

Received July 16, 2019; reviewed; accepted October 25, 2019

## Effects and mechanism of Bayer red mud on co-reduction with a saprolitic laterite ore to prepare ferronickel

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**Abstract:** Co-reduction of a saprolitic laterite and waste Bayer red mud was investigated to prepare ferronickel powder. The synchronous reduction and comprehensive recovery of nickel and iron in the low-grade laterite ores and iron in the red mud were realized. At the red mud dosage of 50 wt%, ferronickel powder with nickel and iron grades of 5.58 wt% and 89.91 wt% was obtained. The corresponding nickel and total iron recoveries were 93.11 wt% and 90.23 wt%, respectively. The red mud enhanced the nickel recovery of the saprolitic laterite ore evidently, attributing to the formation of low-melting anorthite, omphacite, and diopside during co-reduction. This led that NiO in the saprolitic ore was released. Meanwhile, obvious melting phenomenon of the roasting system was appeared, enhancing the growth of the ferronickel particles.

**Keywords:** red mud, laterite ore, co-reduction, ferronickel powder

### 1. Introduction

Red mud (RM) is a hazardous waste produced vastly by aluminum industry worldwide (Borra, et al. 2016). The global residue inventory reached an estimated 3.5 billion tons in 2014 (Xue, et al. 2016), increasing by approximately 120 million tons per annum (Santini, et al. 2015). The appropriate management of red mud is becoming a global environmental concern following increased awareness of the need for environmental protection (Xue, et al. 2016). At present, the study on the utilization method of red mud is mainly divided into three kinds, including recovery of the valuable elements (Borra, et al. 2015; Borra, et al. 2016; Liu and Li; 2015; Xue, et al. 2016), production of construction materials (Dodoo-Arhin, et al. 2017; Liu and Poon 2016; Wang, et al. 2017), and gas purification and wastewater treatment (Bento, et al. 2016; Deihimi, et al. 2018; Wang, et al. 2008). However, overall, red mud is still transported to the damming for the wet storage yard. The utilization rate is still low, and the large scale utilization of red mud is still the main key of using red mud in the future.

Laterite ores especially saprolitic laterite ores are refractory nickel resources, the nickel and iron in which could be effectively recovered by the process of direct reduction followed by magnetic separation (Zheng, et al. 2014). Compared with rotary kiln-electric furnace (RKEF) process, direct reduction followed by magnetic separation was of low energy-consumption, as the nickel-bearing and iron-bearing minerals were reduced to metallic state below the melting point and then the generated ferronickel alloy was separated with slag through magnetic separation. A comparison of direct reduction followed by magnetic separation and high temperature smelting separation was carried out (Cao, et al. 2017). Results showed that the energy consumption of the former is 30 wt% lower than that of the latter. However, alkaline metal compounds usually must be added to enhance reduction of laterite ores (Liu, et al. 2015b; Wang, et al. 2016; Wang, et al. 2018).

Given the above-mentioned facts, a Bayer red mud was co-reduced with a low-grade saprolitic laterite ore followed by magnetic separation for preparation of the ferronickel powder in this current study. Co-reduction refers to the simultaneous reduction of nickel, iron in laterite ore and iron in red mud as far as possible. The effects of the red mud dosages, the reductant dosages, and the reduction temperature on co-reduction of the saprolitic laterite ore and red mud were investigated, and the roasting conditions were determined. XRD and SEM-EDS analysis were conducted to study the changes of mineral composition, migration and growth of metallic particles of co-reduced ores obtained under different conditions, thereby revealing the mechanism of co-reduction of the saprolitic laterite ore and the red mud.

## 2. Experimental

### 2.1. Materials

The saprolitic laterite ore was from the Philippines, and the sample has a high silica and magnesia content (Table 1). In Table 1, the meaning of TFe is the content of all iron elements in the corresponding ores. Fig. 1 shows the X-ray diffraction (XRD) analysis of the saprolitic laterite ore. The sample is mainly composed of silicate minerals, including clinochlore (A), nepouite (B), lizardite (C), and enstatite (G). And there is a small amount of goethite (F). Gangue minerals are primarily kaolinite (D) and quartz (E). The saprolitic laterite ore was crushed and screened to 100 wt% passing 0.5 mm.

