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Sticking behavior of iron ore–coal pellets and its inhibition

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ABSTRACT

Most previous studies on iron ore–coal pellets (ICPs) have focused on their reduction, but studies on their sticking behavior have not been reported. The sticking behavior of iron ore–coal pellets (ICPs) at high temperatures under a load of 0.1 MPa was studied. Temperature was determined to be an important factor that affects the sticking behavior: the sticking increased with increasing temperature; the sticking index was 89.28% at 1373 K but only 4.78% at 1223 K. The sticking mechanism results from the intergrowth of metallic iron and ferrous oxide crystals between pellet boundaries. High-melting-point materials formed by the combination of MgO and Fe_xO_y, can effectively prevent this intergrowth of iron, and the addition of a dolomite powder coating reduces the sticking index from about 90% to about 10%. The addition of limestone and iron ore powder was not found to have any beneficial effect of sticking inhibition.

1. Introduction

Ironmaking without the use of coke has attracted significant attention due to a shortage of metallurgical coke resources, with iron ore–coal pellets (ICPs) rapidly emerging as one of the more promising noncoking coal raw materials. ICPs have already been applied to rotary hearth furnaces (RHFs), which were originally developed as a means to treat the fines and waste oxides generated in steel plants [1,2]. Currently, research into ICPs has mostly been focused on reduction, specifically the reduction mechanism and reaction rate [3–8]. However, this neglects other behaviors that occur during the reduction process, such as softening and sticking. Sticking behavior has previously been identified and studied with regard to direct-reduced iron (DRI), which is produced by iron oxide pellets (IOPs) and natural gas [9–13]. Studies performed by Lingyun Yi and co-workers indicated that sticking of IOPs was caused by fibrous iron and fresh iron with high activity. Sticking behavior relieved with the addition of H_2 in reducing gas for the porous iron precipitation on the interface [13]. But ICP is different from IOP for it has high coal content and much lower H_2 in its reducing gas. However, similar studies into the sticking behavior of ICPs have not been reported, even though this is of great significance to the optimization of current production techniques and reactors, as well as to the development of new reactor designs.

The sticking behavior of ICPs was therefore studied through a series of reduction experiments under load. It was found that this phenomenon does exist and that it can be inhibited by coating the ICPs. The mechanisms of sticking and its inhibition are discussed in detail, along with SEM analysis.

2. Experimental

2.1. Materials

All raw materials and coatings used in this experiment were obtained from Anhui province in China. Their chemical compositions are listed in Table 1 and Table 2, respectively.

2.2. Apparatus

All experiments were conducted in the device shown in Fig. 1. A SiC resistance furnace with a maximum working temperature of 1673 ± 2 K was used for heating. For each reduction experiment, a 500 g ICP sample was placed into the furnace at 473 K, with a total gas flow rate of 5 L/min (4.5 L/min N_2, 0.5 L/min CO_2), and the sample load was a pressure of 0.1 MPa provided by high-pressure Argon. The samples were then heated at a rate of 6 K/min and held at specified temperatures for 30 min. ICPs' reduction temperatures in previous studies were mostly set between 1173 K and 1473 K generally [15]. The reduction of ICPs is very slow before 1423 K but it becomes faster after 1423 K. So the specified temperatures in this work were 1223, 1323, 1423 and 1523 K. Finally, the reduced pellets were cooled to room temperature in a nitrogen atmosphere.

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Table 1
Chemical composition of iron ore, dolomite and limestone.

Composition (%)	TFe	SiO_2	Al_2O_3	FeO	CaO	MgO	S	P
Iron ore	68.11	2.67	1.02	27.16	0.11	0.26	0.28	0.03
Dolomite	–	1.19	–	–	30.77	20.60	0.01	–
Limestone	–	1.15	–	–	53.78	0.79	0.05	–

2.3. Methods

Clusters consisting of two or more pellets were each dropped 20 times from a height of 1 m onto a steel plate surface. The percentage of clusters remaining after each drop was calculated as the sticking percentage (SP). The number of drops was plotted against this SP value, with the area under the curve calculated as the sticking index (SI). This SI value is equal to zero when no clusters of two or more pellets remain and 100 when all pellets remain clustered and do not disintegrate during the drop tests.

A schematic of the method used for coating the ICPs is shown in Fig. 2. During this coating procedure, raw materials were added to the right pan pelletizers and coatings were added to the left pan pelletizers, respectively. When the pellets attained sufficient size, they were moved out of the right pan and onto the conveyor belt, which transferred them to the left pan. In this left pan, the coating materials were bonded to the outer surface of the pellets to create a coating layer. The coating materials were added according to the quality ratio, which was 7.5% of the raw materials used in this experiment.

3. Results

3.1. Sticking behavior of ICPs and IOPs

Initially, the sticking behavior of ICPs and IOPs was studied. The specified temperature for reduction was 1523 K, with the IOPs heated in air rather than in the N_2/CO_2 atmosphere used with the ICPs.

