International Journal of Minerals, Metallurgy and Materials
Volume 21, Number 4, April 2014, Page 339
DOI: 10.1007/s12613-014-0914-9

Effect of aluminum oxide on the compressive strength of pellets

Jian-liang Zhang, Zhen-yang Wang, Xiang-dong Xing, and Zheng-jian Liu

School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China

(Received: 27 June 2013; revised: 18 October 2013; accepted: 21 October 2013)

Abstract: Analytical-reagent-grade Al_2O_3 was added to magnetite ore during the process of pelletizing, and the methods of mercury intrusion, scanning electron microscopy, and image processing were used to investigate the effect of Al_2O_3 on the compressive strength of the pellets. The results showed that, as the Al_2O_3 content increased, the compressive strength of the pellets increased slightly and then decreased gradually. When a small amount of Al_2O_3 was added to the pellets, the Al_2O_3 combined with fayalite ($2FeO{\cdot}SiO_2$) and the aluminosilicate ($2FeO{\cdot}2Al_2O_3{\cdot}5SiO_2$) was generated, which releases some iron oxide and reduces the inhibition of fayalite to the solid phase of consolidation. When Al_2O_3 increased sequentially, high melting point of Al_2O_3 particles hinder the oxidation of Fe_3O_4 and the recrystallization of Fe_2O_3, making the internal porosity of the pellets increase, which leads to the decrease in compressive strength of the pellets.

Keywords: magnetite; ore pellets; alumina; compressive strength; porosity; microanalysis

Because of a rapid increase in iron ore consumption, high-grade ore deposits have been gradually exhausted [1]. The alumina content in iron ores is increasing incrementally. For example, the alumina content of iron ores from the Newman and Hamersley mines in Australia and from the Carlo Degas and Goa mines in India is greater than 2wt% [2]. The ratio of high-aluminum ores will continue to increase in ore matching. Compressive strength is an important parameter for measuring the quality of ore pellets. Because of their repeated transportation and accumulation before charging, the finished pellets can withstand a harsh mechanical action. In this process, the pellets with a higher compressive strength will produce less patch and powder, which can guarantee a good permeability after charging [3-4]. Thus, the effect of aluminum oxide on the compressive strength of ore pellets is an important research topic.

Recently, several scholars have studied this problem. Zhang *et al.* [5] pointed out that, as the Al_2O_3 content increases from 1.5wt% to 4.5wt%, the compressive strength of ore pellets decreases from 3800 N to 2900 N. This decrease occurs because the increased amount of Al_2O_3 reduces the viscosity of the silicate binding phase, which leads to an increase in porosity. Thus, the compressive strength of ore pellets decreases gradually with increasing Al_2O_3 content. However, the volume of research related to the relationship between Al_2O_3 and compressive strength at the microscopic level is limited.

By changing the raw material content of alumina in pelletized ores and by using the methods of mercury intrusion and scanning electron microscopy (SEM) analysis, we studied the effect of alumina on the compressive strength of ore pellets and explored the function of alumina in the process of pellet roasting.

1. Experimental

1.1. Raw materials

The magnetic iron ore was acquired from a large iron and steel enterprise in northern China. Its composition is shown in Table 1.

Table 1. Chemical composition of magnetite used in the experiments wt%

TFe	FeO	CaO	MgO	Al_2O_3	SiO_2	S	P
67.26	27.55	0.30	0.34	0.80	4.55	0.06	0.05

As shown in Table 1, the magnetite iron ore used in the experiment has a high grade of 67wt%. The FeO content is

Corresponding author: Zhen-yang Wang E-mail: Wangzheny@126.com

high, which is beneficial to solid-phase consolidation. Gangue is less, and the content of harmful elements is low. Therefore, this magnetite is a good raw material for pelletization [6].

Bentonite was added to the pellets at a concentation of 2wt%. The composition and bonding properties of bentonite are shown in Tables 2 and 3.

