Effect of Magnetite Concentrate Particle Size on Pellet Oxidation Roasting Process and Compressive Strength

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During the roasting process of pellets, the particle size of the magnetite concentrates affected its component content, which correlated well with the oxidation roasting process and metallurgical properties of the pellets. In this work, using high-silicon iron ore concentrates as raw material, the effect of high-silicon iron ore concentrates with different particle size on the oxidation behavior of pellets was studied. Coats-Redfern data processing model was carried out to calculate the oxidation kinetics parameters of high-silicon iron ore concentrate. The research results showed that the refinement of high-silicon iron ore concentrates could reduce the SiO₂ content to 1.96% and increase the pellet grade to 69.94%. At a heating rate of 15°C/min, the refinement of particle size reduced the activation energy to 45.73 kJ·mol⁻¹, which could greatly improve the degree of oxidation of pellets and increase the consolidation strength to 3213 N. The iron ore concentrates more than 74 μm had lower activation energy at a higher heating rate, whereas an opposite trend was identified for the iron ore concentrates less than 74 μm. Consequently, reducing the particle size range of high-silicon iron ore concentrates can effectively improve the physical and chemical properties and smelting indexes of iron ore concentrates, which indicated the direction of rational utilization of the high-silicon iron ore concentrates.

KEY WORDS: high-silicon iron ore concentrates; particle size; activation energy; consolidation strength.

1. Introduction

Particle size and specific surface area of iron-bearing raw material are decisive parameters for the production of the pellets, which significantly influence the pellet quality. Generally, the finer the crude are ground, the higher iron grade the concentrates have based on the theory of mineral processing. Thereby using the finer particles in pelletizing process can not only improve the iron grade of pellets, but also the quality of green pellet which directly depends on the proportion of fine particles defined by both specific surface area and size distribution.1–3) It is generally agreed that the pellets would obtain superior quality when the specific surface area and mass fraction of −0.074 mm particle size of iron ore concentrates respectively is higher than 1800 cm²·g⁻¹ and 90%,4) yet the specific surface area of most iron ore concentrates merely reaches 500–1600 cm²·g⁻¹ in the mineral processing plants.5) Therefore, the magnetite concentrates still require to be re-ground in pelletizing plant to meet the demand of suitable particle sizes for the production of pellets. Furthermore, it is well known that the oxide pellets obtain the excellent mechanical strength by the recrystallization of Fe₂O₃ from oxidizing crystallization of Fe₃O₄ during the roasting process at high temperature.6) Thus, the oxidation conversion degree of magnetite to hematite is also one of the key parameters for the roasted pellets to obtain the desired mechanical strength.7,8)

China is rich in poor iron ore, lacking of iron ore resource with low silica. Considering the economic benefit and resource conditions, majority of pelletizing plants in China produced the pellets using high-silicon magnetite concentrate (SiO₂>4%) with relative coarse particle size, which contribute to a poor quality compared with the abroad pellets due to its uneven particle sizes distribution and poor pelletizing ability. Although a certain degree of researches on particle sizes of the magnetite concentrates have been carried out to determine the relation between the pelletizing parameters and the quality of green pellets and thereby evaluate whether the size distribution is appropriate,9,10) fewer studies have been conducted the effect of particle sizes and SiO₂ on the synergistic mechanism of oxidative consolidation in iron ore concentrates. It has been shown that particle size has an important influence on the oxidation behavior of iron ore concentrates.11–13) In the study of high temperature processing of vanadium and titanium pellets, Han et al.14) found that pellets diameter had a significant effect on the degree of pellet oxidation. Under the same oxidation conditions, the degree of pellet oxidation decreased with increas-
ing pellet diameter (12–20 mm). The oxidation degree of pellets reached 92.92% under the condition of pellet diameter of 12 mm. In contrast, the oxidation degree of pellets with a diameter of 16 mm was only 64%. However, the above studies have paid less attention to the effect of particle sizes of magnetite concentrates on the oxidation process of pellets, especially for the oxidation behavior of high-silicon magnetite concentrates with different particle sizes.