The sticking behavior of ICPs and IOPs is illustrated in Fig. 3, which shows a difference in their respective SP and SI values at 1523 K. Initially, the SP of the IOPs gradually decreased with an increasing number of drops, reaching 7.6% by the 14th drop when almost all of the pellets became separated. However, with the ICPs there was only a very small decrease in SP as the number of drops increased, with the SP still at 99.5% after the 20th drop when almost all of the pellets were sticking. The sticking degree of the pellets is indicated by the SI value at the 20th drop [9,12,13]. For the IOPs, this value was 26.5%, which is considerably lower than the 99.7% obtained with the ICPs; thus, the sticking behavior of the ICPs is far more serious. Consequently, ICPs are far more difficult to smelt using conventional IOP producing reactors, such as grate-rotary kilns or shaft furnaces. It is therefore important to study the sticking behavior of ICPs in order to find ways in which sticking can be inhibited or accommodated by new reactor designs.

3.2. Influence of temperature on sticking

It can be seen from Fig. 4 that the SP of the ICP reduced at 1223 K gradually decreased with an increase in the number of drops, reaching 0.0% after five drops. The SI value meanwhile was only 4.8% by the 20th drop. Fig. 4 shows a similar trend for the ICP reduced at 1323 K, although the SP was not reduced to 0.0% by the 20th drop and there was a less significant change in SP after the 4th drop. By the 20th drop, the SP was still 5.2%, with many pellets still sticking, whereas the SI was 18.0%.

The SPs also decreased with an increasing number of drops with the 1423 K and 1523 K samples, but the SPs were notably different from the 1223 K and 1323 K samples. At 1423 K, the SP was maintained at approximately 99.1% up to the 9th drop, with almost all of the pellets sticking together. The SP decreased rapidly by the 11th drop, with some separation of the pellets occurring at this time. Once the 15th drop was passed, the change in SP began to decrease, although it remained at 66.4% by the 20th drop. Similarly, the SI was 89.3% after the 20th drop. With the 1523 K sample, the SP was very high at nearly 100% after every drop due to almost all of the pellets sticking together, whereas the SI was 99.1% after the 20th drop.

The SI of the pellets increased with increasing temperature, as can be seen in Fig. 5. This increase in magnitude of SI was minimal below 1323 K, but it increased rapidly beyond this temperature. At 1423 K, the SI was nearly 85%, and at 1523 K it was nearly 100%. It therefore seems likely that the move of pellets in the reactor will become very difficult when temperatures exceed 1423 K due to severe sticking. However, the reduction of pellets is very slow at temperatures below 1423 K [14], and so ICPs should ideally be treated prior to reduction production. A description of the proposed treatment is given in a subsequent section.

Table 2
Chemical composition of coal.

Composition (%)	Ash	Volatile	Sulfur	Fixed carbon
Coal	10.53	8.51	0.41	80.27

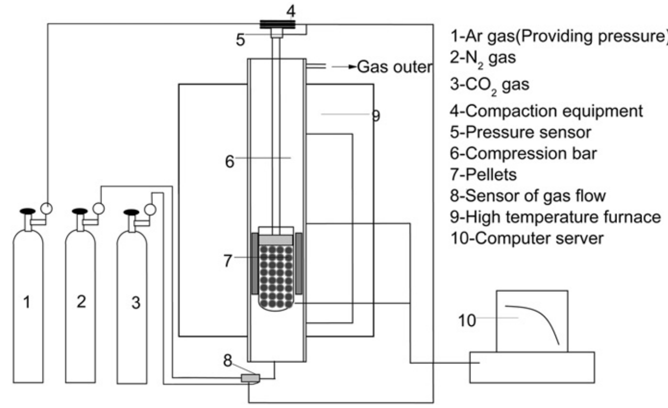

Fig. 1. Schematic diagram of the experimental apparatus used.

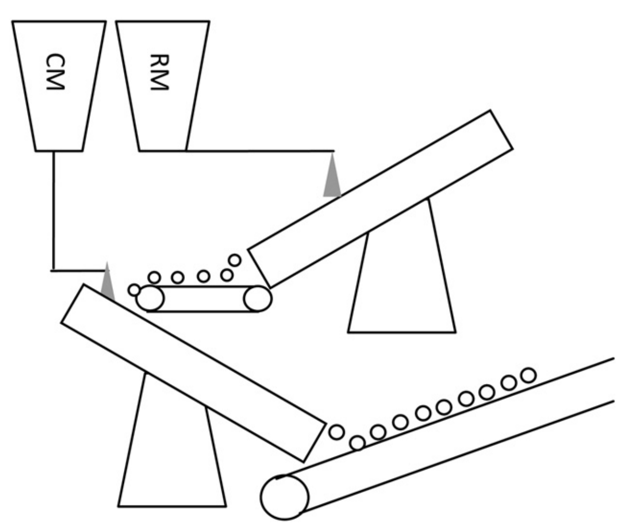

Fig. 2. Experimental procedure used for coating (RM: raw materials, CM: coating materials).