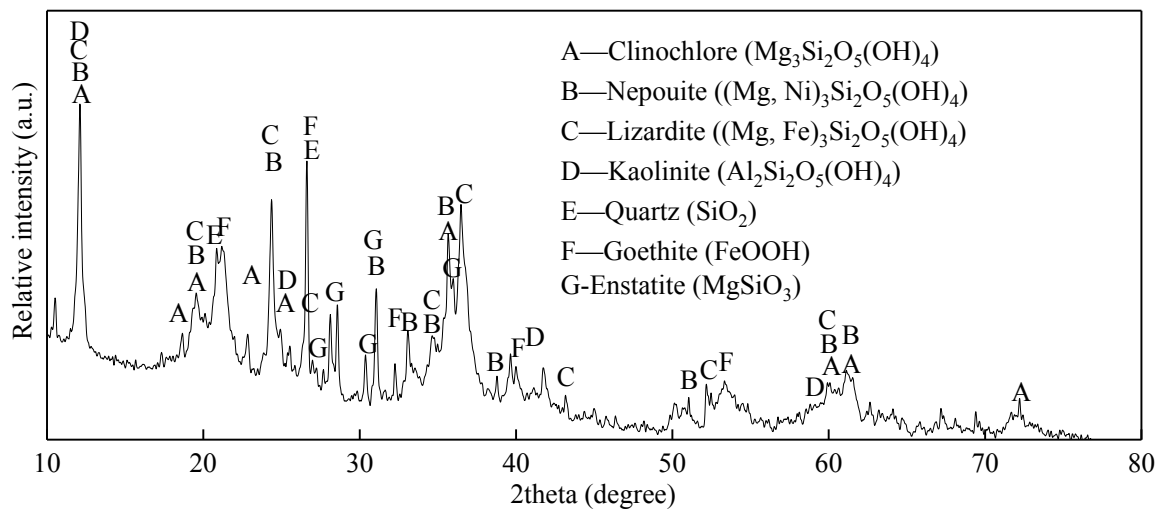


Fig. 1. XRD pattern of the saprolitic laterite ore

The chemical components of the Bayer red mud used are given in Table 1. The iron grade of red mud is 24.78 wt%, which is necessary to consider comprehensive recovery. The contents of CaO and Na<sub>2</sub>O are 13.94 wt% and 7.07 wt% respectively. Obviously, the content of alkaline earth metal elements in red mud is high. Fig. 2 shows the XRD analysis of the Bayer red mud. The main minerals of the Bayer red mud were hematite (Fe<sub>2</sub>O<sub>3</sub>), corundum (Al<sub>2</sub>O<sub>3</sub>), andradite (Ca<sub>3</sub>(Fe<sub>0.87</sub>Al<sub>0.13</sub>)<sub>2</sub>(SiO<sub>4</sub>)<sub>1.65</sub>(OH)<sub>5.4</sub>), calcite (CaCO<sub>3</sub>), and cancrinite (Na<sub>6</sub>Ca<sub>2</sub>Al<sub>6</sub>Si<sub>6</sub>O<sub>24</sub>(CO<sub>3</sub>)<sub>2</sub>). In other word, iron in the red mud was in the form of hematite and andradite, sodium existed mainly in the form of cancrinite, and calcium existed mainly in calcite, andradite and cancrinite.

Table 1. Main chemical components of the saprolitic laterite ore and the red mud (wt%)

Component	Ni	TFe	CaO	Na <sub>2</sub> O	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	Cr <sub>2</sub> O <sub>3</sub>
Laterite ore	1.69	15.71	0.76	-	41.44	3.93	20.42	-		0.49	1.39
Red mud	-	24.78	13.94	7.07	10.36	11.94	0.52	0.13	7.03	0.21	0.25

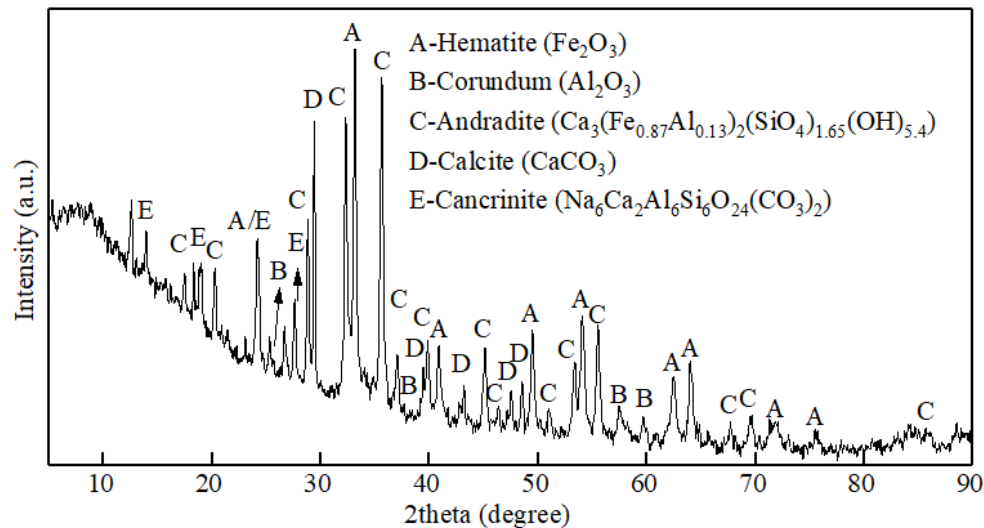


Fig. 2. XRD pattern of the Bayer red mud

Anthracite was used as the reductant, and the components of the coal sample used is given in Table 2. Anthracite was crushed and screened to 100 wt% passing 0.5 mm, which was easy to use in laboratory.

Table 2. Components of the anthracite used as a carbon source for reduction (wt%)

Component	Fixed Carbon	Volatiles	Ash	Moisture	Sulphur	Calorific value (MJ kg <sup>-1</sup> )
Content	82.38	3.48	11.66	2.48	0.37	29.60

## 2.2. Research methods

The material preparation before co-reduction was as follows: The 20 g saprolitic ore with the Bayer red mud and the anthracite in specific proportions was fully mixed. The dosages of anthracite and red mud were in weight of the saprolitic ore. The red mud dosages were varied in the range of 0 wt%-60 wt% and the anthracite dosages varied in the range of 6 wt%-12 wt%.

The co-reduction roasting of the saprolitic ore and the red mud were carried out as follows. The mix of saprolitic ore, the red mud, and the anthracite was placed in a graphite crucible and roasted in a FLM-1400 muffle furnace (Shengli Test Instrument Co., Ltd., Shanghai, China) at a set temperature. To guarantee the reduction atmosphere during co-reduction stage, the graphite crucible was covered. The purpose of the co-reduction stage was to achieve co-reduction of the nickel-bearing and iron-bearing ores in the saprolitic ore as well as the iron ores in the red mud, forming ferronickel phase in the co-reduced ores. According to the previous research, the ferronickel products can be obtained from a high-iron and low-nickel laterite ore by reduction and magnetic separation process when the co-reduction was conducted at 1200°C for 50 min. In this study, the co-reduction temperature and duration were also 1200°C and 50 min, respectively.

