter design of the reduction experiment is reasonable.

![Figure 6](https://example.com/figure6.png)

**Figure 6.** The gradual reduction swelling index (RSI) of pellets prepared from the Bayan Obo iron ore concentrate. The experimental results show that RSI values of pellets prepared from the Bayan Obo iron ore concentrate in three stages are 6.9, 4.1, and 24.0%, respectively, and the RSI in the second stage is the smallest, and RSI in the third stage is the largest. The total RSI can reach 35%. This situation belongs to malignant swelling. Next, the reasons for the...
3.2. Study on the Reduction Kinetics of Pellets in Stages.

3.2.1. Reduction of Pellets Prepared from the Bayan Obo Iron Ore Concentrate in the First Stage. When the reaction \( 3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow \text{Fe}_3\text{O}_4 + \text{CO}_2 \) occurs, the weight of pellets should decrease, but as shown in Figure 7, the weight of pellets in the first stage of reduction increased at three different temperatures. The reason for the increase in the weight of pellets in the first stage of reduction is due to carbon deposition. The carbon precipitation reaction is \( 2\text{CO} = \text{C} + \text{CO}_2 \). Moderate carbon precipitation can lower the melting point of molten iron, but excessive carburization will cause carbon to deposit in the pores of the pellets and generate internal stress during the reduction process, resulting in a decrease in the strength of the pellets. Temperature and gas composition are the main factors affecting carbon deposition. In the first stage of reduction, the temperature is low (the highest temperature is \( 873.15 \) K), the gas flow is small (300 mL/min), the reduction rate is slow, and the rate of carbon deposition is faster than the reduction rate of pellets. Therefore, the weight of pellets will increase in the first stage of reduction.

SEM was used to observe the micromorphology of the pellet samples before reduction and the first stage of reduction, as shown in Figure 8. Compared with before reduction (Figure 8a), the pellet sample after the first stage of reduction (Figure 8b) has more pores and a looser structure. The reason is that the deposited carbon is dispersed around the iron oxide, hindering the chemical reaction of the iron oxide. EDS analysis of the carbon element was performed on the pellet samples before reduction and the first stage of reduction, as shown in Figure 9. Figure 9a shows the distribution of carbon in the pellet sample before reduction. The carbon element content is low and scattered in the pellets. These carbon elements are contained in the raw material itself. Figure 9b shows the distribution of carbon in the pellet sample in the first stage of reduction. The carbon is significantly increased and gathered around the pores. The above analysis shows that the pellets will deposit carbon when the temperature is low and the gas flow is small. The presence of carbon will accelerate the reduction process of pellets and increase the swelling rate of pellets.

3.2.2. Reduction of Pellets Prepared from the Bayan Obo Iron Ore Concentrate in the Second Stage. Figure 10 shows the reduction degree curves of pellets prepared from the Bayan Obo iron ore concentrate at a temperature of 1073.15–1173.15 K and a gas flow of 500 mL/min (CO% = 60%). As shown in Figure 9, temperature has a significant effect on the second stage of reduction, and the 35th minute is the turning point of the curves of the reduction degree versus time. At 0–35 min, the reduction rate at the three temperatures is basically the same. Over 35 min, the higher the temperature, the faster the reduction speed and the shorter the time to reach 100% reduction.

Equations 2–4 were used to process the reduction degree data in the second stage and the linear fitting was performed. The fitting results are shown in Figure 11. The fitting degree of eq 2 was the best. Therefore, the reaction process in the second stage of reduction was mainly controlled by the interface chemical reaction. In eq 2, the slopes (reaction rate \( k \)) corresponding to 1073.15, 1123.15, and 1173.15 K are \( 0.93 \times 10^{-2} \), \( 1.12 \times 10^{-2} \), and \( 1.25 \times 10^{-2} \), respectively. Then, the apparent activation energy of the chemical reaction can be calculated according to the Arrhenius formula.