Therefore, in this work, the effect of particle sizes on oxidation kinetic parameters and consolidation strength of the high-silicon pellets was investigated, which was expected to guide for improving the quality of the pellets.

2. Materials and Methods

2.1. Physical and Chemical Properties of Magnetite Concentrate

The iron ore concentrate used in this experiment was supplied by a steel plant from Shandong province in China. Particle size was analyzed by laser particle size analyzer and the results are shown in Fig. 1 and Table 1. Table 2 presents the main chemical components of the iron ore concentrate, indicating a high-silicon magnetite type with the SiO₂ content of 7.91%. In addition, the specific surface area of iron ore was 3768 cm²·g⁻¹ and the particles less than 74 μm accounted for 80%. Figure 2 shows the XRD patterns of raw material. Magnetite (Fe₃O₄), magnesium ferrite (MgFe₂O₄), iron silicon oxide (Fe₂.₉₅Si₀.₀₅O₄), wollastonite (CaSiO₃) and cordierite (Mg₂(Al₂Si₅O₁₈)) could be determined, which corresponded well to the typical magnetite mineral characteristics.

2.2. Experimental Method

The iron ore concentrate was screened into four size fractions using standard sieves, namely, >106 μm, 74–106 μm, 45–74 μm and <45 μm, which were used for subsequent experiments. The chemical composition, particle size distribution, and X-ray diffraction of iron ore concentrates with different particle size ranges were measured and used to evaluate the variation of physicochemical properties and phase of iron ore concentrates after screening.

Thereafter, 4 g iron ore concentrates with different particle sizes were pressed into a cylindrical shape at 15 MPa for 1 min by a stainless-steel die with a 20 mm inner diameter. The roasting experiments were carried out in an electric resistance furnace of three-temperature zone (Luoyang Shen Jia Instruments Ltd, China), which is shown in Fig. 3. Figure 4 presents an overview of the procedure used in the roasting experiments. The sample was first heated up to 450°C in air atmosphere with a heating rate of 6°C/min for removing the moisture. Then, the temperature was improved to 950°C at a rate of 8°C/min to undergo the preheating. After that, the sample continued to be heated up to 1250°C with a heating rate of 10°C/min and was roasted in air atmosphere. The time of the drying, pre-heating and roasting process was determined to be 15 min, and the air was introduced at 15 L/min. Finally, the sample was naturally cooled to ambient temperature under room temperature conditions. Continuous crystal strength was measured by an electronic universal testing machine. Scanning Electron Microscope and Dmax-RB91-0459 X-ray diffractometer using Cu-Kα radiation (Scanning speed: 2θ, 1°/min) were carried out to compare the microscopic morphology and phase composition changes of the pellets before and after roasting.

SDT Q600 DSC-TGA (TA Instruments, USA) was employed to measure both thermogravimetric and differential thermal analysis of iron ore concentrate with different

![Fig. 1. The particle size distribution of original sample. (Online version in color.)](image1)

![Fig. 2. XRD pattern of original sample. (Online version in color.)](image2)

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**Table 1.** The particle size distribution of iron ore concentrate (wt.%).

<table>
<thead>
<tr>
<th>Size (μm)</th>
<th>&gt;106</th>
<th>74–106</th>
<th>45–74</th>
<th>&lt;45</th>
<th>Dv(50)/μm</th>
<th>S(1)/cm²·g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>6.27</td>
<td>6.75</td>
<td>20.79</td>
<td>66.19</td>
<td>3768</td>
<td>34.1</td>
</tr>
</tbody>
</table>

Note: (1) S is the specific surface area.

**Table 2.** The chemical compositions of iron ore concentrate (wt.%).

<table>
<thead>
<tr>
<th>Components</th>
<th>TFe</th>
<th>FeO</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>66.08</td>
<td>28.76</td>
<td>0.54</td>
<td>7.91</td>
<td>0.36</td>
<td>0.41</td>
</tr>
</tbody>
</table>
particle sizes, in order to study the oxidation kinetics of the transition from magnetite concentrate to hematite. The sample was fixed in the mass of 10 mg. The DSC-TGA experiment was carried out with 50 mL/min air in a shielding gas of 100 mL/min argon gas, and the sample was heated from ambient temperature to 1 250°C. The test data of weight variation values (TG) and heat flow rate (DSC) were automatically saved during the entire process of heating. Generally, the weight variation values of magnetite concentrate were used to calculate the oxidation conversion degree and further to obtain the apparent activation energy.

