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PREPARATION OF MgO ADDED IRON ORE PELLETS AND EFFECTS ON A PILOT SCALE BLAST FURNACE OPERATION

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Abstract

The preparation of MgO bearing iron ore pellets in the mini and pilot scales, and the application for 4070m3 blast furnace were conducted in this paper. The results show that with increasing the MgO content, the compressive strength of fired pellets decreased significantly, while the metallurgical performances, such as RI (reducibility index), RDI (reduction degradation index) and RSI (reduction swelling index) were improved. The scanning electron microscope with energy dispersive spectrometry was used to test the microstructures and the compositions of iron oxide, and the slag of pellets. With increasing the MgO content, MgO exists in the form of magnesium ferrite and monticellite, which presents the high melting temperature, decreasing the content of liquid phase. The pilot scale experiment was performed on a commercial running grate-rotary kiln with the annual output of 2.4 million tons of pellets, which agrees with the results obtained in the mini scale experiment. The application of MgO-bearing pellets was carried out in the 4070 m^3 blast furnace of Meisteel China, and the production indexes improved with increasing the yield and reducing the coke ratio, and the total benefits are 7067 USD/d, which presents the superior economic benefits.

Keywords: *MgO-bearing iron ore pellets; Reducibility index; Reduction degradation index; Reduction swelling index; Blast furnace; Application*

1. Introduction

Iron ore pellets as the indispensable burden of blast furnace show many benefits, such as high iron grade(> 63%TFe), high physical strength and uniform and size distribution, high and even porosity, less loss on ignition or volatiles, easy reducibility, and lower abrasion during transportation and use [1]. In recent years, under the pressure of energy saving and emission reduction in the iron and steel industry, the proportion of pellets charging into the blast furnace increase, and higher requirements were put forward for the quality and metallurgical performances of the pellets [2-7]. By increasing the content of MgO in iron ore pellets, not only the metallurgical performances of pellets are improved, but also the MgO content in sinter (another burden of blast furnace) decrease, because the excess MgO in sinter causes many negative effects such as the sintering rate, the fuel rate, and the sinter strength and reducibility deteriorate [8-11].

The previous studies reported the influence of pellet MgO content on the qualities and the microstructures of hematite pellets [12-17]. The results presented that by increasing the content of MgO, RDI and RSI of pellets were improved. MgO either enters the magnetite lattice to form magnesium ferrite or dissolves in the slag phase [18-20]. In this paper, the preparation of MgO bearing iron ore pellets were manufactured in the mini and pilot scales. The micro-structures and consolidation mechanism analysis of fired pellets were investigated, and the application of MgO-bearing iron ore pellets in the blast furnace was also carried out.

2. Experimental

2.1 Raw materials

The raw materials employed for manufacturing

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the green balls include the magnetite concentrate, calcined magnesite and bentonite. The chemical composition was analyzed by energy dispersive XRF (X-Ray Fluorescence: EAGLE III, America). The particle size distribution was analyzed according to Iron ore--Determination of size distribution by sieving of China (GB/T 10322.7-2004). The chemical composition and size distribution of all the materials are shown in Tables 1 and 3, respectively. The physical properties of bentonite are shown in Table 2. The magnetite concentrate presents the iron grade higher than 64% and low impurities, such as S and P. As shown in Table 3, the particle size of magnetite concentrate is very fine with 86.12% passing 37 μm and 96.92% passing 74 μm, which is much finer than that of common iron ore concentrate with about 70-80% passing 74 μm for pelletizing [21].

The particle size of bentonite is 92.93% passing 74 μm. Calcined magnesite was calcined at the temperature of 1023-1073K (750-800°C) for 30 min from the natural magnesite ore, which presents the MgO content of 84.23%.

Table 1. *Chemical composition of the raw materials/wt%*

Content	Magnetite concentrate	Calcined magnesite	Bentonite
TFe	64.67	1.38	4.63
FeO	23.97	—	—
SiO_2	7.40	7.42	59.56
Al_2O_3	0.33	1.94	22.94
CaO	0.52	3.47	1.95
MgO	0.52	84.23	1.29
P	0.02	0.06	0.23
S	0.01	0.09	0.01

Table 2. *The physical properties of bentonite*

Expanding volume/ $ml·2g^{-1}$	colloid index/ml· $(15g)^{-1}$	Water absorbancy /%	Methylene blue index /g· $(100g)^{-1}$	Montmorillonite content/%
23	96.5	325.70	32.5	73.53

