Increasing the Mixing Rate of Metalized Pellets in Blast Furnace Based on the High-temperature Interactivity of Iron Bearing Materials

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The softening and melting dripping properties of increasing mixed rate of metalized pellets were investigated. The experimental results showed that the softening and melting properties of the lump ores or oxidized pellets were dramatically improved by interaction between lump ores (or oxidized pellets) and metalized pellets, while there was no obvious interaction between sinters and metalized pellets. On the basis of the constant basicity of mixed burden, the softening and melting start temperatures reduced and softening and melting interval became wide as the mixing rate of metalized pellets was increasing from 0% to 56%. The influence of the mixed rate of metalized pellets, less than 25%, on the properties of mixed burden is little. When the rate was more than 25%, the properties of mixed burden would rapidly deteriorate. With a large number of metalized pellets, especially 56% sinters replaced, the properties of mixed burden were worst. According to the element migration of burden interface observed, it was found that the diffusion of Ca and Si between oxidized pellets and sinters (or metalized pellets) was obvious. However, the phenomenon between metalized pellets and sinters was weaker. Thus, it was confirmed that the strong interaction must happen between burdens, the nature differences of which were larger.

KEY WORDS: blast furnace; sinter; lump ores; pellets; metalized pellets; softening and melting dripping; interaction; element migration.

1. Introduction

China has an annual capacity of 700 million tons of crude steel, together with more than 70 million tons of dust. Some parts of the dust have relatively high contents of elements such as C, Zn, K and Na, is called zinc-containing metallurgical dust. Presently, such kind of dust has been recycled in the sintering plant. However, this way not only wastes a lot of valuable elements, but also obviously deteriorates the quality of sintering, due to containing of Zn, K and Na elements and the fine particle size of the dust.1,2) So, it is necessary to how reasonably utilize the kind of dust. The rotary hearth furnaces (RHF) can produce metalized pellets for BF production through handling and recycling this kind of dust while the elements such as Zn, K and Na could also be utilized as secondary resources.

Apparently, the metalized pellets produced by RHF should be charged in BF for iron-making process, mainly because the quantity of slag of molten steel is too large if the metalized pellets serve as steel coolant. On the other hand, lots of advantage or disadvantage will be brought with the increase of metalized pellets, such as endothermic reaction of direct reduction, the indirect reaction of lumpy zone and the softening and melting property.3–5) Usually, the properties of the iron bearing burden such as sinter, pellets and lump ores have been widely investigated and it was found that performance difference among them was large.6–9) Furthermore, the previous researchers had also investigated the blast furnace burden structure by the metallurgical performance of iron bearing burden and the interaction mechanism between the sinters, oxidized pellets and lump ores.10,11) However, few investigations had focused on the metalized pellets used as the blast furnace ironmaking burden. In this paper, the softening properties and interactivity of metalized pellets with other iron bearing materials were researched. Besides, the high-temperature interaction between burdens was also discussed based on appearance observation and elements migration.

2. Experimental

2.1. Method of Preparing Metalized Pellets

By adjusting the dust content of the bag house filter, the ratio of C/O and the moisture content were controlled in 1:1 and 12 wt%–13 wt%, respectively. After the dust (Chemical compositions of mixed different steel plant dust are shown in Table 1) was mixed uniformly, the pillow-shaped bri-

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quettes in dimension of 20 mm×30 mm×40 mm (L×W×H) and about 28 g in weight were produced by a twin-roller machine. And then the briquettes were dried adequately at 105°C for 2 hours. Metalized Pellets were obtained from the prereduction of the briquettes at 1300°C for 15 minutes in Si–Mo furnace.12)

2.2. Physical and Chemical Properties of Iron Bearing Materials

Chemical compositions of BF iron bearing materials are shown in Table 2, which includes sinters (S), oxidized pellets (P), lump ores (L) and metalized pellets (M). With the chemical composition of the metalized pellets compared with that of lump ores and oxidized pellets, it is found that the difference of iron grade and gangue content is not large while the S content of the metalized pellets is higher than that of lump ores and oxidized pellets. However, the influence of the S content on BF operation is minimal because during primary slag formation, the effect of Ca, Si, Mg and Al on slag system is larger and the effect of a small amount of S content on the slag formation is little.