After natural cooling in the air, the co-reduced ores were crushed to particle size with a diameter less than 2 mm, and then processed by wet grinding in RK/BK triple-rollers and four-drums mill. Pulp density in grinding pulp is 60 % solid by weight. Because of the different grindability of co-reduced ores obtained under different roasting conditions, it is difficult to make different co-reduced ore reach the same grinding fineness. So here the grinding time was used instead of the grinding fineness. Subsequently, a CXG-99 magnetic tube (Handan Xuanyu New Building Materials Co., Ltd., Handan, China) was used to separate the ferronickel phase and the slag to prepare the ferronickel powder. The general standard in industry requires that nickel grade of low nickel-containing ferronickel powder product is more than 1.6 wt%, and iron grade is more than 85 wt%. Therefore, the minimum accepted value for nickel grade and iron grade in the obtained ferronickel powder are 1.6 wt% and 85 wt%, respectively. The magnetic field strength was 0.18 Tesla.

Nickel grade, nickel recovery, iron grade, and total iron recovery of the ferronickel powder were adopted as evaluation indices of co-reduction of the saprolitic ore and the red mud followed by magnetic separation. The total iron recovery of ferronickel powder was calculated based on the following formula:

$$\varepsilon_{Fe} = \frac{M_{FN} \cdot \beta_{FN}}{M_S \cdot \alpha_S + M_R \cdot \alpha_R} \quad (1)$$

where  $\varepsilon_{Fe}$  is the total iron recovery of ferronickel powder,  $M_{FN}$  is the mass of ferronickel powder,  $\beta_{FN}$  is the iron grade of ferronickel powder,  $M_S$  is the mass of the saprolitic ore,  $\alpha_S$  is the iron grade of the saprolitic ore,  $M_R$  is the mass of the added red mud based on its dosage,  $\alpha_R$  is the iron grade of the red mud.

### 2.3. XRD and SEM-EDS analysis

The XRD experiments were performed on a Japan Science Ultima IV diffractometer using Cu K $\alpha$  radiation ( $\lambda=0.15406$  nm) at an operation voltage of 40 kV and a current of 40 mA. The microstructure and particle size were determined using a scanning electron microscope (Zeiss EVO 18) equipped with energy dispersive spectroscopy (Quantax, Bruker, Germany).

## 3. Results and discussion

### 3.1. Effect of Bayer red mud dosages on co-reduction and magnetic separation

#### 3.1.1. Effect of Bayer red mud dosages on magnetic separation

The Bayer red mud dosages were tested under the conditions that the reduction temperature was 1200°C for 50 min and the anthracite dosage was 6 wt%. The co-reduction roasting-magnetic separation results under different dosages of the Bayer red mud are shown in Table 3. As shown in Table 3, the red mud enhances nickel recovery of the saprolitic laterite ore obviously.

Table 3. Effects of Bayer red mud dosages on co-reduction and magnetic separation (wt%)

Red mud dosages	Mix			Ferronickel powder			
	Iron grade	Nickel grade	Yield	Iron grade	Nickel grade	Total iron recovery	Nickel recovery
0	15.71	1.69	24.05	45.12	2.97	69.07	42.27
20	17.22	1.41	31.05	50.57	3.88	75.98	71.29
40	18.30	1.21	26.80	60.27	5.24	63.04	83.10
50	18.73	1.13	26.85	64.56	6.21	61.69	98.66
60	19.11	1.06	25.36	66.63	6.51	55.24	97.65

In the absence of the red mud, the iron and nickel grades of the ferronickel powder obtained are quite low, only 45.12 wt% and 2.97 wt%, respectively. And the corresponding recoveries are also low, just 69.07 wt% and 42.27 wt%, respectively. Along with increasing the red mud dosages from 0 wt% to 60 wt%, the nickel and iron grades are improved, the nickel recoveries are improved, and the total iron recoveries are initially improved and then reduced. At the red mud dosage of 50 wt%, the nickel recovery is highest, reaching to 98.66 wt%. The corresponding nickel and iron grade are 6.21 wt% and 64.56 wt%, respectively. And the total iron recovery is 61.69 wt%. Notably, the total iron recoveries are decreased when the red mud dosage is exceeding 20 wt%. It is due to that the red mud dosages are increased which leads to an increase of iron minerals that need to be reduced. However, the anthracite dosages remain constant, which could not provide sufficient reduction atmosphere. Additionally, Ni is primarily reduced before the iron; thus, based on the reduction period, the total iron recovery is decreased.

In order to consume the red mud as much as possible, the Bayer red mud dosage is determined to be 50 wt%.

### 3.1.2. Effect of Bayer red mud dosages on mineral transformation

The effect of the red mud dosages on the mineral compositions of the co-reduced ores are performed, as shown in Fig. 3. Obviously, the mineral compositions of the co-reduced ores are different in the absence and presence of the red mud.