Table 3. *Particle size distributions of the raw materials /wt%*

Particle Size	Magnetite concentrate	Calcined magnesite	Bentonite
> 74 μm	3.08	2.75	7.07
43-74 μm	5.25	13.97	20.50
37-43 μm	5.55	12.60	19.41
< 37 μm	86.12	70.68	53.02

2.2 Methods

2.2.1 Mini-scale studies

The experimental procedures include green pellets preparation, pellets drying, pellets preheating and firing processes. The green balls were prepared from magnetite concentrate, calcined magnesite, and 1.0% bentonite in a disc pelletizer of 800 mm in diameter and 150 mm rim depth, rotating at 38 r/min and inclining at 47° horizontally. The green balls were achieved at sizes in the range of 9 to 16 mm in diameter, and the green pellets moisture was about 7 %. The pellets were dried in an oven at 378K (105°C) for 4 hours. The dried pellets were put into a corundum crucible with 100 mm in length, 40 mm in width, and 20 mm in height, pushed into the preheating zone of the electrically heated horizontal tube furnace with 600 mm in width and 50 mm in diameter, and preheated at 1198K (925°C) for 12min. Then the preheated pellets were taken out of the furnace and cooled in the air or directly pushed forwards into a higher temperature zone for firing at 1473K (1200°C) for 9 min. The fired pellets were taken out and cooled in air naturally. 60 pellets with 10-12.5 mm in diameter were chosen to be tested using the compressive strength tester (WDW-QT-10, Shandong Province, China) loading at the of 15mm/min according to ISO4700-2007. Cold fired pellets were tested for RI, RDI and RSI according to the standards of ISO 7215, 4698 and 4696-2, respectively. The microstructures of pellets were measured by scanning electron microscope with energy dispersion system after the samples had been mounted and polished by grinder polisher (BUEHLER AutoMet 250, America).

2.2.2 Pilot scale studies

The pilot scale experiment was performed on a commercial running grate-rotary kiln with the annual output of 2.4 million tons in Ma'anshan steel company, China. First, the green balls were loaded into the cage with 80mm in height and 75 mm in diameter. The cage manufactured from 2520 series high temperature resistant steel constitutes 16 bolts with 7 mm in diameter and the gap of 8mm between the adjacent bolts.

In every batch, 20 cages were loaded into the grate. In the updraft stage, the hot air at a temperature of 339K (66°C) was flowed through the pellets bed. In the downdraft stage, the hot air at a temperature of 613K (340°C) was applied. In the preheating stage I, dried pellets were preheated at 953-1033K (680-760°C); in the preheating stage II, first preheated pellets were further preheated at 1163-1223K (890-950°C). The drying and preheating time was 18 min at the grate moving speed of 3.07 m/min, and then the preheated pellets were moved into the rotary kiln with the 1.03 r/min firing at the temperature of 1493-1523K (1220-1250°C) for 15 min. Then the fired pellets were moved to forced draft circular cooler for 60 min at the rotary speed of 1.28 m/min. Cold fired pellets were tested for compressive strength and metallurgical performance using the same methods are used with the mini scale.

3. Results and discussion

3.1 Mini scale studies

3.1.1 Compressive strength of fired pellets

From Figure 1, the compressive strength of the fired pellets decreased rapidly with increasing the MgO content. The compressive strength of the fired pellets reduced from 5182 to 3850 N when MgO content increased from 0.52% (without adding calcined magnesite) to 2.50%. This is due to the increase of MgO content, increasing the slag melting temperature, decreasing the liquid phase content during the roasting process [17]. The consolidation ability of iron grains decreased, reducing the compressive strength of the pellets. With the increase

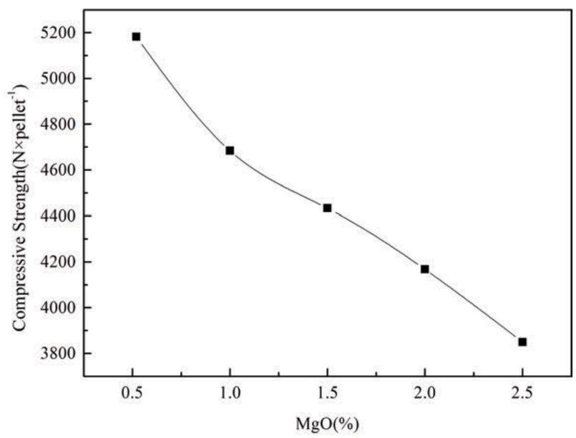

Figure 1. *Influence of MgO content on the compressive strength of pellets in the mini scale (Preheating at 1198K (925°C) for 12min and roasting at 1473K (1200°C) for 9min)*

of the amount of MgO, the magnesium-containing solid solution formed by the pellet during the calcination process is mainly present between the Fe_2O_3 grains, forming a slag phase connection, and a small amount of unmineralized MgO particles are still

