

# Mechanism of sodium sulfate in promoting selective reduction of nickel laterite ore during reduction roasting process



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## ABSTRACT

A high nickel grade ferronickel was produced from laterite ore using the selective reduction-wet magnetic separation process, with the addition of sodium sulfate ( $\text{Na}_2\text{SO}_4$ ). The ferronickel concentrate assaying 9.87% Ni, with a nickel recovery of 90.90% can be obtained, when laterite ore was reduced at 1200 °C for 50 min with the addition of 10 wt.%  $\text{Na}_2\text{SO}_4$  and 2 wt.% coal. Based on the results of the X-ray Diffraction, Scanning Electron Microscopy, and Energy Dispersive X-ray Spectroscopy analyses, the thermal decomposition and reduction reaction of  $\text{Na}_2\text{SO}_4$  were carried out. Sodium oxide from the thermal decomposition of  $\text{Na}_2\text{SO}_4$  reacted with silicate minerals to form nepheline. The formation of the molten phase accelerated the migration rate of the metallic particles and suppressed the reduction of the ferrous minerals in the weak reduction atmosphere. Sulfur reacted with metallic iron to form troilite, thereby facilitating the aggregation of ferronickel particles to form bigger particles.

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## 1. Introduction

Nickel laterite ore is divided chemically and physically into two distinct types, namely, saprolitic (silicate/hydrosilicate) and limonitic (oxide/hydroxide) ores (Rhamdhani et al., 2009). The nickel in the nickel laterite ore is closely associated with iron oxide and silicate minerals as isomorphous substitution for iron and magnesium in the lattice (Dalvi et al., 2004; Mskalyk and Alfantazi, 2002). Laterites cannot be beneficiated via physical methods because of their complex mineralogy. Thus, the pyrometallurgical method has been applied commercially to extract nickel from the nickel the laterite ore. Pyrometallurgical techniques have been used to treat saprolitic laterite to produce ferronickel concentrate or nickel matte (King, 2005; Kyle, 2010). However, this method is energy intensive during the production of ferronickel concentrate from laterite ores because it involves two high temperature steps: pre-reduction at 850 °C to 1000 °C, followed by smelting at 1500 °C to 1600 °C, in an electric furnace to separate the ferronickel from the silica-magnesia slag (Norgate and Jahanshahi, 2011). Therefore, an alternative route of direct reduction followed by physical separation with less energy consumption has been suggested. The proposed process is an easy and environmentally friendly technique, and exhibits selective extraction of nickel over iron. The ferronickel

concentrate obtained from this process can be directly used to make stainless steels.

Recently, several investigations on the reduction roasting of nickel laterite ore followed by magnetic separation to produce ferronickel concentrate have been performed. Kim et al. have investigated the concentration of nickel from low-grade laterite (Ni 1.50%, TFe 22.33%) using calcination at 500 °C for 1 hour and wet magnetic separation. He showed that the nickel grade increased from 1.5% to 2.9%, but the nickel recovery was only 48% (Kim et al., 2010). Li et al. have extracted nickel from low-grade nickel laterite ore (Ni 1.09%, TFe 9.16%) using a solid-state deoxidization method (Li et al., 2012a,b). A ferronickel concentrate with a nickel grade of 4.50% and recovery of 80.00% has been obtained. However, these studies have not obtained ferronickel concentrate with high nickel grade (>8%) via reduction roasting and magnetic separation without additives.