The Arrhenius formula is

\[
  k = A \exp \left( \frac{-E_a}{RT} \right) 
\]  

(6)

In the formula, \( k \) is a chemical reaction rate constant; \( A \) is the preexponential or frequency factor; \( E_a \) is the apparent activation energy of the reaction, J/mol; \( R \) is the gas constant, 8.314 J/(mol·K); and \( T \) is the temperature, K. Finding the logarithm on both sides of the formula 7

\[
  \ln k = \frac{-E_a}{RT} + \ln A 
\]  

(7)

The relationship between \( \ln k \) and \( 1/T \) can be drawn using formula 7, and the results are shown in Figure 12. According to the slope, the apparent activation energy of the chemical reaction is found to be \( 117.99 \) kJ/mol, and the goodness-of-fit (R²) is 0.9905. Studies have shown that when a dense solid
reactions with a gas, the apparent activation energy of the interfacial chemical reaction ranges from 42 to 420 kJ/mol.58

The above fitting results meet the requirements. Therefore, the reduction process in the second stage of pellets prepared from the Bayan Obo iron ore concentrate is controlled by the interfacial chemical reaction. In the second stage of reduction, the main reaction is the direct reduction of iron oxides with a high chemical valence, which is a reaction of $Fe^{3+} \rightarrow Fe^{2+}$ in which the chemical valence decreases. The apparent activation energy is 117.99 kJ/mol, the reaction energy barrier is higher, and the reaction rate is slower. Therefore, the swelling rate of pellets at this stage is relatively small.

3.2.3. Reduction of Pellets Prepared from the Bayan Obo Iron Ore Concentrate in the Third Stage. Figure 13 shows the reduction degree curves of pellets prepared from the Bayan Obo iron ore concentrate in a temperature range of 1073.15–1173.15 K and a gas flow of 500 mL/min (CO% = 100%). As shown in Figure 13, the slope of the curves is larger, which indicates that the reaction speed is faster in the third stage of reduction, and the pellets react violently in this stage.

Equations 2–4 were used to process the reduction degree data in the third stage and the linear fitting was performed. The fitting results are shown in Figure 14. Since the fitting straight lines obtained by eqs 2 and 3 are similar, the limiting link of the third stage of reduction is obtained. Therefore, the kinetic curves and apparent activation energy corresponding to the two equations are obtained according to the Arrhenius formula.

The relationship between lnk and $1/T$ corresponding to the two equations is shown in Figure 15. According to the slope, it can be calculated that the apparent activation energy of the interfacial chemical reaction is found to be 13.7 kJ/mol, and the apparent activation energy of the internal diffusion is 15.9 kJ/mol. Studies have shown that the apparent activation energy of the reaction controlled by the interfacial chemical reaction ranges from 42 to 420 kJ/mol, and the apparent activation energy of the reaction controlled by internal diffusion ranges from 4.2 to 21 kJ/mol.58 The results show that the calculated apparent activation energy of internal diffusion meets the requirements, but the apparent activation energy of the interfacial chemical reaction is not within the above range. In addition, the calculated apparent activation.
energy of internal diffusion is higher than the apparent activation energy of the interfacial chemical reaction. In summary, the limiting link in the third stage of reduction is internal diffusion.

In the third stage of reduction, the main reaction is the reduction of iron oxides with a low chemical valence, which is the reaction of $\text{Fe}^{2+} \rightarrow \text{Fe}$ in which the chemical valence decreases. The limiting link is the diffusion of the gas through the product layer. The apparent activation energy is 15.9 kJ/mol, the reaction energy barrier is lower, and the reaction rate is faster. Therefore, the reduction reaction of pellets occurs violently, and the reduction swelling behavior is remarkable.

4. CONCLUSIONS

The reduction of pellets prepared from the Bayan Obo iron ore concentrate was analyzed through thermogravimetric experiments and kinetic calculations in three stages. The reason for the abnormal swelling of pellets prepared from the Bayan Obo iron ore concentrate was analyzed from the perspective of kinetics for the first time. The specific conclusions are shown below.
(1) In the first stage of reduction, the weight of pellets prepared from the Bayan Obo iron ore concentrate increased due to the occurrence of carbon deposition. Carbon deposition is also one of the reasons for the swelling of pellets in the first stage of reduction. In this stage, the RSI of pellets is 6.9%.

(2) In the second stage of reduction, the limiting link of the reaction of pellets prepared from the Bayan Obo iron ore concentrate is the interfacial chemical reaction; the activation energy is 117.99 kJ/mol, the reaction energy barrier is higher, and the reaction rate is slower. In this stage, the reduction swelling rate of pellets is lower, and the RSI of pellets is 4.1%.