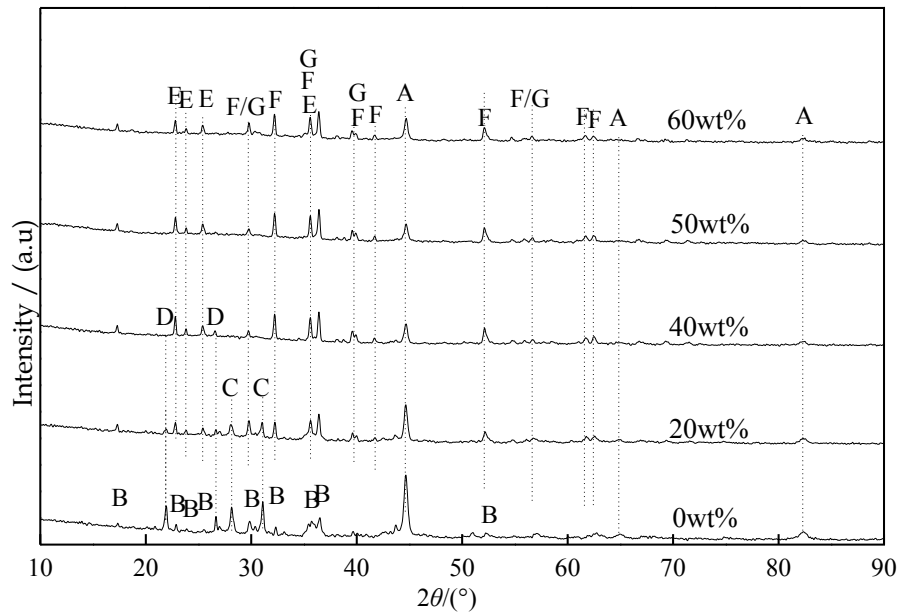


Fig. 3. XRD patterns of the co-reduced ores as a function of different red mud dosages: A - Kamacite (Ni, Fe); B - Forsterite ( $\text{Mg}_2\text{SiO}_4$ ); C - Enstatite ( $\text{MgSiO}_3$ ); D - Quartz ( $\text{SiO}_2$ ); E - Anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ); F - Omphacite ( $\text{NaCaMgAl}(\text{Si}_2\text{O}_6)_2$ ); G - Diopside ( $\text{CaMgSi}_2\text{O}_6$ )

In the absence of the red mud, the main phase is the kamacite (A), and there is also a small amount of forsterite (B), enstatite (C), and quartz (D). Previous research has suggested that NiO and FeO would combine with free quartz during reduction roasting to form olivine, which leads to further reduction difficulties (Liu, et al. 2015a). Thus, in the absence of the red mud, the nickel recovery is only 42.27 wt% and the iron recovery just 69.07 wt% (Table 3).

With 20 wt% red mud, the phase of the co-reduced ore is still mainly the kamacite (A), and still has a small amount of enstatite (C) and quartz (D). However, the forsterite (B) disappears, and the anorthite (E), omphacite (F), and diopside (G) appear. In addition, the enstatite (C) disappears with increasing the red mud dosage to 40 wt%, and the quartz disappears at the red mud dosage of 50 wt%. With increasing the red mud dosage from 20 wt% to 60 wt%, the peaks of anorthite (E), omphacite (F), and diopside (G) are enhanced.

According to the phase transformation, the reason why red mud significantly improves the recovery of nickel from the saprolitic laterite ore during the co-reduction process is as follows. CaO, Na<sub>2</sub>O, and Al<sub>2</sub>O<sub>3</sub> in the red mud react with the chemical components "SiO<sub>2</sub> and MgO" in the laterite ore during the co-reduction process, forming new phases "anorthite (E), omphacite (F), and diopside (G)". Meanwhile, NiO in the laterite ore are released, enhancing the reduction of the laterite ore. The synchronized reduction and comprehensive recovery of the iron oxide in the mix of the saprolitic ore and the red mud can be realized under further optimized reduction conditions. Thus, in the presence of the 50 wt% red mud, the ferronickel powder with nickel grade of 6.21 wt% and nickel recovery of 98.66 wt% is obtained (Table 3).

### 3.1.3. Effect of Bayer red mud dosages on microstructure of the co-reduced ores

To further reveal the effect mechanism of the red mud dosages on co-reduction of the saprolitic ore and the red mud, the microstructure of the co-reduced ores with the red mud dosages was analyzed, as shown in Fig. 4. Figs. 4(a)-(e) are the microstructure of the co-reduced ore and Figs. 4 (a') to (e') are the magnified view of the marked areas in the Figs. 4 (a)-(e).