Table 2. Chemical composition of bentonite used in the experiments wt%

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	Burning loss
68.40	13.95	1.69	1.51	2.48	0.90	0.45	8.94

Table 3. Physical characteristics of bentonite used in the experiments

Colloid index / (mL·(15 g)$^{-1}$)	Expansion volume / (mL·g^{-1})	Content of methylene blue adsorbed / (g·(100 g)$^{-1}$)	Montmorillonite content / wt%	Water absorption content (2 h) / wt%	–200 mesh content / wt%
100	15	32.0	72.7	158	98.5

As shown in Tables 2 and 3, the experimental bentonite has high montmorillonite content and small grain size, which indicates that the bentonite is a high-quality pellet binder [7].

The Al_2O_3 additive used in the experiment was analytically pure Al_2O_3 from Sinepharm Chemical Reagent Co.

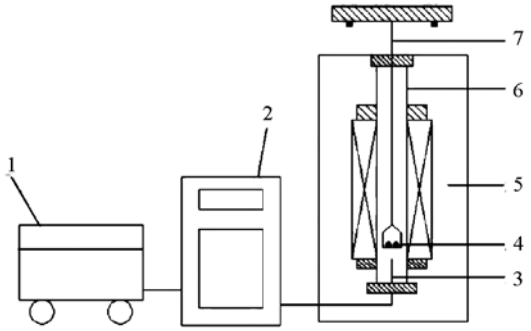
1.2. Experimental methods

Mixed with additional moisture (8 ± 0.5)wt%, a series of Al_2O_3 green pellets with compositions listed in Table 4 were made by using a balling disc. The green pellets were subsequently placed into a constant-temperature drying box at 105°C for 4 h. 10–12.5 mm balls were elected from each group of dry pellets and weighed approximately 30 g, which were used for oxidizing roasting.

Table 4. Compositions of the pelletizing mixtures wt%

Number	Magnetite	Al_2O_3	Bentonite
1	98.0	—	2
2	97.5	0.5	2
3	97.0	1.0	2
4	96.5	1.5	2
5	96.0	2.0	2
6	95.5	2.5	2

The process of oxidizing roasting was conducted in a temperature-programmed tubular resistance furnace. The green pellets were placed in the resistance furnace at 900°C. The temperature inside the furnace was then increased to 1280°C at a rate of 5°C/min and maintained at 1280°C for 20 min [8]. Air was allowed to flow through the furnace via the air compressor and control cabinet at a flow rate of 1.5 L/min during the whole process. When the roasting process was completed, the pellets were allowed to cool to room temperature along with the furnace, and the experimental oxidized pellets were subsequently obtained [9–10]. The oxidizing roasting equipment is shown in Fig. 1.



1—Air compressor, 2—Control cabinet, 3—Thermocouple, 4—Pellets, 5—Tubular resistance furnace, 6—Alumina tube, 7—Molybdenum wire basket.

Fig. 1. Schematic diagram of the oxidizing roasting setup.

The compressive strength of six groups of pellets was measured using a pressure test machine. Each group was measured in six replicate trials. The pore size distribution and porosity of each group of pellets were measured using a mercury injection apparatus. The microscopic analysis of pellet center sections was performed by SEM. The main parameters of the balling disc, the pressure testing machine, and the mercury injection apparatus are shown in Table 5.

Table 5. Main parameters of the experimental equipment

Equipment	Main parameters
Balling disc	Diameter 0.5 m; revolution speed 13–65 r/min; angle 0–45°
Pressure testing machine	range 10 kN
Mercury injection apparatus	Pore size 0.003−1080 μm; pressure 413.6 MPa

2. Results and discussion

The compressive strength of the six groups of pellets is shown in Fig. 2. As evident in Fig. 2, the compressive

strength of the pellets increased slightly and then decreased gradually with increasing Al_2O_3 content. When the Al_2O_3 content in the pellets was increased from 1wt% to 1.5wt%, the compressive strength increased from 3307 N to 3403 N. However, when the Al_2O_3 content was further increased to 3.5wt%, the compressive strength decreased from 3403 N to 2855 N.

The pore size distribution and porosity of the six groups of pellets were measured using the mercury injection apparatus, and the results are shown in Fig. 3.

As shown in Fig. 3, when the Al_2O_3 content was increased from 1wt% to 1.5wt%, the porosity decreased slightly. However, when the Al_2O_3 content was increased from 1.5wt% to 3.5wt%, the porosity increased gradually from 22% to 27% and the main peak of pore diameter increased from 5 μm to 18 μm. These results indicate that an increase in the Al_2O_3 content resulted in a larger internal pore size and a more scattered pore size distribution [11].