(3) In the third stage of reduction, the limiting link of the reaction of pellets prepared from the Bayan Obo iron ore concentrate is the internal diffusion-reaction; the activation energy is 15.9 kJ/mol, the reaction energy barrier is lower, and the reaction rate is faster. In this stage, the reduction reaction of pellets occurs violently, and the reduction swelling behavior is remarkable, and the RSI of pellets is 24.0%.

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**Figure 14.** Reaction kinetics analysis of different restrictive links in the third stage.

**Figure 15.** Relationship between lnk and 1/T in the second stage.
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REFERENCES

(1) Gu, F. Q.; Zhang, Y. B.; Li, G. H.; Zhong, Q.; Luo, J.; Su, Z. J.; Rao, M. J.; Peng, Z. W.; Jiang, T. Preparation of blast furnace burdens by composite agglomeration process: effect of distribution of magnetite and hematite concentrates in pelletized and matrix feed. J. Iron Steel Res. Int. 2020, 27, 1363–1371.

(2) Hallin, M.; Hooey, L.; Sterneland, J.; Thulin, D. Lkb's experimental blast furnace and pellet development. Metall. Res. Technol. 2002, 99, 311–316.

(3) Zhou, D. D.; Cheng, S. S.; Wang, Y. S.; Jiang, X. The production of large blast furnaces during 2016 and future development of ironmaking in China. Ironmaking Steelmaking 2017, 44, 714–720.

(4) Ye, K. W.; Feng, G. S. New concept of the blast furnace burden structure. Chin. Metall. 2011, 21, 1–9.

(5) Wang, X. D.; Jin, Y. L. Strategy analysis and testing study of high ratio of pellet utilized in blast furnace. Iron Steel 2021, 56, 7–10.

(6) Zhu, R. L. Discussion on future development direction of ironmaking technology and exploratory practice of Baosteel. Iron Steel 2020, 55, 2–10.

(7) Xu, M. X.; Zhang, Y. L. Analysis of pellet technology and production of China in 21st century. Sintering Pelletizing 2017, 42, 25–30.

(8) Zhang, F. M. Development and prospect of green and low carbon ironmaking technologies in Shougang. Iron Steel 2020, 55, 11–18.

(9) Zhang, S. H.; Wang, B. Y.; Lan, C. C.; Liu, X. J.; LÜ, Q. Prospects and present status of pellets chemical composition control. Iron Steel. 2020, 55, 19–26.

(10) Wang, X. D.; Hao, L. Y. Analysis of modern ironmaking technology and low-carbon development direction. Chin. Metall. 2021, 31, 1–5.

(11) ShangGuan, F. Q.; Zhou, J. C.; Wang, H. F.; Li, X. P. Climate change and decarbonization development of steel industry. Iron Steel. 2021, 56, 1–6.

(12) Luo, G. P.; Liu, A. K.; Wang, Y. B.; Zhu, J. G. Influence of MgO on the reduction swelling performance of alkali pellets. Sintering Pelletizing 2016, 41, 33–56.

(13) Liu, A. K.; Luo, G. P.; Wang, Y. B.; Zhu, J. G. The influence of K, Na and F on reduction swelling of hematite pellets. J. Inn. Mong. Univ. Sci. Technol. 2016, 35, 113–116.

(14) Ji, W. D.; Jia, X. M.; Zhao, J. F.; Liu, J. Q. Development and application of high production and low consumption technology for large-scale straight-grate induration machine. Min. Eng. 2019, 17, 30–33.

(15) Shen, M. S.; LÜ, Z. Y.; Kang, W. G.; Bai, X. G.; Li, Y. Z.; Meng, W. X. Abnormal reduction swelling mechanisms of pellets from Bayan Obo iron ore. Chin. Metall. 2021, 31, 17–21.

(16) Li, Z. C.; Wang, Y.; Chai, Y. F.; Wang, Y. C.; Luo, G. P.; Song, X. W. Effect of bentonite on strength of raw pellets and finished pellets prepared from Bayan Obo iron concentrate. Chin. Metall. 2021, 31, 19–24.