Reduction roasting with additives for obtaining high nickel grade ferronickel concentrate has recently become a hot research topic. Cao et al. studied the reduction roasting-magnetic separation process of low-grade nickel laterite ores, with Ni 1.86% and Fe 13.59%. He found that effective reduction occurred, and the ferronickel concentrate containing 10.83% Ni, with a nickel recovery of 82.15%, was obtained. The reduction was carried out at 1200 °C for 40 min, with the addition of 20%  $\text{Na}_2\text{CO}_3$  and 15% coal (Cao et al., 2010; Sun et al., 2011). Zhu et al. conducted selective reduction and wet magnetic separation of nickel laterite ores (Ni 1.42%, Fe 23.16%) at 1100 °C for 60 min, with the addition of 6% calcium sulfate and 5% coal. The experiments showed that the nickel grade of the ferronickel concentrate could reach up to 6.00%, with a nickel recovery of 92.10% (Zhu et al., 2012). Li et al. reported that the nickel grade and recovery of ferronickel were 9.48%

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and 83.01%, respectively, when the nickel laterite (Ni 1.91%, Fe 22.10%) was reduced at 1100 °C for 60 min with the addition of 20% sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) (Li et al., 2012a,b).

The reaction mechanism of the selective reduction of nickel laterite ore has also been investigated recently. A number of researchers suggested that the selectivity of reduction depends mainly on the reduction atmosphere and silica level; the presence of sulfur (S) significantly promotes ferronickel particle growth to improve nickel enrichment in the metallic phases (Zhu et al., 2012). However, another researcher reported that the reduction of ferrous minerals in the presence of  $\text{Na}_2\text{SO}_4$  was not inhibited by the formation of fayalite or forsterite, whereas the decrease of iron metallization was attributed to the formation of troilite (FeS) (Li et al., 2012a,b).

According to the aforementioned studies, relatively few studies have carried out the reduction roasting process of nickel laterite ore with high iron grade of over 30%. In their research, Jiang et al. (2012) obtained a ferronickel concentrate with a nickel grade of 9.52% and a recovery of 84.04% from high iron grade laterite ore (Ni 1.49%, TFe 34.69%) using selective reduction and magnetic separation process, with the addition of 7%  $\text{Na}_2\text{SO}_4$  at 1200 °C for 50 min. However, the mechanism of  $\text{Na}_2\text{SO}_4$  that affects the selective reduction of nickel laterite was not investigated.

In the current study, extracting ferronickel concentrate from nickel laterite ore was carried out using the reduction roasting and magnetic separation processes, with the addition of  $\text{Na}_2\text{SO}_4$ . The phase and microstructure transformation of nickel laterite ore in the reduction process were investigated using X-ray Diffraction Analysis (XRD) and Scanning Electron Microscopy with X-ray Energy Dispersive Spectrum (SEM-EDS). Moreover, the effects of different additives were also observed.

## 2. Materials and methods

### 2.1. Raw material

The chemical analysis of the nickel laterite ore from Philippines was determined by X-ray Fluorescence, as shown in Table 1. The distribution of nickel in the laterite ore was obtained using the chemical phase analysis methodology, as shown in Table 2, in which 95.94% of nickel is associated with silicates. Thus, the laterite used belongs to the saprolitic laterite ore.

The sodium sulfide ( $\text{Na}_2\text{S}$ ), sodium oxide ( $\text{Na}_2\text{O}$ ), S, and  $\text{Na}_2\text{SO}_4$  used in the study were of chemical grade. Bituminous coal was used as reductant. The proximate analysis of the coal shows that fixed carbon, ash, volatile matter, and S content are of 30.65%, 46.36%, 23.00%, and 2.32%, respectively.

### 2.2. Experimental methods

The nickel laterite ore was crushed to 95 wt.% passing 4 mm. The crushed laterite sample was thoroughly mixed with different additives (the amount of additive varied from 0 wt.% to 10 wt.%) and 2% soft coal. The laterite mixture, additive, and coal were placed in a graphite crucible, in which the reducing atmosphere could be maintained. The crucible was then placed into a muffle furnace chamber at 1200 °C, and then withdrawn after 50 min.