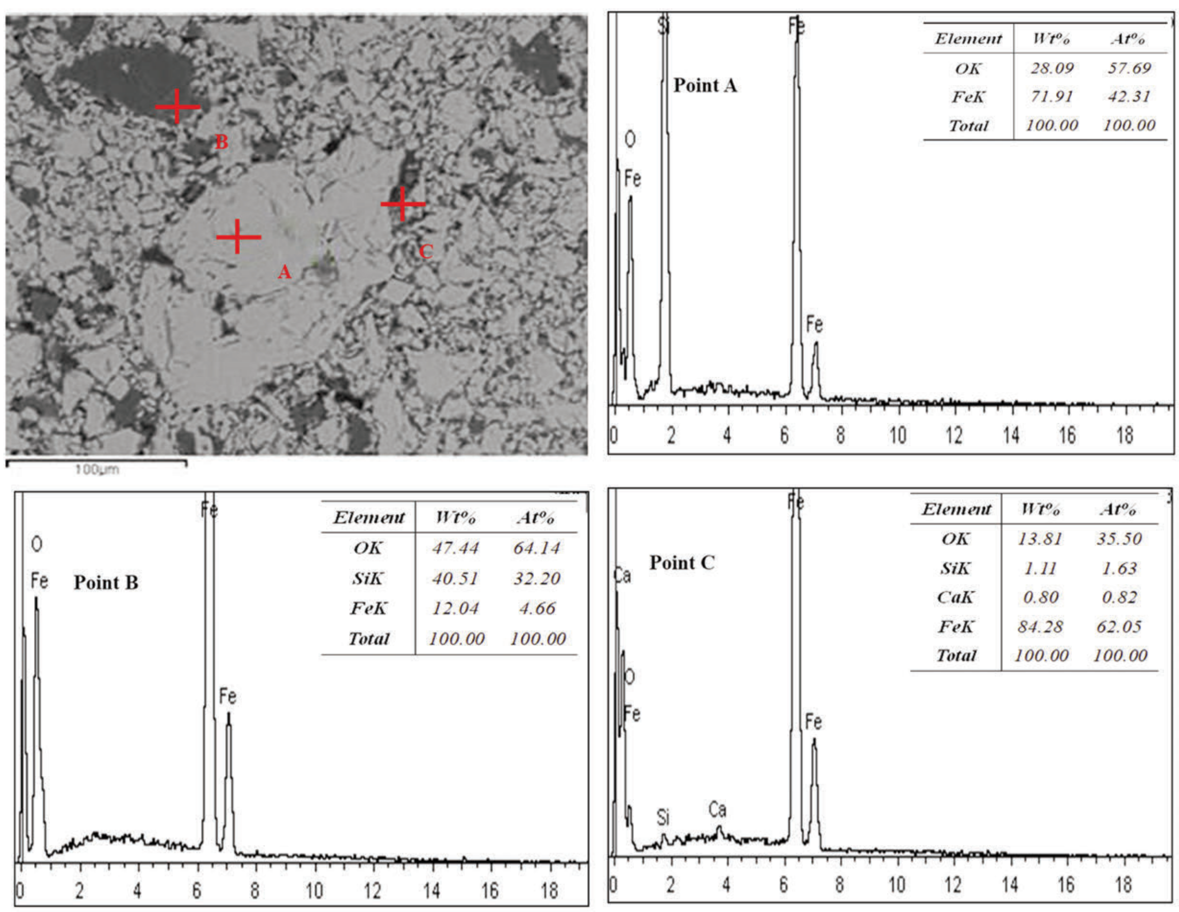

Figure 2. *The SEM-EDS of fired pellets with 0.52% MgO without adding magnesite*

present inside the pellet, leading to the lower compressive strength.

3.1.2 Microstructures and compositions of fired pellets

The SEM-EDS of fired pellets without adding magnesite is shown in Figure 2 Point A shows that the hematite grains are very pure, and Fe_2O_3 content is close to 100%, which indicated that the magnetite had been completely oxidized to produce the hematite grains in the firing process. The hematite grain is larger with the average size larger than 30 µm, and some grains are larger than 200 µm. Point B shows that the main slag phase is fayalite, this is mainly due to the high content of SiO_2 in magnetite concentrate (7.40% SiO_2), which reacted with FeO of the magnetite to produce fayalite in the roasting process. Point C shows that the inclusions between hematite grains mainly are hematite, and a small amount of calcium silicate.