(17) Chai, Y. F.; Jia, P. F.; Wang, Y.; Luo, G. P.; Wang, Y. C.; Song, X. W. Effect of basicity on compressive strength of Bayan Obo iron concentrate ore briquetting. Chin. Metall. 2020, 30, 14–18.

(18) Carstensen, J. T. Stability of solids and solid dosage forms. J. Pharm. Sci. 1974, 63, 1–14.

(19) Koga, N.; Criado, J. Influence of the particle size distribution on the CRTA curves for the solid-state reactions of interface shrinkage type. J. Therm. Anal. 1997, 49, 1477–1484.

(20) Koga, N.; Criado, J. Kinetic analyses of solid-state reactions with a particle-size distribution. J. Am. Ceram. Soc. 1998, 81, 2901–2909.

(21) Jander, W. Reaktionen im festen zustande bei höheren temperature reaktionsgeschwindigkeiten endotherm verlaufender umsetzungen. Z. Anorg. Allg. Chem. 1927, 163, 1–30.

(22) Booth, F. A note on the theory of surface diffusion reactions. Trans. Faraday Soc. 1948, 44, 796–801.

(23) Gintling, A.; Brounshtein, B. Concerning the diffusion kinetics of reactions in spherical particles. J. Appl. Chem. USSR 1950, 23, 1327–1338.

(24) Crank, J. The Mathematics of Diffusion, 1st ed.; Oxford University Press: Oxford, 1979; pp 15–32.

(25) Valensi, G. Kinetics of the oxidation of metallic spheres and powders. Compt. Rend. 1936, 202, 309–312.

(26) Carter, R. Kinetic model for solid-state reactions. J. Chem. Phys. 1961, 34, 2010–2015.

(27) Chou, K. C.; Xu, K. A new model for hydriding and dehydriding reactions in intermetallics. Intermetallics 2007, 15, 767–777.

(28) Shimada, E.; Yamashita, H.; Matsumoto, S.; Ikuma, Y.; Ichimura, H. The oxidation kinetics of spherically shaped palladium powder. J. Mater. Sci. 1999, 34, 4011–4015.

(29) Chou, K. C.; Li, Q.; Lin, Q.; Jiang, L. J.; Xu, K. D. Kinetics of absorption and desorption of hydrogen in alloy powder. Int. J. Hydrogen Energy 2005, 30, 301–309.

(30) Chou, K. C.; Hou, X. M. Kinetics of high-temperature oxidation of inorganic nonmetallic materials. J. Am. Ceram. Soc. 2009, 92, 585–594.

(31) Luo, Q.; An, X. H.; Pan, Y. B.; Zhang, X.; Zhang, J. Y.; Li, Q. The hydriding kinetics of Mg-Ni based hydrogen storage alloys: a comparative study on Chou model and Jander model. Int. J. Hydrogen Energy 2010, 35, 7842–7849.

(32) Wu, G. X.; Zhang, J. Y.; Li, Q.; Chou, K. C. A new model to describe absorption kinetics of Mg-based hydrogen storage alloys. Int. J. Hydrogen Energy 2011, 36, 12923–12931.

(33) Chou, K. C.; Luo, Q.; Li, Q.; Zhang, J. Y. Influence of the density of oxide on oxidation kinetics. Intermetallics 2014, 47, 17–22.

(34) Avrami, M. Kinetics of phase change I-general theory. J. Chem. Phys. 1939, 7, 1103–1112.

(35) Avrami, M. Kinetics of phase change II. J. Chem. Phys. 1940, 8, 212–214.

(36) Avrami, M. Kinetics of phase change III. J. Chem. Phys. 1941, 9, 177–180.

(37) Kempen, A. T. W.; Sommer, F.; Metteimejer, E. J. Determination and interpretation of isothermal and non-isothermal transformation kinetics; the effective activation energies in terms of nucleation and growth. J. Mater. Sci. 2002, 37, 1321–1332.
Liu, F.; Sommer, F.; Bos, C.; Mittemeijer, E. Analysis of solid state phase transformation kinetics: models and recipes. Int. Mater. Rev. 2007, 52, 193−212.

Rios, P.; Villa, E. Transformation kinetics for inhomogeneous nucleation. Acta Mater. 2009, 57, 1199−1208.