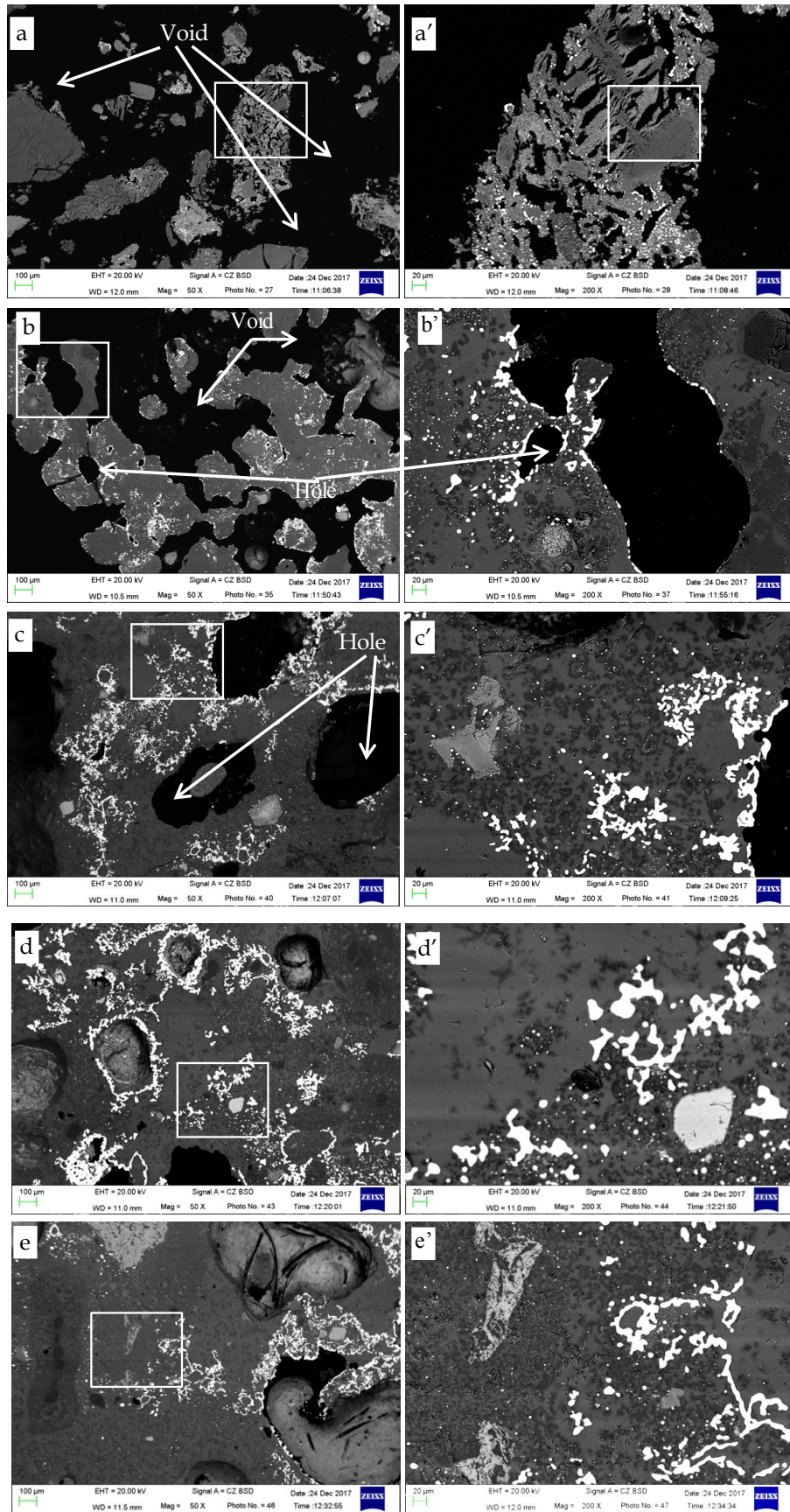


Fig. 4. SEM of the co-reduced ores as a function of different red mud dosages: (a, a') 0 wt%; (b, b') 20 wt%; (c, c') 40 wt%; (d, d') 50 wt%; (e, e') 60 wt%

As shown Figs. 4 (a) and (a'), in the absence of the red mud, the roasted ore has no melting phenomenon. There are particles of different sizes in the roasted ore, and there are voids between particles and particles. Lots of the white-bright ferronickel particles belong to micro disseminated tectonic in the gangue and do not assemble in large particles, staying at the original position. The size of the ferronickel particles is generally in the range of 0-10  $\mu\text{m}$ .

Figs. 4 (b)-(e) show that, with increasing the red mud dosage, the co-reduced ores gradually bond together to form a whole with holes distributed among it. The appearance of holes may be due to the liquid phase substances that hinder the diffusion of the reducing agent generated from anthracite gasification. The obvious melting phenomenon of the co-reduced ores occurs and the melting intensifies, which indicates that the liquid phase of roasting system increases in the presence of red mud and increasing the red mud dosage. This is consistent with the appearance of diffraction peaks of anorthite (E), omphacite (F), and diopside (G) with low melting point in the co-reduced ores (Fig. 3). Increase of the liquid phase can promote aggregation of the metal phase (Li, et al. 2015). Therefore, here, the addition of the red mud can enhance the aggregation and growth of the ferronickel particles, as shown in Figs. 4 (b')-(e'). The ferronickel particles have obvious boundaries with gangue minerals. In the presence of 50 wt% the red mud, the size of the ferronickel particles is generally in the range of 20-30  $\mu\text{m}$  (Fig. 4 (d')). These explain the phenomenon that the nickel and iron grades of the ferronickel powder increase with an increase of the red mud dosage from 0 wt% to 50 wt% (Table 3).

To sum up, during the co-reduction process, the alkaline components in the red mud take part in the reaction of roasting system, forming low melting point minerals and releasing the nickel oxide. Meanwhile, the liquid phase of roasting system increases, thus enhancing the reduction of nickel in the saprolitic laterite ore.

### 3.2. Effect of anthracite dosages on co-reduction and magnetic separation

In order to comprehensively recover nickel and iron in the saprolitic ore and iron in the red mud and ensure total iron recovery, the effect of anthracite dosage on co-reduction was investigated in the presence of 50 wt% the red mud. The reduction temperature was 1200°C and the duration was 50 min.

#### 3.2.1. Effects of the anthracite dosage on magnetic separation

In the presence of 50 wt% the red mud, the effects of anthracite dosages on co-reduction followed by magnetic separation in the range of 6 wt%-12 wt% at 1200°C for 50 min are shown in Table 4.

Table 4. Effects of the anthracite dosages on co-reduction and magnetic separation (wt%)

Anthracite dosages	Mix			Ferronickel powder			
	Iron grade	Nickel grade	Yield	Iron grade	Nickel grade	Total iron recovery	Nickel recovery
6			26.85	64.56	6.21	61.69	98.66
9	18.73	1.13	35.65	60.23	4.00	76.41	84.38
12			39.05	58.94	3.53	81.91	81.57

When the anthracite dosages are increased from 6 wt% to 12 wt%, the total iron recoveries are improved. This indicates that an increase of the anthracite dosage is favorable to achieving recovery of the iron from the saprolitic ore and the red mud synchronously as much as possible. It is due to that the increase of the anthracite dosage enhances the reduction atmosphere and strengthened the reduction of iron minerals in the mix of the saprolitic ore and the red mud. Thus, the anthracite dosage is determined to be 12 wt% to obtain ferronickel powder with nickel grade of 3.53 wt%, nickel recovery of 81.57 wt%, iron grade of 58.94 wt%, and total iron recovery of 81.91 wt%.