The SEM-EDS of fired pellets with 1.50% MgO is shown in Figure 3. Point A shows that the hematite grains are still very pure, and Fe_2O_3 content is close to 100%, and its consolidation form is hematite recrystallization. Point B shows that the main slag phases are fayalite and magnesium ferrite, and the content of Mg is 6.52% (corresponding to 10.87% MgO), which indicated that part of MgO formed magnesium ferrite, and Mg^{2+} could instead of Fe^{2+} form the solid solution containing FeO and MgO in the firing process. Point C shows that the inclusions between the hematite grains mainly are monticellite, which presents the higher melting temperature than fayalite.

The SEM-EDS of fired pellets with MgO content of 2.50% is shown in Figure 4. Point A shows that the hematite grains are still very pure with the consolidation form of hematite recrystallization. Point B shows that the main components of the slag phase are fayalite and magnesium ferrite. Compared with

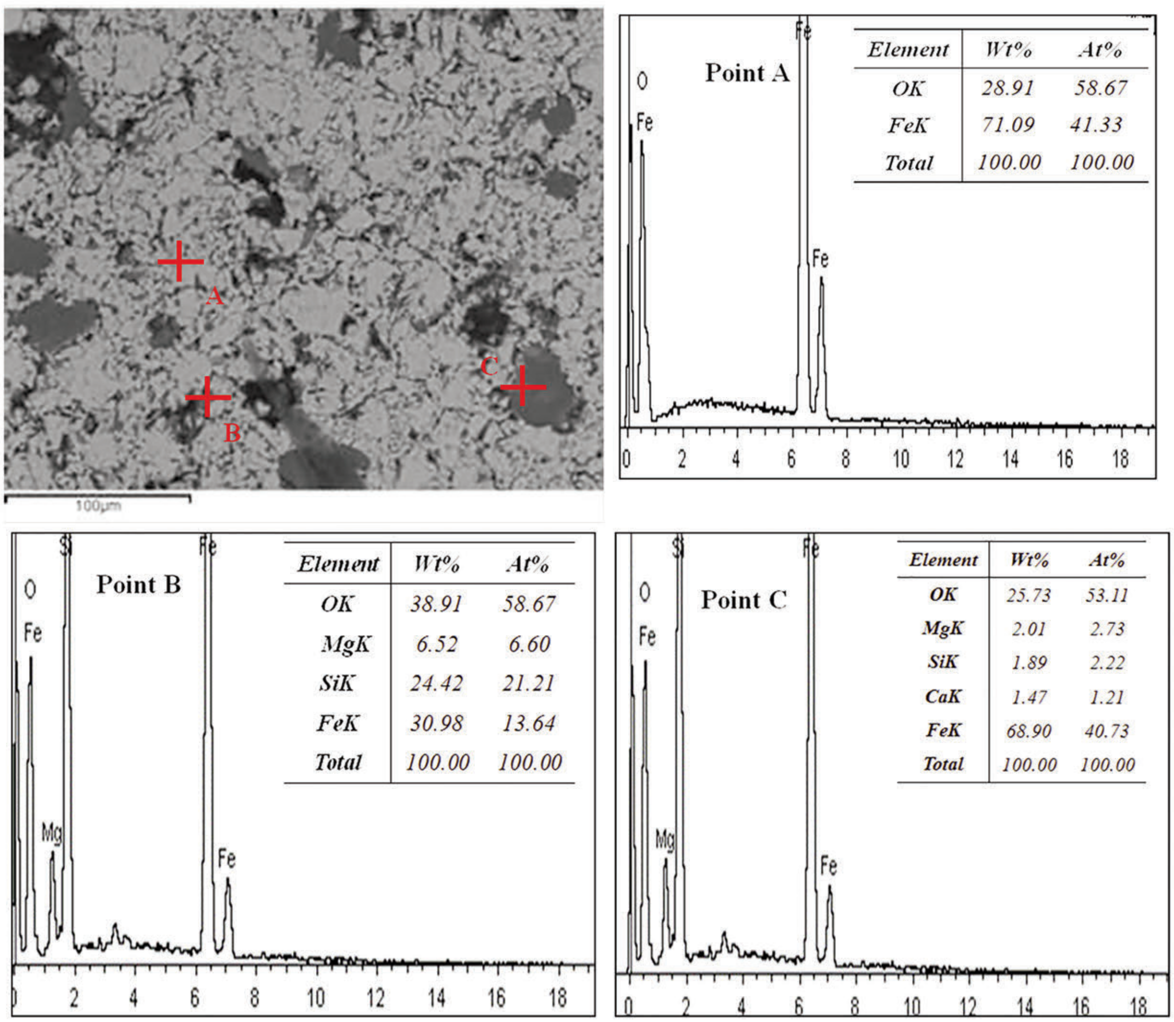

Figure 3. *The SEM-EDS of fired pellets with 1.50% MgO*

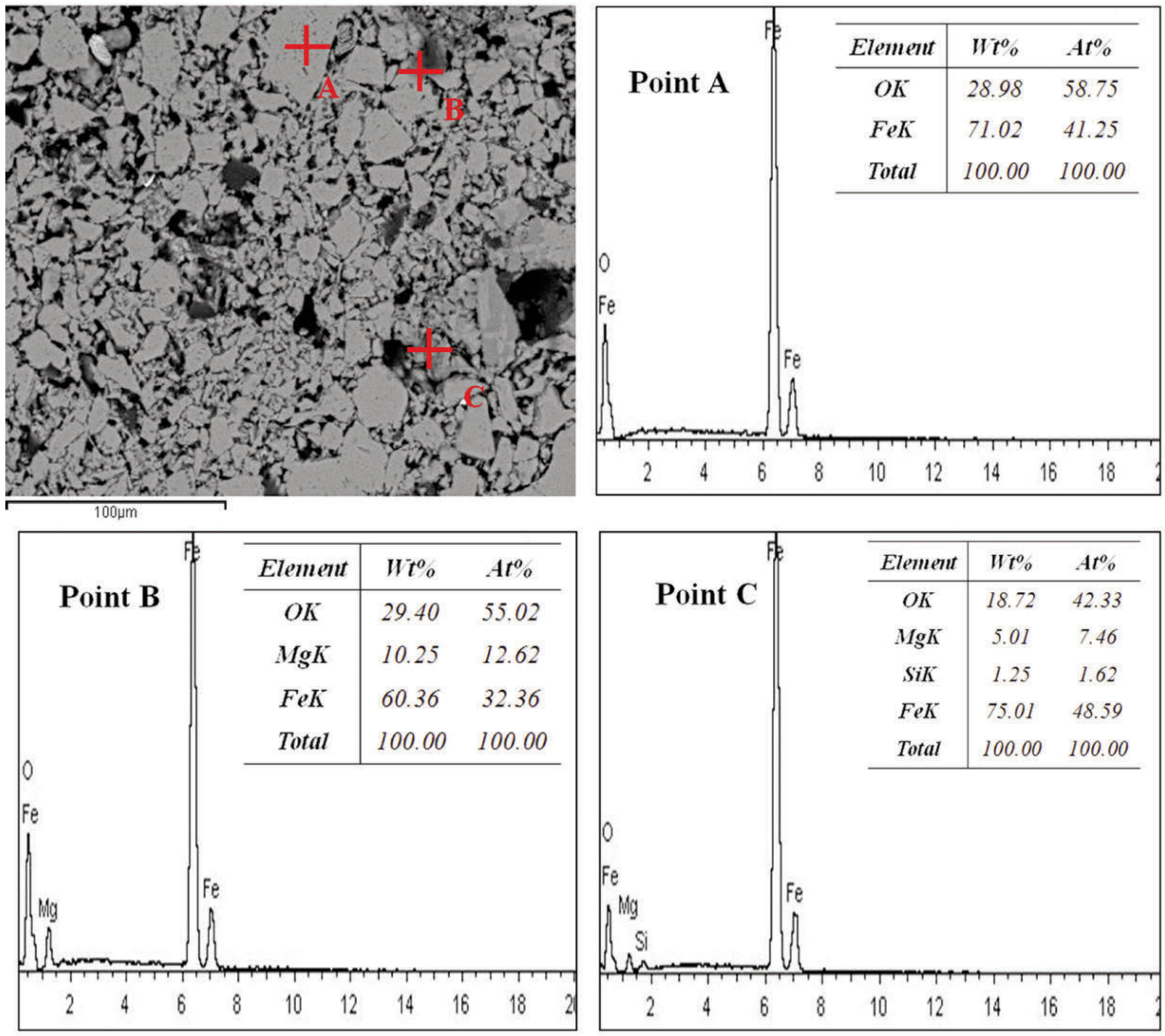

Figure 4. *The SEM-EDS of fired pellets with 2.50% MgO*

the fired pellets with 1.50% MgO, the content of Mg is higher with 10.25% (corresponding to 17.08% MgO), which indicates that part of MgO formed magnesium ferrite, and Mg^{2+} could instead of Fe^{2+} form the solid solution containing FeO and MgO in the firing process. Point C shows that the inclusions between the hematite grains mainly are magnesium ferrite and a small amount of forsterite.