Jagle, E.; Mittemeijer, E. The kinetics of grain-boundary nucleated phase transformations: simulations and modeling. Acta Mater. 2011, 59, 5775−5786.

Robson, J. D. Modeling competitive continuous and discontinuous precipitation. Acta Mater. 2013, 61, 7781−7790.

Pang, Y.; Sun, D.; Gu, Q.; Chou, K. C.; Wang, X.; Li, Q. Comprehensive determination of kinetic parameters in solid-state phase transitions: an extended Jonhson-Mehl-Avrami-Kolomogorov model with analytical solutions. Cryst. Growth Des. 2016, 16, 2404−2415.

Chen, W.; Wang, X.; Lei, Y.; Li, Y.; He, S.; Q.; Liao, Z. H. Isothermal reduction kinetics of high-phosphorus iron ore carbon-containing pellets. Iron Steel 2020, 55, 11−15.

Zhao, W. G.; Gao, Q.; Wang, Y. B.; Peng, J.; An, S. L. Research on kinetics of rich hydrogen reduction of Bayan Obo iron concentrate pellets. Iron, Steel, Vanadium, Titanium 2015, 36, 115−131.

Wu, C. B.; Zhang, J. B.; Wu, Q. J.; Yue, L. Analysis on reaction dynamics model of pellets. J. Chongqing Univ. 2015, 38, 11−16.

Jiang, W. F.; Ma, T. F.; Hao, S. J.; Zhao, S.; Zhang, Y. Z. Study on reduction kinetics and influencing factors of carbon-containing zinc pellets. Multipurp. Util. Miner. Resour. 2020, 1, 146−150.

Chen, S. M.; Duan, D. P.; Han, H. L. Research on thermodynamics and kinetics analyzing of SrSO4 carbon containing pellets. J. Hunan Univ., Sci. Technol. 2019, 34, 100−108.

Zhu, D. Q.; Wang, D. Z.; Pan, J.; Tian, H. Y.; Xue, Y. X. A study on the zinc removal kinetics and mechanism of zinc-bearing dust pellets in direct reduction. Powder Technol. 2021, 380, 273−281.

Yuan, X. L.; Luo, F. M.; Liu, S. F.; Zhang, M. Y.; Zhou, D. S. Comparative study on the kinetics of the isothermal reduction of iron ore composite pellets using coke, charcoal and biomass as reducing agents. Metals 2021, 11, No. 340.

Zhong, R. H.; Yi, L. Y.; Huang, Z. C.; Jiang, X.; Cai, W. Reduction mechanism and kinetics of a low grade iron ore coal composite pellets improved by sodium salt. ISIJ Int. 2020, 60, 649−655.

Wang, H.; Sohn, H. Effect of CaO and SiO2 on swelling and iron whisker formation during reduction of iron oxide compact. Ironmaking Steelmaking 2011, 38, 447−452.

Rao, Y. K. The kinetics of reduction of hematite by carbon. Metall. Trans. 1971, 2, 1439−1447.

Ginsling, A. M.; Brounshtein, B. I. Concerning the diffusion kinetics of reactions in spherical particles. J. Appl. Chem. USSR 1950, 23, 1327−1338.

Huang, X. K. Iron and Steel Metallurgy Principle, 4th ed.; Metallurgical Industry Press: Beijing, 2013; pp 413−461.

Wu, S. L.; Wang, X. L. Iron and Steel Metallurgy (Part of Ironmaking), 4th ed; Metallurgical Industry Press: Beijing, 2019; pp 125−197.

Fan, Y. J.; Zhang, Y. H.; Li, Z. C.; Chai, Y. F.; Wang, Y. C.; Luo, G. P.; An, S. L. Mechanism on reduction swelling of pellets prepared from Bayan Obo iron ore concentrate. Ironmaking Steelmaking 2021, 48, 1158−1168.

Grabke, H. Corrosion by carbonaceous gases, carburization and metal dusting, and methods of prevention. Mater. High Temp. 2000, 17, 483−487.

Tian, Y. W.; Zhai, X. J.; Liu, K. R. A Concise Course of Metallurgical Physical Chemistry, 2nd ed.; Chemical Industry Press: Beijing, 2011; pp 203−286.