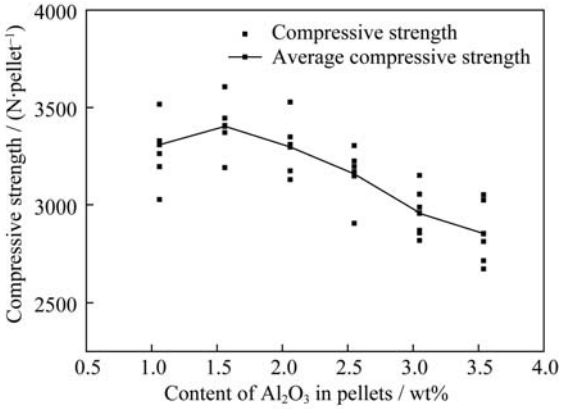


Fig. 2. Effect of Al_2O_3 content on the compressive strength of pellets.

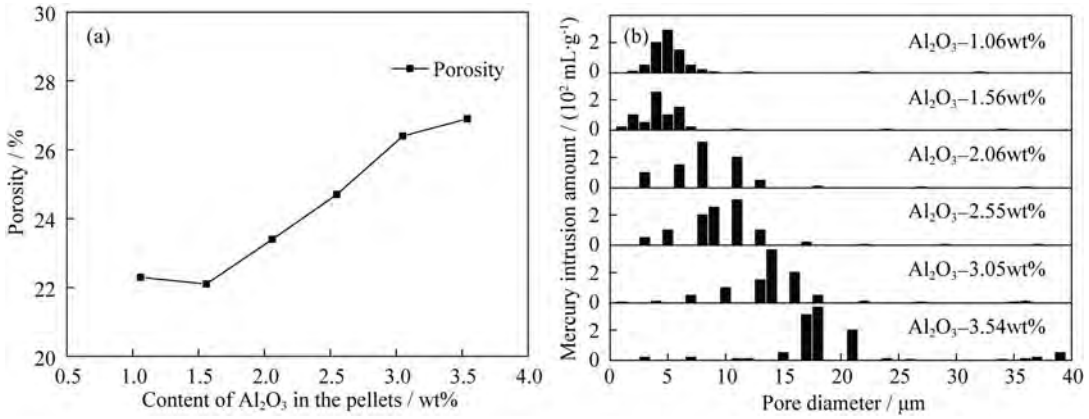


Fig. 3. Effect of Al_2O_3 content on the porosity (a) and pore distribution (b) of pellets.

The centers of the cross-sections of pellets with different Al_2O_3 contents were analyzed by SEM [12]. Moreover, using software, we processed the images such that the base and aperture were represented as black and blue regions, respectively, and thereby calculated the porosity based on the SEM images. The results are shown in Fig. 4.

Fig. 4 shows that pellets represented in images (a) and (b) are relatively dense and have fewer cracks and low porosity. The pore area fraction was approximately 18%. However, pellets represented in images (c) to (f) exhibit more internal cracks, greater porosities, larger pore sizes, and more disordered pore distributions. The pore area fraction ranged from 19% to 28% in these samples.

During the oxidizing roasting of magnetite pellets, the increase in their compressive strength occurs primarily through solid-phase consolidation [13], i.e., the microcrystalline connection of newly generated Fe_2O_3 crystallites and the recrystallization and polycrystallization of the already grown Fe_2O_3 crystallites. In this process, grains in the pellets proceed sequentially through aggregation, combination, and growth. The pore size becomes small, and the ball shrinks into a compact whole, which results in a substantial increase in compression strength of the pellets [14]. Therefore, anything that hinders oxidation from Fe_3O_4 to Fe_2O_3 and the recrystallization and polycrystallization of Fe_2O_3 will reduce the compressive strength of the pellets [15].