The oxidation conversion degree (α) (from magnetite to hematite) can be determined by the Eq. (1):

$$\alpha = \frac{m_0 - m_T}{m_0 - m_{\infty}}$$ ........................................(1)

where, α is conversion degree, \(m_0\) is initial sample mass (g), \(m_T\) (g) is the sample mass at a particular temperature \(T\) and \(m_{\infty}\) (g) is the sample mass after the complete conversion from Fe₃O₄ to Fe₂O₃.

Since magnetite oxidation was a non-isothermal reaction, its oxidation reaction was calculated using the Coats-Redfern method.\(^{15}\) For the solid-state oxidation reaction, the reaction rate is generally represented as Eq. (2). The temperature dependence of the rate constants was calculated from Arrhenius equation given as Eq. (3). Under a certain heating rate \(\beta\), Eq. (2) could be transformed to Eq. (4).

$$\frac{d\alpha}{dt} = kf(\alpha)$$ ........................................(2)

$$k = Ae^{\frac{-E_a}{RT}}$$ ........................................(3)

$$\frac{d\alpha}{dT} = \frac{A}{\beta}e^{\frac{E_a}{RT}}f(\alpha)$$ ........................................(4)

Where \(f(\alpha)\) represents a model function of \(\alpha\), \(A\) represents the pre-exponential factor (s\(^{-1}\)), \(\beta\) represents the heating rate (K·min\(^{-1}\)), \(k\) represents the rate constant (s\(^{-1}\)), \(E_a\) represents the reaction activation energy (kJ·mol\(^{-1}\)), \(R_g\) is the gas constant (kJ·mol\(^{-1}\)·K\(^{-1}\)).

The Coats-Redfern method is expressed as Eq. (5).

$$\left[1 - (1 - \alpha)^{1-n}ight] = \frac{ART^2}{\beta E_a} \left[1 - \frac{2RT}{E_a}\right] e^{\frac{E_a}{RT}}$$ ........................................(5)

Where \(n\) is reaction order. The Eq. (5) after the logarithmic arrangement could be transformed to Eq. (6) or (7).

$$\ln\left[\frac{1 - (1 - \alpha)^{1-n}}{1 - n}\right] = \ln\left[\frac{AR}{\beta E_a} \left[1 - \frac{2RT}{E_a}\right]\right] - E_a \frac{1}{RT}, n \neq 1$$ ........................................(6)

$$\ln\frac{-\ln(1-\alpha)}{T^2} = \ln\frac{AR}{\beta E_a} \left[1 - \frac{2RT}{E_a}\right] - E_a \frac{1}{RT}, n = 1$$ ........................................(7)

As the oxidation reaction of magnetite is the first-order reaction, its kinetic parameters are calculated by Eq. (7). Moreover, the value of \(-2RT/E_a\) approaches zero,

$$\ln\frac{AR}{\beta E_a} \left[1 - \frac{2RT}{E_a}\right]$$ can be simplified to \(\ln\frac{AR}{\beta E_a}\). The plots of \(1/T\) vs \(\ln\left[-\ln(1-\alpha)/T^2\right]\) obtains the pre-exponential factor and apparent activation energy from the intercept and slope of the curve.

3. Results and Discussion

3.1. Composition and Main Phase Changes of Iron Ore Concentrates with Different Particle Sizes

The particle size distribution and chemical compositions of magnetite concentrate with different particle size are measured and the results are listed in Fig. 5 and Table 3. Respectively, it could be observed that the particle size of concentrates appeared obvious classification. After screening, the iron ore concentrates of >106 μm differed in compositions from the other particle sizes, especially the content of SiO₂ was high as 15.31%. Except for >106 μm iron ore concentrates, the grade of the iron ore concentrates gradually increased, approaching 4%. The SiO₂ content had
an apparent change, dropping from 7.91% to 1.96%, which reached the level of a low-silicon iron concentrates. The Al₂O₃ and MgO compositions changed inconspicuously, both showing a decreasing trend. Particularly, compared with the distribution of original sample, the specific surface areas of iron ore concentrates grew from 3,768 cm²·g⁻¹ to 5,877 cm²·g⁻¹.