3.1.3 Metallurgical performances (RI, RSI, RDI) of fired pellets

Figure 5 shows the RI (reduction index) and RSI (reduction swelling index) of fired pellets prepared with different MgO contents. The RI of the fired pellets was improved with the increasing of MgO content. With the content of MgO increased from 0.52% to 2.50%, the RI increased from 73.69% to 74.92%. Increasing MgO content could restrain the reduction swelling of pellets effectively. With the content of MgO increased from 0.52% to 2.50%, the RSI decreased from 17.20% to 13.82%. This is mainly

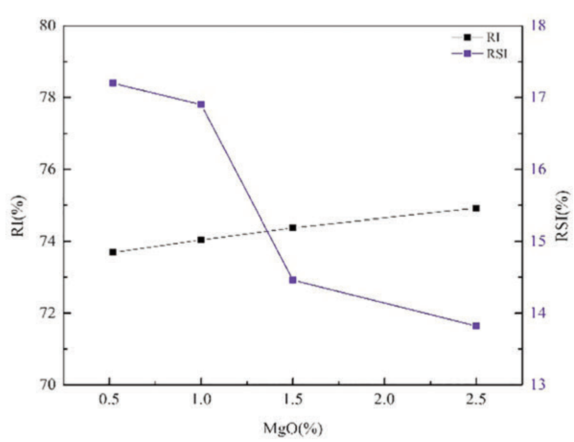

Figure 5. *Influence of MgO content on RI and RSI of fired pellets in the mini scale*

because with the increase of MgO content of pellets, stable magnesium ferrite or monticellite is formed in the firing process. The Mg^{2+} could replace the Fe^{2+} to form the solid solution of FeO and MgO and tended to stabilize in the reducing process, which restrained the swelling behaviors. From Figure 6 [22], the melting point of slag increases as the MgO content is increased, which would improve the swelling behaviors of fired pellets [23].

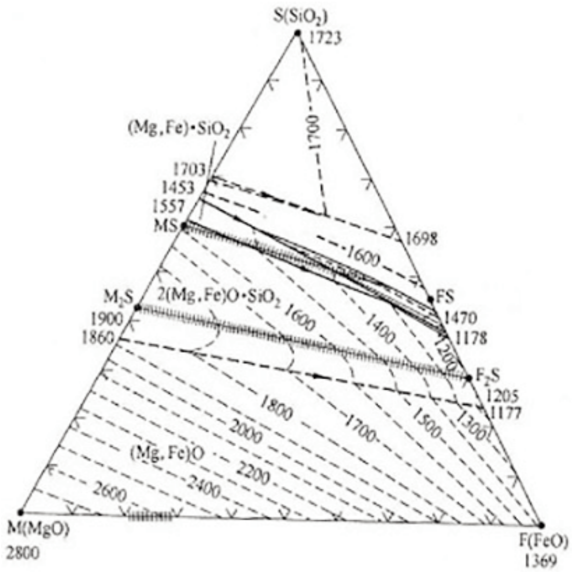

Figure 6. FeO-MgO-SiO_2 ternary phase diagram

Figure 7 shows the variation of the RDI (reduction degradation index) of fired pellets with different MgO content. It is shown in the graph that the RDI of pellets can be effectively restrained by increasing the MgO content. With the content of MgO increased from 0.52% to 1.50%, the $RDI_{+3.15mm}$ increased from 93.92% to 97.38%, and the $RDI_{+6.3mm}$ increased from 81.45% to 95.14%.This is principally because pellets could form more stable liquid phase silicate and magnesium ferrite in the firing stage when mixed with magnesium flux to regulate the content of MgO, thus restraining low-temperature reduction disintegration of the pellets. In addition, MgO could improve the melting point of slag phase, so it is not easy to melt in the reduction process, maintaining a high strength, also restrained the low temperature reduction disintegration of pellets.

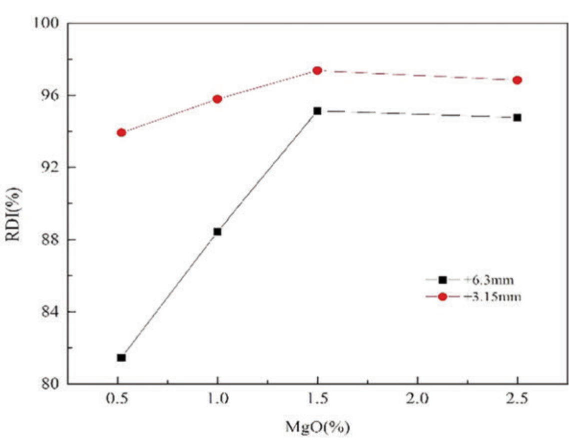

Figure 7. Influence of MgO content on RDI of fired pellets in the mini scale

3.2 Pilot scale studies

In order to further verify the laboratory (mini scale) results of MgO-bearing pellets, two types of pellets containing 0.52%MgO and 1.50%MgO were carried out in a running commercial pelletizing plant. Figure 8 and 9 shows that the cages containing green pellets were loaded into the chain grate and the cages containing fired pellets were recovered from the belt after cooling machine.