The oxidation of Fe_3O_4 is incomplete in regions where the diffusion of oxygen is weak. Fe_3O_4 will combine with SiO_2 to form fayalite ($2FeO{\cdot}SiO_2$) at 1000°C. Fayalite has a low melting point (1205°C) and will continue to form lower-melting compounds with iron oxide, such as $2FeO{\cdot}SiO_2$–Fe_3O_4 (1142°C) and $2FeO{\cdot}SiO_2$–FeO (1177°C). Some liquids can be formed in this process that wrap a portion of unoxidized Fe_3O_4 and formative Fe_2O_3, which hinders the continued oxidation of Fe_3O_4 and the recrystallization of Fe_2O_3. Simultaneously, fayalite combines portions of FeO

and Fe_3O_4, which hinders the continued oxidation of FeO and Fe_3O_4 and reduces the crystallinity of Fe_2O_3. We calculated the Al_2O_3–SiO_2–FeO ternary phase diagram using the thermodynamics software of Factsage 6.2. As shown in Fig. 5, when a small amount of Al_2O_3 is added, the Al_2O_3 will enter into the silicate system, forming $2FeO{\cdot}2Al_2O_3{\cdot}5SiO_2$ at 1083°C; the formation of this phase thereby reduces the quantities of FeO and Fe_3O_4 combined with SiO_2 and releases some FeO and Fe_3O_4, which reduces the ability of fayalite to inhibit the recrystallization and polycrystallization and improves the crystallinity of Fe_2O_3. Consequently, the compressive strength of the pellets is slightly elevated. However, with further increases in the Al_2O_3 content, some Al_2O_3 diffuses throughout the pellets. The high-melting Al_2O_3 particles will hinder the diffusion of ions within the lattice and the growth of grains. Thus, the compressive strength of the pellets gradually decreases as the content of Al_2O_3 increases sequentially.