The XRD patterns of the screened samples are shown in Fig. 6. It could also be proved that as the main gangue phase, the SiO₂ content of iron ore concentrates decreased with the reduction of the particle size, which could be attributed to the higher hardness of SiO₂-bearing phases than the Fe-contained phase, finally resulting in a higher Fe content in the smaller particles. It was apparent that the CaSiO₃ phase and Mg₃(Al₅Si₃O₁₈) phase trended to diminish with the particle size becoming finer, which was consistent with the variations of chemical compositions.
3.2. The Non-isothermal Oxidation Process of Iron Ore Concentrates with Different Particle Sizes

Figure 7 is the TGA plots of weight change of magnetite concentrates with temperature in air atmosphere. It was envisaged from the figure that the oxidation of magnetite concentrate obeyed the parabolic rate constant and the oxidation reaction did not happen immediately.\(^\text{16-19}\) When the temperature was lower than 500°C the weight of the sample increased continuously, mainly due to the endothermic decomposition reaction of crystal water. At the temperature ranging from 500 to 1,050°C, the sample oxidation occurred at a very high rate, the whole oxidation process was completed at 1,050°C. In addition, hematite started to decompose into the secondary magnetite when the temperature was beyond 1,050°C. This is because the entire oxidation process is accompanied by a large release of heat, as in Eq. (8). As the temperature is higher, this will result in the decomposition of the hematite and the formation of secondary magnetite.\(^\text{18,20}\) The thermogravimetric analysis results shown in Fig. 7 also confirm that when the temperature was greater than 1,050°C, the weight gain shows a negative growth trend.

\[
4\text{Fe}_3\text{O}_4(s) + \text{O}_2 = 6\text{Fe}_2\text{O}_3(s), \Delta H = -119 \text{ kJ/mol} \quad \text{(8)}
\]

Therefore, the oxidation temperature range was limited to 500–1,050°C for the kinetics analysis. Based on TGA plots, the oxidation conversion degree (\(\alpha\)) of the samples was calculated by Eq. (1), which is shown in Fig. 8. Except for <45 μm sample, the maximal conversion degrees of all samples were obtained at 1,050°C and then decreased, which followed the parabolic kinetics.\(^\text{17}\) As could be seen from Fig. 8, the conversion degree under the same temperature was improved gradually when the particle size became finer. Additionally, the reduction of particle size decreased the temperature of the maximum conversion degree at the same heating rate. The reason for this was that the finer particle size of mineral powder possessed the higher specific surface area and lower SiO₂ content, which was conducive to form the more uniform distribution of voids inside the pellet, promoting the full contact between mineral powder and air, as a result the gas-solid reaction was enhanced.

The plots of \(\ln \left[ \ln \left( 1 - \frac{\alpha}{\alpha_0} \right) / T^2 \right] vs 1/T\) and fitted lines are demonstrated in Fig. 9. Their Slopes were \(-5.712, -6.759, -6.674, -5.658\) and \(-5.504\) with relative intercepts of \(-8.4565, -7.8135, -7.7313, -8.4684\) and \(-8.1040\). When the heating rate \(\beta\) was fixed at 15°C/min, using the slopes and intercept of the fitted lines, the activation energy (\(E_a\)) and pre-exponential factor (\(A\)) values could be obtained by Eq. (7), the result is shown in Table 4.