2.3. Experimental Methods

2.3.1. Interaction Characteristics of Mixed Burden

In this study, the test on the reducibility of the sinters, oxidized pellets and lump ores is respectively carried out according to the present standard test method in China (GB13241-91). The softening properties of the iron bearing materials were measured with the infrared furnace (shown in Fig. 1). In Fig. 1, the scorification occurred between the sample plate composed of refractory material and the bottom of the sample during experiments, but the influence of this point on the observation and analysis of the samples is little and ignored. The experimental procedure is the same as that from the literature11) except keeping constant temperature (1200°C) for 0.5 h. The temperature (T10%) at which the volume shrinkage is 10% is defined as the softening start temperature, and the temperature (T40%) at which the volume shrinkage is 40% is defined as the softening end temperature. ΔT (the softening interval) = T40% - T10%. Furthermore, the softening characteristics of mixed burden were investigated at 1200°C when the metallized pellets were mixed with the sinters, oxidized pellets and lump ores, respectively. And the mixed rate is 0, 20%, 40%, 60%, 80% and 100%, respectively.

2.3.2. The Softening and Melting Properties of Iron Bearing Materials

The softening properties of the mixed burden were measured with the softening and melting dripping furnace (shown in Fig. 2). The 6 types of samples were used for mixing ratios of metallized pellets and iron bearing burdens as shown in Table 3. The mixed burden of S:P:L=15:4:1 was considered as the base case, in which the ratio of metallized pellets was not used. Meanwhile, the basicity of mixed burden at different experimental scheme was the designated as same values (1.38±0.01). For keeping constant basicity, the ratio of sinters was reduced with the increase of metallized pellets proportion. However, if the proportion of metallized pellets after reaching 56% increased continuously, the basicity can’t be guaranteed. Thus, the six experiments of different the proportions of metallized pellets were carried out.
The concrete steps are shown as follows. First, the iron bearing materials were broken and sieved into the samples of 10.0–12.5 mm. The coke and samples were positioned into the reaction tube with the inner diameter ($\phi 55$ mm $\times$ 300 mm). Secondly, with the pure nitrogen at 5 L/min, the samples was heated to the designated temperature (500–600 °C) and then heated at 10 °C/min with the reducing gas (the flow rate: 12 L/min; the composition :30% CO and 70% N$_2$). Lastly, the softening and melting properties were measured and the experiment was ended at certain dripping degree, namely the volume shrinkage stop of samples. Furthermore, the softening and melting index and physical significance were included in Table 4. The symbols and meaning of the softening start temperature and softening end temperature used in this section are the same with that in “Softening Properties of Metalized pellets” above.

### Table 3. The raw materials ratio (mass%).

<table>
<thead>
<tr>
<th>sample</th>
<th>S</th>
<th>P</th>
<th>L</th>
<th>M</th>
<th>Basicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>75</td>
<td>20</td>
<td>5</td>
<td>0</td>
<td>1.38</td>
</tr>
<tr>
<td>M15</td>
<td>55</td>
<td>25</td>
<td>5</td>
<td>15</td>
<td>1.38</td>
</tr>
<tr>
<td>M25</td>
<td>42</td>
<td>28</td>
<td>5</td>
<td>25</td>
<td>1.38</td>
</tr>
<tr>
<td>M35</td>
<td>28</td>
<td>32</td>
<td>5</td>
<td>35</td>
<td>1.37</td>
</tr>
<tr>
<td>M45</td>
<td>15</td>
<td>35</td>
<td>5</td>
<td>45</td>
<td>1.38</td>
</tr>
<tr>
<td>M56</td>
<td>0</td>
<td>39</td>
<td>5</td>
<td>56</td>
<td>1.37</td>
</tr>
</tbody>
</table>

### Table 4. The softening and melting dripping index and physical significance.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Physical Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_s$</td>
<td>Melting Start Temperature (°C), the temperature at pressure drop of burden layer, 490 Pa.</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Maximum differential pressure (Pa)</td>
</tr>
<tr>
<td>$T_D$</td>
<td>Dripping Temperature (°C), the temperature at which dripping starts.</td>
</tr>
<tr>
<td>$\Delta T_{D-S}$</td>
<td>Melting Interval ($T_D-T_S$) (°C)</td>
</tr>
<tr>
<td>$R_D$</td>
<td>Shrinkage rate of Dripping Start (%)</td>
</tr>
<tr>
<td>$R_P$</td>
<td>Shrinkage rate of rapid rise of differential pressure (%)</td>
</tr>
<tr>
<td>$H$</td>
<td>Thickness of Melting and Dripping zone (mm), namely $h_D-h_P$</td>
</tr>
<tr>
<td>$S$</td>
<td>Permeability index (kPa°C) namely $S=\int_{T_s}^{T_D} (\Delta P-\Delta P_t)dT$</td>
</tr>
</tbody>
</table>