With increasing the anthracite dosages, the nickel grade and iron grade diminish. Researches (Li, et al. 2011, Wang, et al. 2011) have indicated that in the direct reduction process, increasing the reductant dosages would result in that the metal particles can be difficult to gather and grow. Therefore, here, increasing the anthracite dosages is unfavorable to aggregation of the ferronickel particles. The



intergrowth particles of fine ferronickel and gangue are separated into the ferronickel powder through the magnetic separation, resulting in the decline of nickel and iron grade of ferronickel powder; or the intergrowth particles are separated into the tailing, leading to low nickel and total iron recovery. However, nickel recovery diminishes as the anthracite dosage increases. The reason for this phenomenon is as follows: Nickel is derived from the saprolitic ore, and the nickel grade of the saprolitic ore is low. Nickel is mainly distributed in serpentine of the saprolitic ore. Iron is derived from two kinds of materials: the red mud and the saprolitic laterite ore. There is a significant difference between the distributions of nickel and iron. The reduction of nickel must be carried out with metallic iron as the carrier to form ferronickel alloy particle, so that the nickel could be recovered through magnetic separation. With increasing the anthracite dosages, the residual carbon increases; meanwhile, the ash originated from the anthracite is increased. These are not conducive to the aggregation and growth of the ferronickel particles, leading to the reduction of the nickel recovery. To further reveal the reason for the decrease of nickel recovery with increasing the anthracite dosages, the microstructures of the co-reduced ores as a function of different anthracite dosages would be analyzed.

### 3.2.2 Effect of anthracite dosages on microstructure of the co-reduced ores

To reveal the mechanism of anthracite dosages on co-reduction, the microstructure analysis of the co-reduced ore obtained as a function of different anthracite dosages is carried out, as shown in Fig. 5.

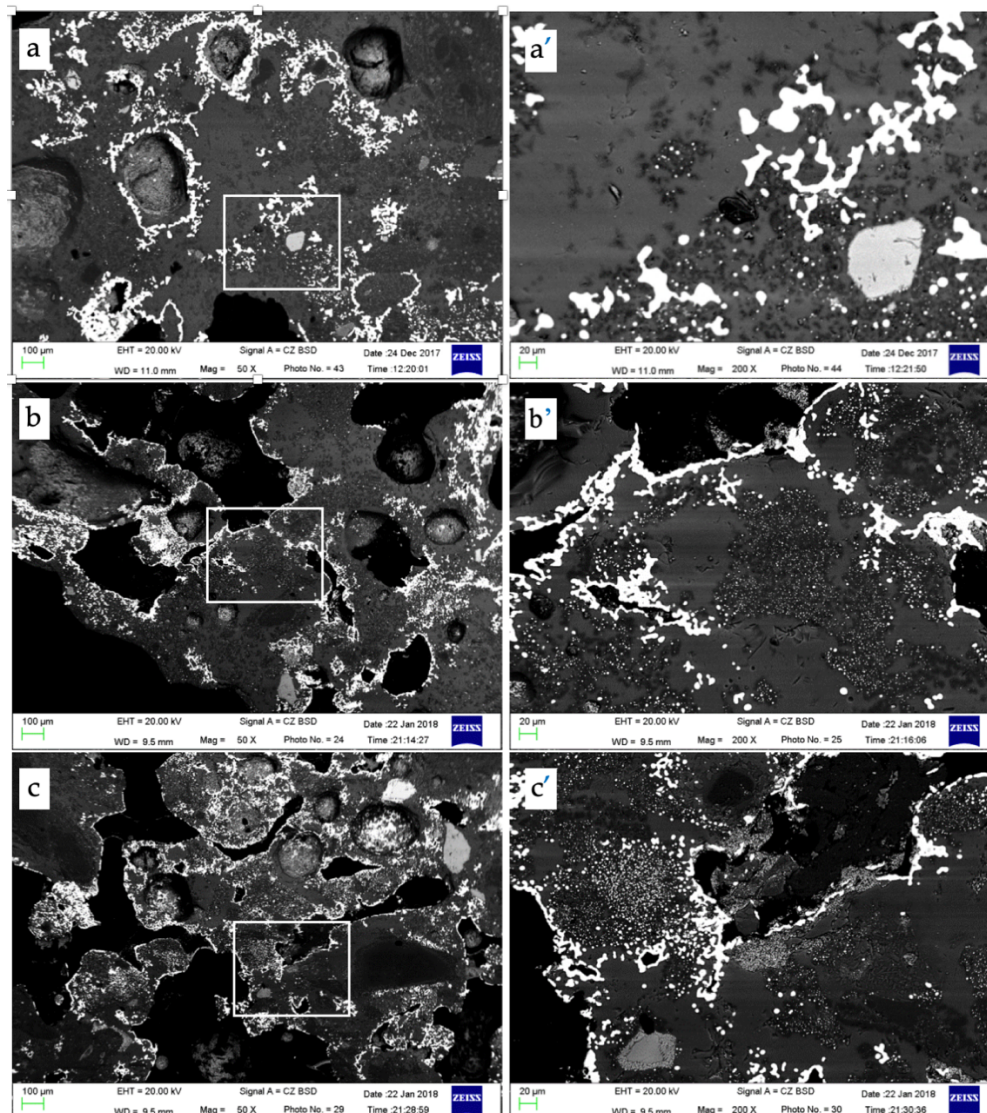


Fig. 5. SEM of the co-reduced ores as a function of different anthracite dosages: (a, a') 6 wt%; (b, b') 9 wt%; (c, c') 12 wt%



Figs. 5 (a') to (c') are the magnified view of the marked areas in the Figs. 5 (a) - (c). With increasing the anthracite dosages from 6 wt% to 12 wt%, the average particle size of bright-white ferronickel particles decreases and the number of fine ferronickel particles increases, which explains the phenomenon on decrease of the nickel and iron grades of ferronickel powders. In addition, at the anthracite dosage of 12 wt%, lots of bright-white ferronickel particles are micro-disseminated in gangue minerals, so the recovery of nickel decreases to 81.57 wt%.