It was evident that the activation energy of each sample was higher than 45 kJ mol\(^{-1}\), these results could illustrate that the oxidation of magnetite concentrates was controlled by the interfacial chemical reaction. Meanwhile, the activa-

![Fig. 7. TGA curves of different particle sizes concentrate (heating rate: 15°C/min). (Online version in color.)](image1)

![Fig. 8. The conversion degree curves of different particle sizes of iron ore concentrate. (Online version in color.)](image2)

![Fig. 9. Coats-Redfern fitting line of iron ore concentrate with different particle sizes. (Online version in color.)](image3)

| Table 4. Activation energy and pre-exponential factor of the samples. |
|:----------------|:---|:---|:---|:---|
| Samples/μm | Original sample | >106 | 74–106 | 45–74 | <45 |
| \(E_a/\text{kJ mol}^{-1}\) | 47.49 | 56.20 | 55.48 | 47.04 | 45.73 |
| \(A/s\) | 5.83 | 13.12 | 14.06 | 5.70 | 7.98 |
tion energy values decreased with a reduction in particle size. This result could be attributed to an increase in the amount of highly reactive activated molecules in the finer particle size samples. Besides, low activation energy favored an increase in the oxidation rate of magnetite concentrates and decreased the temperature of maximal oxidation rate, from 1045°C for >106 μm to 987°C for <45 μm. Correspondingly, the activation energy of magnetite concentrates decreased from 56.20 kJ·mol⁻¹ to 45.73 kJ·mol⁻¹.

In order to determine the controlling step of different oxidation stages, the oxidation procedures in Fig. 9 could be divided into three stages according to temperature ranges: 1) 773–973 K; 2) 973–1173 K; 3) 1173 K < T(\text{max oxidation degree}) which is shown in Fig. 10. And the activation energy of the three stages for each sample was calculated, the results are presented in Fig. 11. In the first stage of oxidation, the activation energy of iron concentrates was between 60–85 kJ·mol⁻¹ and the controlling step in the oxidation reaction was mainly interfacial chemical reaction. As the temperature increasing, the activation energy of the iron concentrate decreased to 18–23 kJ·mol⁻¹ upon entering the second stage. The oxidation rate is hindered by the oxidation reaction on the surface of the magnetite particles and the formation of a dense protective layer of hematite, which makes it difficult for gases to enter the interior. Therefore, the controlling step changed from interfacial chemical reaction to diffusion control within the reaction product layer. It was not difficult to find that at a given particle size, the activation energy of the second stage was always smaller compared with the first stage. This is consistent with previous studies: \( E_A(\text{chemical reaction}) > E_A(\text{diffusion}) \). When the temperature was in the high temperature region, the oxidation of iron ore concentrate entered the third stage. Most of the Fe₃O₄ has been oxidized to Fe₂O₃ at high temperature, where recrystallization of Fe₂O₃ and oxidation of the remaining FeO mainly occurred. At this stage, the dense oxide layer formed in the first two stages of the reaction further prevents the entry of oxygen, thus affecting the reaction process. However, as the temperature is further increased, the protective layer of magnetite begins to recrystallize and becomes sparse, indicating the less resistant to oxygen. The magnitude of the activation energy in the third stage is therefore a result of the mutual limitation of the reaction process and temperature.

3.3. Effect of Heating Rate on the Oxidation Kinetic Parameters of Iron Ore Concentrates

Generally, the chemical reaction rate is closely related to the temperature. In order to compare the effect of heating rate on the kinetic parameters of magnetite concentrates, the samples with the heating rate of 20°C/min were examined by

![](image)

Fig. 10. Coats-Redfern fitting line of iron ore concentrate with different particle sizes in different temperature stages. (Online version in color.)

![](image)

Fig. 11. Change curves of activation energy in different oxidation stages. (Online version in color.)
TGA experiments and the curves of the weight changes are shown in Fig. 12(a). Subsequently, according to the method of previous kinetic calculation method,20,25,26 the activation energy and pre-exponential factor of the samples under the heating rate of 20°C/min were calculated. The fitting lines and calculation results are shown in Fig. 12(b) and Table 5. It could be seen from Table 5 that the activation energy of the samples increased from 45.75 to 51.99 kJ·mol⁻¹ with a heating rate of 20°C/min when the particle size was reduced from >106 μm to <45 μm. By compared with the activation energy of the samples with a heating rate of 15°C/min, as shown in Fig. 13, it was found that except for original sample the heating rates of 20°C/min had an opposite effect on the activation energy of other samples. Besides, the activation energy of the original sample was approximately 48 kJ·mol⁻¹ with the heating rate of both 15°C/min and 20°C/min.