The concrete steps are shown as follows. First, the iron bearing materials were broken and sieved into the samples of 10.0–12.5 mm. The coke and samples were positioned into the reaction tube with the inner diameter ($\phi 55$ mm $\times$ 300 mm). Secondly, with the pure nitrogen at 5 L/min, the samples was heated to the designated temperature (500–600°C) and then heated at 10°C/min with the reducing gas (the flow rate: 12 L/min; the composition :30% CO and 70% N$_2$). Lastly, the softening and melting properties were measured and the experiment was ended at certain dripping degree, namely the volume shrinkage stop of samples. Furthermore, the softening and melting index and physical significance were included in Table 4. The symbols and meaning of the softening start temperature and softening end temperature used in this section are the same with that in “Softening Properties of Metalized pellets” above.

3. Results and Discussion

#### 3.1. The Interaction between Metalized Pellets and Sinters, Oxidized Pellets and Lump Ores

The softening properties of the mixed burden were studied at 1200°C (as shown in Fig. 3). It can be seen that the volume shrinkage of metalized pellets and sinters is almost straight line, which indicates that there is no interaction between metalized pellets and sinters at high temperature. This is because that the impetus of chemical reaction is in shortage, for metalized pellets and sinters are both alkaline that CaO content is respectively 10.97 mass% in metalized pellet and 11.13 mass% in sinters. On the other hand, the volume shrinkage of lump ores and oxidized pellets with respective metalized pellets of different ratios is positive deviation from the calculated value and the deviation amplitudes are different. This indicates that oxidized pellets and metalized pellets, lump ores and metalized pellets interact at high temperature, and the extent of interaction is discrepant.

From the above experimental results, the interaction index INI,$^{11)}$ referring to the interaction abilities between lump ore (pellets or sinters) and metalized pellets at high temperature and the abilities of integrated burden to improve the poor self-softening properties of lump ore (pellets), is calculated. The INIs of the three kinds of iron bearing materials and metalized pellets are shown in Fig. 4. The INIs of lump ores (oxidized pellets) and metalized pellets are higher than that of sinters and metalized pellets, which means that the interaction between lump ore (oxidized pellets) and metalized pellets can improve the softening properties greatly.

#### 3.2. The Softening and Melting Properties of Iron Bearing Materials under Load

The temperature-dependent parameters, pressure drop and shrinkage rate of iron bearing materials in Table 3 are shown in Figs. 5 and 6. In Fig. 5, both T10% and T5 tend to reduce. Meanwhile, T40% tends to increase as the mixing rate of metalized pellets increases, but T5 basically remains
unchanged. Hence, $\Delta T$ and $\Delta T_{D-S}$ is gradually increasing. This result shows that the cohesive zone becomes wider as the mixing rate of metalized pellets increases. The main compositions of metalized pellet and sinter are similar, mainly including metal iron followed by FeO, CaO and SiO$_2$ and then FeO–CaO·SiO$_2$ in sinter can be produced from the mutual reactions. This point was proved from previous research.$^{11}$ Thus, it is inferred that the metalized pellet contains low-melting-point FeO–CaO·SiO$_2$ phase of 1210°C, namely solidus temperature. Then, its ratio increases as the metalized pellets increase, which leads to relatively low T10%. Furthermore, $T_S$ also mainly depends on melting point of low-melting-point slag of FeO.$^{6,13}$ For metalized pellets, according to the phase diagram,$^{14}$ a variety of low melting point materials are generated from the reactions between FeO and different compounds (Table 5). Meanwhile, the slag melting point of metalized pellets and mixed burden calculated is shown in Fig. 7 (The circle points mean the melting point of mixed ore and a circle filled with black means the melting point of metalized pellet.). Increasing the mixing rate of metalized pellets reduces melting point of the slag phase of mixed burden. Therefore, the lower $T_S$ and wider melting interval occur at the higher mixing rate of metalized pellets. In heating and reduction reaction, with part of residual carbon dissolving into iron easily, the melting point of iron phase reduces while the metalized pellets results in the increased slag viscosity of mixed burden. So $T_D$ has a little change due to the comprehensive two kinds of effects above.