### 3.3. Effect of reduction temperature on co-reduction and magnetic separation

Research has shown that the increase in reduction temperature favors the cohesion between nickel and iron as well as the growth of metallic crystal particles (Li, et al. 2013). To improve nickel and iron grades and recoveries, the iron grade and the total iron recovery in the ferronickel powder, the effect of reduction temperature on reduction was tested.

#### 3.3.1 Effect of reduction temperature on magnetic separation

In the presence of 50 wt% the red mud and at the anthracite dosage of 12 wt%, the effects of reduction temperature in the range of 1200°C to 1300°C on co-reduction followed by magnetic separation is studied, as shown in Table 5.

Table 5. Effects of reduction temperature on co-reduction and magnetic separation (wt%)

Reduction temperature (°C)	Mix		Yield	Ferronickel powder			
	Iron grade	Nickel grade		Iron grade	Nickel grade	Total iron recovery	Nickel recovery
1200			39.05	58.94	3.53	81.91	81.57
1250	18.73	1.13	36.35	64.81	4.25	83.84	91.41
1300			34.40	74.84	4.80	91.62	97.70

With increasing the reduction temperature from 1200°C to 1300°C, the nickel and iron grades, and the nickel and iron recoveries all increase. This indicates that increasing the reduction temperature improves co-reduction effects. At the reduction temperature of 1300°C, a ferronickel powder with nickel and iron grades of 4.80 wt% and 74.84 wt% is obtained, respectively. And the corresponding nickel and iron recoveries are 97.70 wt% and 91.62 wt%, respectively.

#### 3.3.2 Effect of reduction temperature on microstructure of the co-reduced ores

In order to reveal the mechanism of reduction temperature on co-reduction, the microstructure analysis of the co-reduced ore obtained as a function of different reduction temperature is performed, as shown in Fig. 6. From Fig. 6, the melting phenomenon of co-reduced ores intensifies with the increase of reduction temperature, which indicates that the liquid phase content in the roasting system increases. This improves the environment for the migration and growth of ferronickel particles, thus improving the co-reduction effect and thereby improving the nickel grade, iron grade, nickel recovery and total iron recovery in ferronickel powder.

### 3.4. Effect of the second-stage grinding on magnetic separation

In the presence of 50 wt% the red mud, at the anthracite dosage of 12 wt%, and at the reduction temperature of 1300°C, the sum of nickel grade (4.80 wt%) and iron grade (74.84 wt%) of the ferronickel powder obtained is only 79.64 wt%, indicating that there are still higher impurities in the ferronickel powder. To decrease the impurity content of the ferronickel powder, secondary grinding and magnetic separation was studied.

At the first-stage grinding time of 15 min, a grinding fineness of - 0.074 mm accounts for 63.98 wt%. When the secondary grinding time is 5 min, 10 min, and 15 min, the fineness of the secondary grinding of - 0.074 mm accounts for 74.16 wt%, 82.63 wt%, and 87.49 wt% respectively. The secondary magnetic

field strength was also 0.18 Tesla. The effect of the secondary grinding on co-reduction followed by magnetic separation is shown in Table 6.