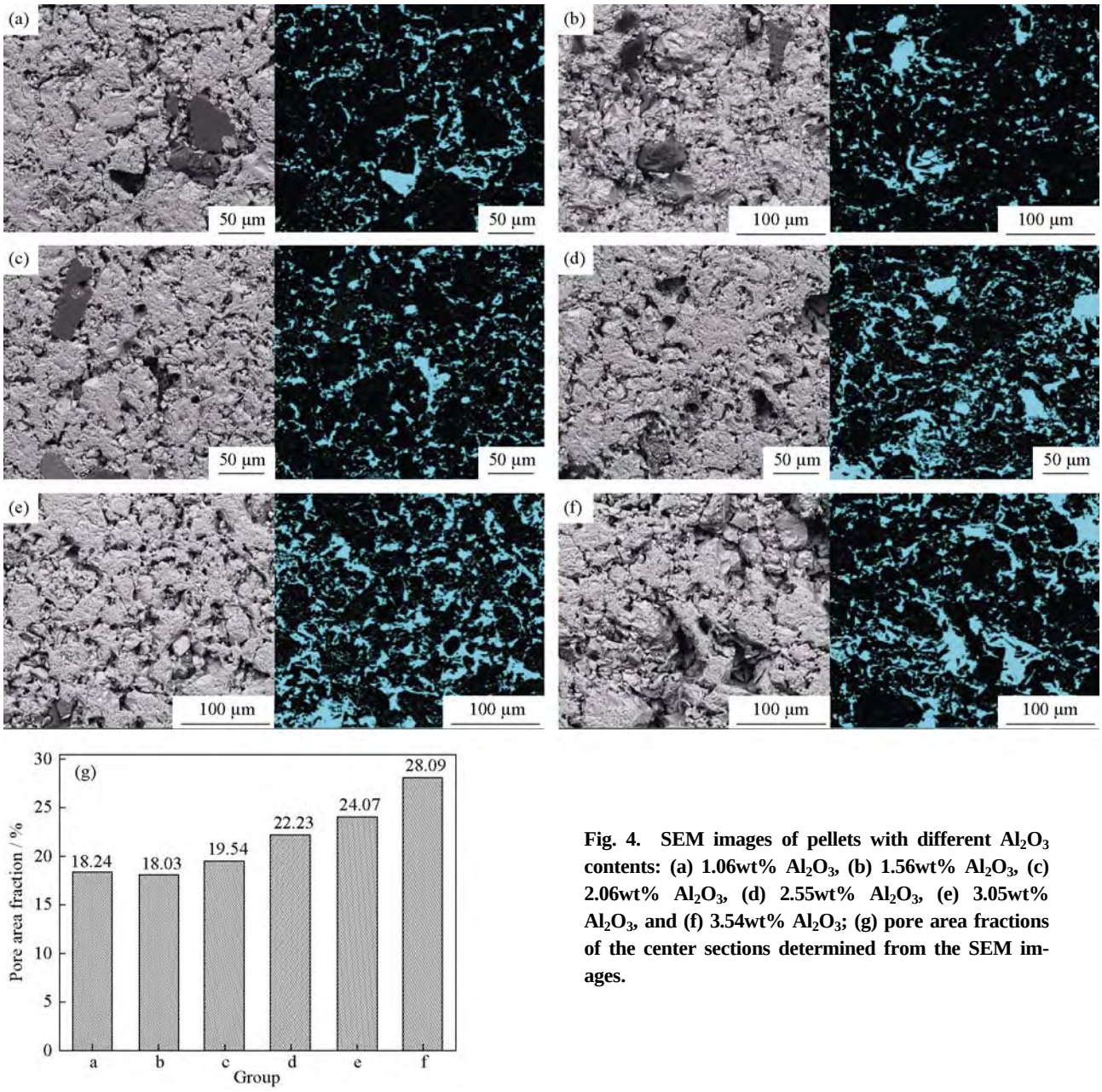


Fig. 4. SEM images of pellets with different Al_2O_3 contents: (a) 1.06wt% Al_2O_3, (b) 1.56wt% Al_2O_3, (c) 2.06wt% Al_2O_3, (d) 2.55wt% Al_2O_3, (e) 3.05wt% Al_2O_3, and (f) 3.54wt% Al_2O_3; (g) pore area fractions of the center sections determined from the SEM images.

The relationship between the compressive strength and the porosity is described by the following empirical formula [7]:

$$R = Kd^{-\alpha}\exp(-\rho p),$$

where R and p represent the compressive strength and the

porosity, respectively, d is the radius of a grain, and K, α, and ρ are coefficients. According to this empirical formula, an increase in porosity of the pellets will reduce their compressive strength.

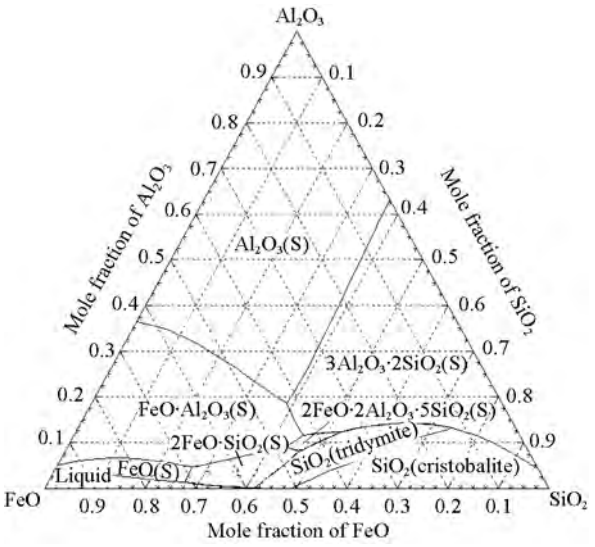


Fig. 5. Al_2O_3–SiO_2–FeO ternary phase diagram.

In conclusion, when the Al_2O_3 content is low, the silicon aluminum acid salts destroy the structure of iron fayalite, reduce the ability of SiO_2 to constrain Fe_3O_4 and FeO, release a portion of iron oxide, diminish the ability of fayalite to inhibit the recrystallization and polycrystallization, and improve the crystallinity of Fe_2O_3. Therefore, the compressive strength of the pellets increases slightly. However, when the Al_2O_3 content is increased further, the high-melting Al_2O_3 particles hinder the continued oxidation of Fe_3O_4 and the recrystallization of Fe_2O_3, which results in an increase in porosity of the pellets, improves the pore size, and makes the pore size distribution uneven. These effects eventually lead to a decrease of the compressive strength of the pellets.

3. Conclusions

(1) When the Al_2O_3 content in the pellets was increased from 1wt% to 3.5wt%, the compressive strength first increased slightly and then gradually decreased. Although the compressive strength decreased to 452 N, this value still satisfies production requirements.

(2) SEM microscopy and subsequent processing of the images revealed that, when the alumina content was low, the cracks were small and the distribution of holes was relatively dispersed. When the alumina content was increased, the cracks became thick and the distribution of holes was concentrated.