In addition, the higher mixing rate of metalized pellets possesses relatively wider $H$ and higher $\Delta P$ and $S$. $R_P$ and $R_D$ basically remains unchanged. It is considered that the

![Fig. 5. The Softening and Melting Dripping interval under different mixing rates of metalized pellets.](image)

![Fig. 6. The metallurgical performance under different mixing rates of metalized pellets.](image)

![Fig. 7. The ternary diagram of slag phase on FeO–CaO–SiO$_2$.](image)

**Table 5.** The melting point of different slag phases.

<table>
<thead>
<tr>
<th>Reactant</th>
<th>FeO–Fe$_3$O$_4$</th>
<th>FeO–SiO$_2$</th>
<th>Fe$_3$O$_4$–2FeO·SiO$_2$</th>
<th>FeO–CaO·SiO$_2$</th>
<th>FeO–SiO$_2$–CaO–Al$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product</td>
<td>Solid solution</td>
<td>2FeO·SiO$_2$</td>
<td>Eutectic</td>
<td>FeO–CaO·SiO$_2$</td>
<td>Silicate</td>
</tr>
<tr>
<td>Melting point /°C</td>
<td>1150–1200</td>
<td>1205</td>
<td>1142</td>
<td>1210</td>
<td>1030–1050</td>
</tr>
</tbody>
</table>
sinter is able to retard the early deformation of the lump ore particles\(^5\) or even probable metalized pellets particles. With the increase of temperature, the liquid phase volume increases. The exuded liquid material will react with carbon present in the adjacent coke layer and the remaining iron oxide will be reduced by a direct reduction reaction. This also leads to the marked increase in pressure drop over the bed. Furthermore, with conspicuous pressure drop increased, the shrinking rate should reduce once, however it tends to rise again just before dripping.\(^{15}\) The maximum differential pressure of mixed burden is controlled by three factors: \(H\) (thickness of melting and dripping zone), the amount of slag phase and slag phase viscosity.\(^{17}\) It is clear that the largest gas resistance exists due to the smallest porosity of layer in dripping zone. Additionally, the slag viscosity increases with the increase of the mixing rate of metalized pellets (as shown in Table 6 in which the data is calculated based on the slag viscosity model from Refs. 18) and 19). Thus, the maximum differential pressure increases. The eigenvalue \(S\) of melting and dripping, namely permeability index, is gradually increasing with the increase of the proportions of metalized pellets. It is integral value of the pressure difference vs. temperature. Therefore, it depends on the variation tendency of differential pressure and melting interval.

In a word, the influence of mixing rate of metalized pellets, less than 25%, on the properties of mixed burden is little. This could be because that the interaction between the oxidized pellets and metalized pellets offset the negative influence of metalized pellets. However, with a large number of metalized pellets, especially 56% sinters replaced, the properties of mixed burden are worst.

3.3. Analysis on the High-temperature Interaction between the Iron Bearing Materials

The extent of the interaction between different lump ores (oxidized pellets) and sinter with high basicity are discrepant.\(^{20,21}\) However, with addition of metalized pellets, it is unclear that whether or how the interaction occurs between different burdens during the softening and melting. Therefore, the conditions of interaction were further tested in this study. As example of M35, the test temperature is respectively 1200°C, 1250°C and 1350°C.

3.3.1. Observation on Appearance and Section of Burden after Cooling

The clear interfaces (Fig. 8) between different burdens gradually become mild adhesive, and finally melting adhesive becomes more closely with the increase of temperature. This is very similar with the phenomenon of interaction between single burdens.\(^{22}\) The sinters and metalized pellets belong to the basic raw material, but the oxidized pellets and lump ores are the opposite. The interaction is intense between the different burdens owing to different nature and the elements such as Ca, Si, Mg and S exchange each other. So the property of mixed burden changes under high temperature. For example, the \(\Delta T\) is from 169°C to 227°C for single lump ore (or pellet). However, this parameter for mixed burden, lump ore (or pellets) + sinter, is from 90°C to 119°C.\(^{23,24}\)

<table>
<thead>
<tr>
<th>Cases</th>
<th>1400°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>1.2185</td>
</tr>
<tr>
<td>M15</td>
<td>1.6955</td>
</tr>
<tr>
<td>M25</td>
<td>2.295</td>
</tr>
<tr>
<td>M35</td>
<td>2.582</td>
</tr>
<tr>
<td>M45</td>
<td>3.009</td>
</tr>
<tr>
<td>M56</td>
<td>3.2631</td>
</tr>
</tbody>
</table>