In the coarse iron ore concentrate, due to the coarse and irregular shape of the particles, more irregular pores would generate between the particles, which provided a good channel for the full contact of the oxygen and the iron oxide. When the heating rate was 15°C/min, compared with the high heating rate of 20°C/min, the longer oxidation time was obtained at oxidation temperature range. For coarse iron ore concentrate, the longer time was required for complete oxidation, while the lower heating rate could just meet the time requirements for complete oxidation. Sufficient oxidation time and contact surface (iron oxide and oxygen) guaranteed the complete oxygenation of iron concentrate from outside to inside. Therefore, the energy source of iron ore concentrates with the particle size of >74 μm at 15°C/min heating rate was mainly provided by the outside temperature, and its oxidation heat was less, so its activation energy was higher. With the gradual refinement of the particle size of iron ore concentrate (<74 μm), the specific surface area of iron ore concentrates increased, and the iron ore concentrate particle oxidation reaction could be completed in a short time. The self-oxidation heat became the main energy transmission source, so the activation energy was reduced.

When the heating rate was increased to 20°C/min, the oxidation time of iron ore concentrate at oxidation temperature range was short. For iron ore concentrate of >74 μm, the external temperature provided less energy for coarse particles in a short time, and it could only achieve the basic oxidation reaction energy required by iron oxides. The heat of oxidation required in the later period was mainly supplied by the internal exothermic reaction of iron ore oxidation. The particle oxidation process mainly showed that the energy generated by its own exothermic reaction reaction transferred from outside to inside. Therefore, the average activation energy of coarser (>106 μm and 74–106 μm) iron ore concentrate decreased from 55.84 kJ·mol⁻¹ to 47.21 kJ·mol⁻¹ compared to the heating rate of 15°C/min. However, with the gradual refinement of the particle size (<74 μm), the activation energy of the samples increased from 45.75 to 51.99 kJ·mol⁻¹ with a heating rate of both 15°C/min and 20°C/min.

### Table 5. Activation energy and pre-exponential factor of iron ore concentrate with a heating rate of 20°C/min.

<table>
<thead>
<tr>
<th>Samples/μm</th>
<th>Original sample</th>
<th>&gt;106</th>
<th>74–106</th>
<th>45–74</th>
<th>&lt;45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ea/kJ·mol⁻¹</td>
<td>48.22</td>
<td>45.75</td>
<td>48.67</td>
<td>52.94</td>
<td>51.99</td>
</tr>
</tbody>
</table>

Fig. 13. Variation curve of activation energy of iron ore concentrate with different particle sizes at a heating rate of 15°C/min and 20°C/min. (Online version in color.)
μm), the specific surface area of the iron ore concentrates particles increased. Although single particles were easy to oxidize, the reduction in particle size reduced the porosity between the particles and hindered the full contact between the particles and oxygen, thus increasing the activation energy. So, after improving the heating rate, the short-term oxidation roasting was difficult to make the particles completely oxidization, and the heat transfer between particles mainly depended on the heat conduction among particles. The self-oxidation heat released less, more energy of the oxidation process was derived from the outside temperature. Therefore, the average activation energy required for the oxidation of small-diameter iron ore concentrate particle increased from 46.39 kJ·mol⁻¹ with a heating rate of 15°C/min to 52.47 kJ·mol⁻¹ with a heating rate of 20°C/min.

3.4. Effect of Particle Size on Consolidation Strength of Roasted Pellet

It was well known that the consolidation strength of pellets depended on the magnetite or hematite content and the oxidation, crystallization and linkage between the particles. Generally, fine outgrowths formed on the surface of oxidized particles were conducive to the formation of bonds between particles. Therefore, to investigate the particle size effects on consolidation strength, the consolidation strength of each pellet was tested by an electronic universal testing machine. The result is listed in Table 6.