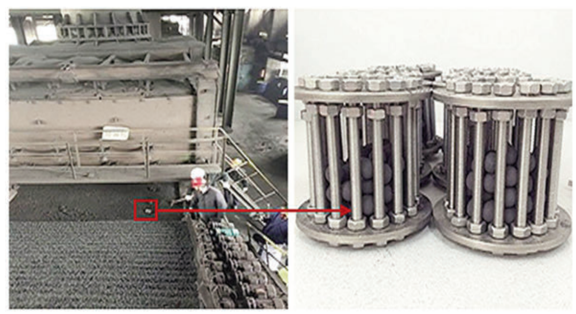

Figure 8. Cages containing the green pellets were loaded into the chain grate

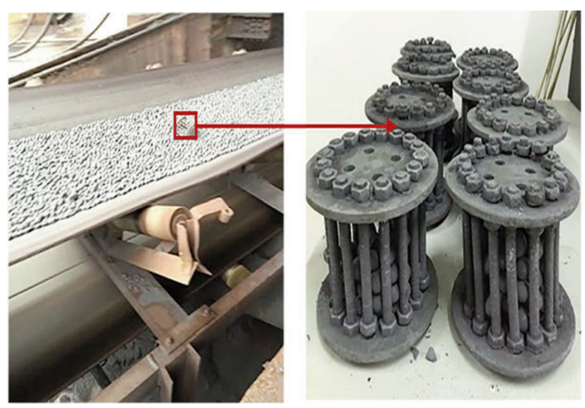

Figure 9. Cages containing the fired pellets were recovered from the belt after cooling machine

3.2.1 Properties of fired pellets produced in pilot scale

The properties of fired pellets obtained in the pilot scale are shown in Table 4 and 5. The compressive strength of fired pellets obtained from the pilot scale decreased as increasing the MgO content, which agrees with the result of the mini scale experiments. The oxidizing atmosphere of pilot scale was weaker than that of the mini scale, and the magnetite could not be oxidized completely, as shown by the FeO content in Table 5. Compared with the mini scale test, the FeO content decreased in the pilot scale test, leading to the low compressive strength. With the increase of MgO content from 0.52% to 1.50%, the RI and RDI increased from 64.42% to 66.23%, and 97.48% to 97.86%, respectively, while the RSI decreased from 9.31% to 8.86%, and the softening temperature and the dropping temperature also increased.

Table 4. *Compressive strength and FeO content of the fired pellets 1.5%MgO in the mini and pilot scales (wt%)*

Item	Compressive strength/N		FeO/%	
	0.52%MgO	1.5%MgO	0.52%MgO	1.5%MgO
Mini scale	5182	4433	0.256	0.524
Pilot scale	4382	4020	0.525	0.789

Table 5. *Influence of MgO content on the metallurgical performance of fired pellets in the pilot scale/ %*

Item	0.52%MgO	1.50%MgO
RI	64.42	66.23
RSI	9.31	8.86
$RDI_{+3.15mm}$	97.48	97.86
Softening starting temperature/°C	1064	1084
Softening ending temperature/°C	1166	1199
Dropping temperature/°C	1353	1389

3.3 Application for blast furnace

The application of MgO-baring pellets was carried out in the 4070 m^3 blast furnace of Meisteel, China from 11th October to 14th November, 2016, and the production parameters are shown in Table 6. The blast furnace burden structure was 76% of sintered ore, 12% of pellets, and 12% of lump ore. Compared with the base period (0.52% MgO), the main indexes of blast furnace improved in the experimental period (1.50% MgO). The blast volume increased from 6553.3 Nm^3/min to 6639.6 Nm^3/min, while the yield increased from 9019.8 $t \cdot d^{-1}$ to 9258.3 $t \cdot d^{-1}$. The coke ratio decreased from 366.2 $kg \cdot t^{-1}$ HM (hot metal) to 356.1 $kg \cdot t^{-1}$ HM, and the coal ratio increased from 119.4 $kg \cdot t^{-1}$ to133.6 $kg \cdot t^{-1}$. The main reason is that as the amount of MgO-bearing iron ore pellets increased, the interval of the blast furnace soft zone decreased, the gas permeability was improved, and the blast volume was increased, which activated the center of the hearth. The airflow distribution was more reasonable, the pressure difference of the blast furnace was lowered, and the heat of the blast furnace was more abundant, which improved the conditions for the blast furnace to increase the coal ratio. The S content of hot metal decreased and the MgO content of slag increased in the experimental period.