*M0–M56 are the experimental cases in Table 3.*

![Fig. 8. Appearance and section of burden after cooling.](image-url)
3.3.2. The Interactions between Oxidized Pellets and Metalized Pellets

Figures 9 and 10 show the elements distribution at interface between metalized pellets and oxidized pellets under different temperatures and the line scanning on Si and Ca at the direction perpendicular to the interface, respectively. It is found from Fig. 9 that the degree of Si and Ca migration is larger while these two elements constitute the basic ingredients of basicity again. Therefore, it is considered that the basicity should be main driving force of element migration. Furthermore, it can be inferred from Fig. 9 that the reaction between SiO$_2$ and CaO aggravates the interactions between metalized pellets and oxidized pellets. The cohesive force strengthens as the temperature is increasing, which makes the interaction interface wider and mutual diffusion of the elements stronger. The process of element migration is described as follows. First, the reaction of SiO$_2$ and CaO at interface produce the low melting point compound and the generation of the liquid phase is advantageous for further diffusion of the elements. Second, the interaction interface broadens, which respectively increases Ca in oxidized pellets and Si in metalized pellets. Fig. 10 also confirms the element migration process and change law of Ca and Si.

The other elements diffusion is not obvious. The main cause is as follows: 1) the differential of element content between the two above pellets is not very small and the obvious migration process is failed to be detected. 2) CaO and SiO$_2$ migration process accompanies chemical combination and generates low melting point compound, which possess a strong chemical potential to drive. It is presumed that migration process of the other elements only belongs to diffusion process.

3.3.3. The Interactions between Oxidized Pellets and Sinters

Figures 11 and 12 show the elements distribution at inter-
face between oxidized pellets and sinters under different temperatures and the line scanning on Si and Ca at the direction perpendicular to the interface, respectively. It is inferred that the interaction strengthens gradually as the temperature is increasing, which is related to the burden properties, as analyzed in the interactions between oxidized pellets and metalized pellets.

### 3.3.4. The Interactions between Metalized Pellets and Sinters

Figures 13 and 14 show the elements distribution at interface between metalized pellets and sinters under different temperatures and the line scanning on Si and Ca at the direction perpendicular to the interface, respectively. It is found that the elements diffusion at the interface is not obvious.

**Fig. 11.** Elements distribution at interface under different temperatures between oxidized pellets and sinters.

**Fig. 12.** The line scanning on Si, Ca, Mg at interface between oxidized pellets and sinters.
And it can be inferred that there is no interaction or the interaction is not obvious due to the alkaline burden though the basicity of metalized pellets is larger. The main cause is that the low melting point compound inside burden isn’t generated. Because the molten liquid phase formed from low melting point compound promotes elements diffusion.

Fig. 13. Elements distribution at interface under different temperatures between sinters and metalized pellets.

Fig. 14. The line scanning on Si, Ca, Mg and Al at interface between metalized pellets and sinters.
Then the interaction interface becomes wide and chemical composition develops to uniform direction. Correspondingly, the scanning results in Fig. 14 also fail to find obvious element migration process.

4. Conclusion

(1) There is no obvious interaction between the metalized pellets and sinters. There is high-temperature interaction between the oxidized pellets and metalized pellets, and this can improve the poor softening properties of the oxidized pellets. Then the abilities to improve the softening properties are discrepant between lump ores (or oxidized pellets) and metalized pellets.

(2) On the basis of the constant basicity of mixed burden, the softening and melting start temperatures reduces and softening and melting interval becomes wide as the mixing rate of metalized pellets is increasing from 0% to 56%. Moreover, the differential pressure and the permeability index both enlarge. The influence of the mixed rate of metalized pellets, less than 25%, on the properties of mixed burden is little. When the rate was more than 25%, the properties would rapidly deteriorate. With a large number of metalized pellets, especially 56% sinters replaced, the properties of mixed burden were worst.

(3) The diffusion of Ca and Si between oxidized pellets and sinters (or metalized pellets) is obvious and the main reaction of scorification is the metalized pellet contains low-melting-point FeO–CaO·SiO2 phase. However, the phenomenon between metalized pellets and sinters is weaker. Thus, it is confirmed that strong interaction must happen between burdens, the nature differences of which were larger.

(4) It is thought that the mixing rate of metalized pellets in burden design, from 0%–25%, is ideal. But the good economic and technical indexes can be achieved in the mill depend on capacity of RHF and operation conditions of BF.

Acknowledgements

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