(3) The compression strength increased slightly after the addition of a small amount of Al_2O_3 to the pellets because Al_2O_3 entered the silicate system, forming $2FeO{\cdot}2Al_2O_3{\cdot}5SiO_2$ at 1083°C. The additional Al_2O_3 can reduce the quantities of FeO and Fe_3O_4 combined with SiO_2, weaken the ability of fayalite to inhibit the solid-phase consolidation, and improve the crystallinity of Fe_2O_3. Thus, the compressive strength increases slightly.

(4) As the content of Al_2O_3 was further increased, the high-melting Al_2O_3 particles hinder the diffusion of ions within the lattice and the growth of grains. It adversely affects the continued oxidation of Fe_3O_4 and the recrystallization of Fe_2O_3, which results in an increase in porosity of the pellets, increases the pore size, and makes the pore size distribution uneven. Consequently, the compressive strength of the pellets gradually decreases.

Acknowledgements

This work was financially supported by the National Key Basic Research and Development Program of China (No. 2011BAC01B02).

References

[1] Z.Y. Li and Q.Y. Yu, BF slag structure adjustment for high Al_2O_3 slag smelting, *Baosteel Technol.*, (2012), No. 3, p. 1.

[2] F. Long, *The Effection on Ironmaking Raw Materials and Metallurgical Process by High Content of Al_2O_3 Iron Ore* [Dissertation], Wuhan University of Technology, Wuhan, 2006, p. 1.

[3] J.Y. Fu, J. Tao, and D.Q. Zhu, *Sintering and Pelleting*, Center South University of Technology Press, Changsha, 1996, p. 281.

[4] K.W. Ye, Heavily push forward the pelletizing production in our country, *Sintering Pelleting*, 32(2007), No. 5, p. 1.

[5] Y.P. Zhang, J.Y. Fu, T. Jiang, Y.B. Yang, The influence of the gangue contents on properties of pellet, *Sintering Pelletizing*, 27(2002), No. 4, p. 11.

[6] B. Das, B.K. Mishra, S. Prakash, S.K. Das, P.S.R. Reddy, and S.I. Angadi, Magnetic and flotation studies of banded hematite quartzite (BHQ) ore for the production of pellet grade concentrate, *Int. J. Miner. Metall. Mater.*, 17(2010), No. 6, p. 675.

[7] Y.M. Zhang, *Pellets Production Technology*, Metallurgical Industry Press, Beijing, 1998, p. 66.

[8] Z.C. Huang, L.Y. Yi, H. Peng, and T. Jiang, Effects of roast temperature on properties of oxide pellets and its gas-based direct reduction, *J. Cent. South Univ. Sci. Technol.*, 43(2012), No. 8, p. 2889.

[9] J.X. Feng, Y. Zhang, H.W. Zheng, X.Y. Xie, and C. Zhang, Drying and preheating processes of iron ore pellets in a traveling grate, *Int. J. Miner. Metall. Mater*., 17(2010), No. 5, p. 535.

[10] Y.K. Zhang, Exploration and practice of low temperature induration process of V–Ti pellets, *Sintering Pelletizing*, 35(2010), No. 6, p. 17.

[11] Q.J. Gao, G. Wei, Y.B. He, and F.M. Shen, Effect of MgO on compressive strength of pellet, *J. Northeast. Univ. Nat. Sci*., 34(2013), No. 1, p. 103.

[12] Z.C. Huang, Y.B. Zhang, Y.M. Chen, and J.M. Zhuang, Microstructure of oxidized pellets mainly made from hematite with magnetite, *J. Cent. South Univ. Sci. Technol*., 34(2003), No. 6, p. 606.

[13] X.L. Wang, *The Ferrous Metallurgy (Part of Iron)*, Metallurgical Industry Press, Beijing, 2009, p. 64.

[14] Q. Xiao, *Theory and Practice of Pelletizing*, Central South University of Technology Press, Changsha, 1991, p. 93.

[15] Y.M. Chen and J. Li, Crystal rule of Fe_2O_3 in oxidized pellets, *J. Cent. South Univ. Sci. Technol*., 38(2007), No. 1, p. 70.