Table 6. *Production parameter of 4070 m^3 blast furnace in the base and experimental periods*

Parameter	Base period	Experimental period
MgO content of pellets/%	0.52	1.50
Blast volume Nm^3/min	6553.3	6639.6
Differential pressure /kPa	166.2	172.4
Yield/ $t \cdot d^{-1}$	9019.8	9258.3
Coke ratio/$kg \cdot t^{-1}$	366.2	356.1
Coal ratio/ $kg \cdot t^{-1}$	119.4	133.6
Slag ratio/ $kg \cdot t^{-1}$	284.6	285.6
Permeability/K	2.48	2.5
Gas utilization rate/ ηCO,%	49.1	49.8
[Si] /%	0.362	0.317
[S] /%	0.0286	0.0244
(MgO)/%	7.09	7.31
Hot metal temperature/°C	1507.7	1508.9
R_2	1.17	1.2

The economic benefits of 4070 m^3 blast furnace in the base and experimental periods are listed in Table 7. The fuel cost decreased 5650 USD/d and the profit of hot metal increased 1417 USD/d, and the total benefits are 7067 USD/d, which presents the superior economic benefits.

Table 7. *Economic benefits of 4070 m^3 blast furnace in the base and experimental periods*

Parameter	Base period	Experimental period	Change	Profit or loss/ $USD \cdot d^{-1}$
Coke ratio/$kg \cdot t^{-1}$	366.2	356.1	-10.1	18888
Coal ratio/$kg \cdot t^{-1}$	119.4	133.6	+14.2	-13239
Yield/ $t \cdot d^{-1}$	9019.8	9258.3	+238.5	1417
Total				7067

Note: The price of coke and coal calculated as 201.99 and 100.70 USD/t, respectively.

4. Conclusions

(1) With increasing the MgO content, the compressive strength of fired pellets decreased significantly, and the RI, RSI and RDI of pellets were improved. MgO exists in the form of magnesium ferrite and monticellite with the increasing of MgO content, which presents the high melting temperature. Compared with the mini scale experiment, the trends of decreasing the compressive strength and RSI of fired pellets and increasing the RI and RDI were consistent with the addition of MgO in the pilot scale production.

(2) Compared with the base period, the main parameter of 4070 m^3 blast furnace improved in the experimental period. The blast volume and the yield increased, while the coke ratio decreased and the coal ratio increased. The total benefits are 7067 USD/d, which presents the superior economic benefits. MgO-bearing iron ore pellets have higher utilization value and promotion prospects in blast furnace ironmaking.

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PRIPREMA PELETA RUDE ŽELEZA SA DODATIM MgO I UTICAJ NA RAD VISOKE PEĆI U PILOT ISTRAŽIVANJU

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Apstrakt

U ovom radu je urađena priprema peleta rude železa sa dodatim MgO u mini i pilot istraživanjima, kao i primena za visoku peć od 4070m³. Rezultati pokazuju da je sa povećanjem sadržaja MgO kompresivna čvrstoća peleta značajno opala, dok su metalurške performanse kao što su RI (indeks reducibilnosti), RDI (indeks redukcije degradacije) and RSI (indeks rasta redukcije) bile poboljšane. Korišćen je skenirajući elektronski mikroskop sa energetski disperzivnom spektometrijom da bi se testirale mikrostruktura i sastav oksida železa i šljake peleta. Sa povećanjem sadržaja MgO, MgO postoji u obliku magnezijum-ferita i montičelita i daje visoku temperaturu topljenja, smanjujući sadržaj tečne faze. Eksperiment na pilot nivou je izveden na komercijalnoj rotacionoj peći sa godišnjom proizvodnjom od 2,4 miliona tona peleta, i slaže se sa rezultatima dobijenim u mini eksperimentu. Primena peleta sa dodatim MgO bila je urađena u visokoj peći od 4070m³, Meistil, Kina; indeks proizvodnje se poboljšao sa povećanjem iskorišćenja i smanjenjem udela koksa, i ukupna dobit je 7067 USD/d, što predstavlja izuzetnu ekonomsku korist.

Ključne reči: *Pelet gvozdene rude sa dodatim MgO; Indeks reducibilnosti; Indeks redukcije degradacije; Indeks rasta redukcije; Visoka peć; Primena.*