It was clear that the consolidation strength of pellets increased from 1 334 N to 3 213 N as the particle size decreased from >106 μm to <45 μm. The micrographs of internal structure for each pellet after oxidation are shown in Fig. 14. It was observed that before oxidizing roasting the magnetite content of the ore powder increased with the particle size decreasing, so the proportion of hematite in the roasted pellets increased significantly and the amount of gangue phase decreased, which were beneficial to improve the compressive strength. Meanwhile, it was found that hematite micro-particles were coalesced to each other, forming a dense structure after oxidation. In pellets produced by coarse concentrates, the SiO₂ and the silicates of iron and calcium were observed, in pellets produced by small-grains concentrates, the micro-particles hematite was mainly formed. From Fig. 15, the peak height of SiO₂

- Table 6. Continuous crystal strength of roasted pellets.

<table>
<thead>
<tr>
<th>Particle sizes/μm</th>
<th>Original sample</th>
<th>&gt;106</th>
<th>74–106</th>
<th>45–74</th>
<th>&lt;45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength (N)</td>
<td>2 036</td>
<td>1 334</td>
<td>2 381</td>
<td>2 466</td>
<td>3 213</td>
</tr>
</tbody>
</table>

- Fig. 15. XRD patterns of the roasted pellets with different particle sizes. (Online version in color.)

Fig. 14. Morphology of iron ore concentrates with different particle size before and after oxidation roasting. (1)–(4): Sample before oxidizing roasting; (5)–(8): Sample after oxidizing roasting. (Online version in color.)
decreases from 3,231 to 1,938. It could be confirmed that the amount of SiO$_2$ phase gradually decreased with particle size reduction, meaning that the concentrate with low Si-bearing minerals could be obtained through screening. Additionally, high SiO$_2$ content was conducive to forming the low-melting-point minerals if roasted together with magnetite or CaO, causing an increase in liquid ratio. The variation of the phase volume fraction with temperature was calculated using FactSage 8.0 thermodynamic software, as shown in Fig. 16. The primary melt amount shows a decreasing trend as the particle size reduces. And when the particle size decreases from >106 μm to 74–106 μm, the primary melt formation temperature increases obviously. As the particle size continues to decrease to 45–74 μm and <45 μm, the primary melt formation temperature shows a decrease trend, which may be attributed to the relatively high content of FeO. According to the previous literature, it has been confirmed that the suitable amount of liquid phase was favor for the diffusion cohesion of solid particles and promoted the crystal grains of Fe$_2$O$_3$ to consolidate, thus improving the strength of pellet. So, consolidation strength of pellets with larger particle size was relatively low. As we known, the Si-bearing minerals would hinder the oxidizing and crystallizing ability of iron oxide during the roasting process and formed a number of unevenly distributed and opened macro-pores, consequently the consolidation strength of the pellets was decreased. Moreover, when the grains were smaller and more regular, due to the oxidation of magnetite, the nascent hematite content inside the pellet was higher and the grains were more closely connected to each other due to the reduction of SiO$_2$ content, the grains were well developed, and a large number of interconnected crystals were formed inside the pellets, thus improving the pellets strength. Therefore, the consolidation strength of pellets could significantly increase with particle size refinement.

4. Conclusions

(1) The concentrate was screened into different particle sizes, and the fine particles had the lower gangue phase content than the coarse one, especially SiO$_2$. This phenomenon could be effectively utilized to improve the grade of the iron ore concentrates through removing the coarse particles, especially for the reasonable application of high-silicon iron ore concentrates.

(2) During the oxidation process, as the particle size of the high-silicon iron ore concentrates decreased, the activation energy reduced, which laid a theoretical foundation for energy-saving and consumption-reduction in the pellets production process.

(3) If high-silicon iron ore concentrates with a particle size of >74 μm were used, the heating rate should be increased, while low-silicon iron ore concentrates with a particle size of <74 μm should be decreased, which made the activation energy at a lower level. It provided a method basis for sufficient oxidation crystallization of pellets under low energy consumption.
The consolidation strength of pellets increased from 1334 N to 2131 N as the decrease of iron ore powder particle size. Crushing high-silicon magnetite into iron ore powder with smaller particle size for oxidation roasting production could effectively improve the metallurgical properties of pellets.

Declaration of Competing Interest
The authors declare there is no potential conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES
15) A. W. Coat and J. Redfern: Nature, 201 (1964), 68. https://doi.org/10.1038/201068a0