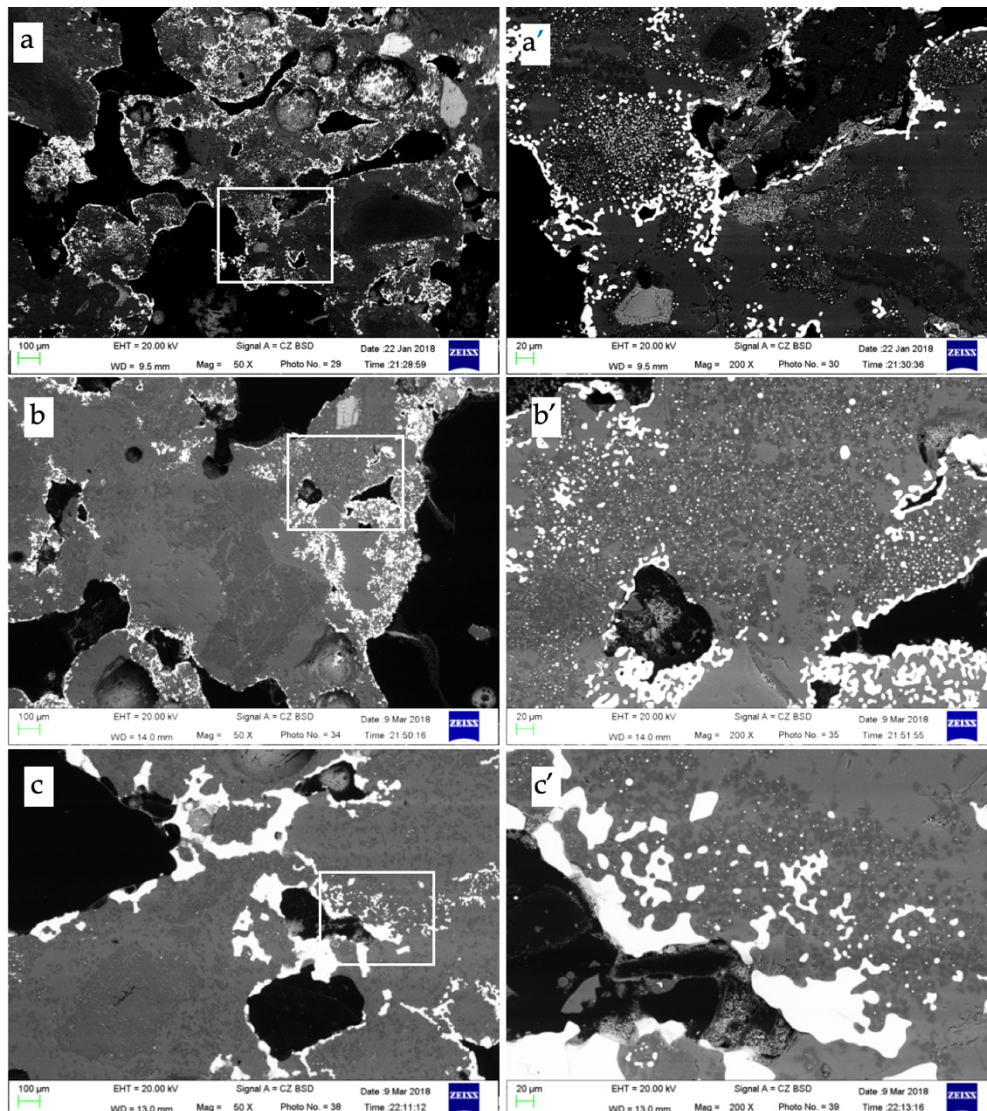


Fig. 6. SEM of the co-reduced ores as a function of different reduction temperature: (a, a') 1200°C; (b, b') 1250°C; (c, c') 1300°C

Table 6. Effects of secondary grinding fineness on co-reduction and magnetic separation (wt%)

Secondary grinding fineness (-0.074 mm)	Mix			Ferronickel powder			
	Iron grade	Nickel grade	Yield	Iron grade	Nickel grade	Total iron recovery	Nickel recovery
No			34.40	74.84	4.80	91.62	97.70
74.16	18.73	1.13	30.65	83.14	5.15	90.68	93.40
82.63			28.20	89.91	5.58	90.23	93.11
87.49			27.30	90.22	5.73	87.65	92.56

Table 6 shows that with the increase of the fineness of the secondary grinding, the iron and nickel grade of ferronickel powder obtained increase, and the total iron recovery and nickel recovery decrease to a certain extent. Increasing of fines in feed resulted in mineral liberation and in such way in gradually decreasing of mass yield into ferronickel powder (magnetic product) at given field intensity. Thus,

particles of best quality only are caught in ferronickel powder (magnetic product), and then recoveries of iron and nickel decrease. When the secondary grinding fineness of  $-0.074$  mm accounts for 82.63 wt%, a ferronickel powder with nickel grade of 5.58 wt%, iron grade of 89.91 wt%, nickel recovery of 93.11 wt% and total iron recovery of 90.23 wt% is obtained. The remaining part of the ferronickel powder and the main chemical components of the corresponding obtained slag as well as their content are shown as Table 7. The remaining part of the ferronickel powder are mainly  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$ , whose content are 1.83 wt%, 0.50 wt%, and 1.44 wt%, respectively. The main components of the corresponding slag are also  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{MgO}$ , whose content are 46.22 wt%, 10.74 wt%, and 18.85 wt%, respectively. And the contents of  $\text{CaO}$  in the slag and  $\text{Na}_2\text{O}$  are 9.03 wt% and 3.89 wt%, respectively.

Table 7. Main chemical components of ferronickel powder and slag (wt%)

Component	Ni	TFe	CaO	$\text{Na}_2\text{O}$	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	MgO	$\text{K}_2\text{O}$	$\text{TiO}_2$	MnO	$\text{Cr}_2\text{O}_3$	$\text{SO}_3$
Ferronickel powder	5.58	89.91	0.19	0.14	1.83	0.50	1.44	-	0.07	0.02	0.12	-
Slag	0.14	3.26	9.03	3.89	46.22	10.74	18.85	0.08	4.16	0.52	1.61	0.41

In sum, during co-reduction of the saprolitic ore and the red mud, the simultaneous reduction and comprehensive recovery of nickel and iron in the saprolitic ore and iron in the red mud can be realized. During co-reduction, the red mud enhanced the reduction of the saprolitic laterite ore obviously. The reason is as follows.  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{Al}_2\text{O}_3$  in the red mud react with the chemical components " $\text{SiO}_2$  and  $\text{MgO}$ " in the laterite ore during the co-reduction process, forming new phases "anorthite (E), omphacite (F), and diopside (G)". Meanwhile,  $\text{NiO}$  in the laterite ore are released, improving the reduction of the laterite ore. Furthermore, obvious melting phenomenon of the roasting system appears, enhancing the growth of the ferronickel particles. In addition, increasing the reduction temperature was also favorable to aggregation and growth of ferronickel particles.

#### 4. Conclusions

Co-reduction conditions followed by magnetic separation of the saprolitic laterite ore and the red mud are determined and as follows. The red mud dosage is 50 wt%, the anthracite dosage is 12 wt%, and the reduction temperature is  $1300^\circ\text{C}$  for 50 min. The first grinding fineness of  $-0.074$  mm accounts for 63.98 wt%, the secondary grinding fineness of  $-0.074$  mm accounts for 82.63 wt%, and the first and secondary magnetic field strength are both 0.18 Tesla. A ferronickel powder with nickel grade of 5.58 wt%, iron grade of 89.91 wt%, nickel recovery of 93.11 wt% and total iron recovery of 90.23 wt% is obtained.

The red mud has a great effect on enhancing nickel recovery of the saprolitic laterite ore, attributing to the formation of low-melting anorthite, omphacite, and diopside during co-reduction. It led to that  $\text{NiO}$  in the saprolitic ore was released, improving the reduction of the saprolitic ore. Meanwhile, obvious melting phenomenon of the roasting system appeared, enhancing the growth of the ferronickel particles. Furthermore, increasing the reduction temperature was also favorable to aggregation and growth of ferronickel particles.

#### Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51874017) and the Inner Mongolia University of Science and Technology Innovation Fund (2019QDL-B28).

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