**Table 1**  
Chemical analysis of laterite ores.

	Fe <sub>total</sub>	Ni	MgO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	MnO	SO <sub>3</sub>
Content wt.%	34.69	1.49	12.28	20.05	3.03	2.27	1.34	0.37
	Co <sub>2</sub> O <sub>3</sub>	RuO <sub>2</sub>	CaO	ZnO	TiO <sub>2</sub>	V <sub>2</sub> O <sub>5</sub>	LOI	
Content wt.%	0.28	0.2	0.15	0.05	0.05	0.03	23.72	

**Table 2**  
Nickel distribution ratio at different phases in the raw ore.

Existential phases	Sulfides	Oxides	Silicates	Total
Nickel grade (%)	0.012	0.048	1.43	1.49
Fraction (%)	3.25	0.81	95.94	100.00

The roasted ore was cooled to room temperature and ground to about 90.00 wt.% passing 0.043 mm in a rod mill. The slurry was separated in a CXG-99 Davies Magnetic Tube at a magnetic field intensity of 0.18 T. The magnetic product obtained was referred to as ferronickel concentrate. Nickel grade, nickel recovery, and iron recovery in the ferronickel concentrate were used to determine the effect of selective reduction on the final ferronickel concentrate.

### 2.3. XRD and SEM-EDS analysis

XRD patterns were recorded using a diffractometer (Rigaku D/Max 2500, Japan) under the following conditions: radiation Cu K $\alpha$  of 150 mA, tube current and voltage of 40 kV, scanning range of 10° to 90°, step size of 0.02°, and scanning speed of 5°/min. Polished sections were prepared to observe the morphological changes and analyze the element content of the reduced products using Scanning Electron Microscopy (Carl Zeiss EVO18, Germany) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector (Bruke XFlash Detector 5010, Germany). ESEM images were recorded in backscatter electron modes operating in low vacuum mode at 20 kV.

## 3. Results and discussion

Our results show that the nickel grade of the ferronickel concentrate increased from 3.69% to 9.52% and the nickel recovery increased to 84.04% with the addition of 7%  $\text{Na}_2\text{SO}_4$ , in contrast to those ferronickel concentrate without additive (Jiang et al., 2012). Thus, the enrichment of nickel in ferronickel concentrate is more effective in the presence of  $\text{Na}_2\text{SO}_4$ .

The products of thermal decomposition and reducing reaction of  $\text{Na}_2\text{SO}_4$ , including  $\text{Na}_2\text{S}$ ,  $\text{Na}_2\text{O}$ , and S, were used as additives to be mixed with laterite ores to investigate the mechanism of  $\text{Na}_2\text{SO}_4$  that affects the selective reduction of the nickel laterite ore. The mixtures were roasted at 1200 °C for 50 min with the addition of 2% coal as reductant. The results can determine whether  $\text{Na}_2\text{SO}_4$  produces the thermal decomposition and reduces the reaction in the reduction roasting process.

### 3.1. Effect of different additives on nickel grade and recovery

The magnetic separation results of the roasted ore with the addition dosage ranging from 0% to 10% are shown in Fig. 1. The additives are  $\text{Na}_2\text{S}$ ,  $\text{Na}_2\text{O}$ , S, and  $\text{Na}_2\text{SO}_4$ , respectively.

With the increase of  $\text{Na}_2\text{S}$  dosages to 10% as shown in Fig. 1, the nickel grade exhibited a significant improvement, from 3.69% to 10.86%; nickel recovery also increased to 92.09%. However, the additive dosage further increased the results in a corresponding decrease of nickel recovery, from 92.09% to 88.56%. A sharp decrease in iron recovery from 62.39% to 24.62% was also observed. These results prove that the effect of  $\text{Na}_2\text{S}$  on the enrichment and recovery of nickel is efficient.

The experimental results of different S dosages show that the nickel grade of ferronickel concentrate increased to 7.21% although the nickel and iron recovery decreased sharply from 82.47% to 73.07% and 62.39% to 29.43%. The decrease in iron recovery indicates that S significantly affects the selective reduction of the nickel laterite ore.

The nickel grade increased marginally from 3.69% to 4.62% when the dosage of  $\text{Na}_2\text{O}$  was up to 10%, as shown in Fig. 1(c). The nickel recovery increased significantly from 82.47% to 96.35%, whereas

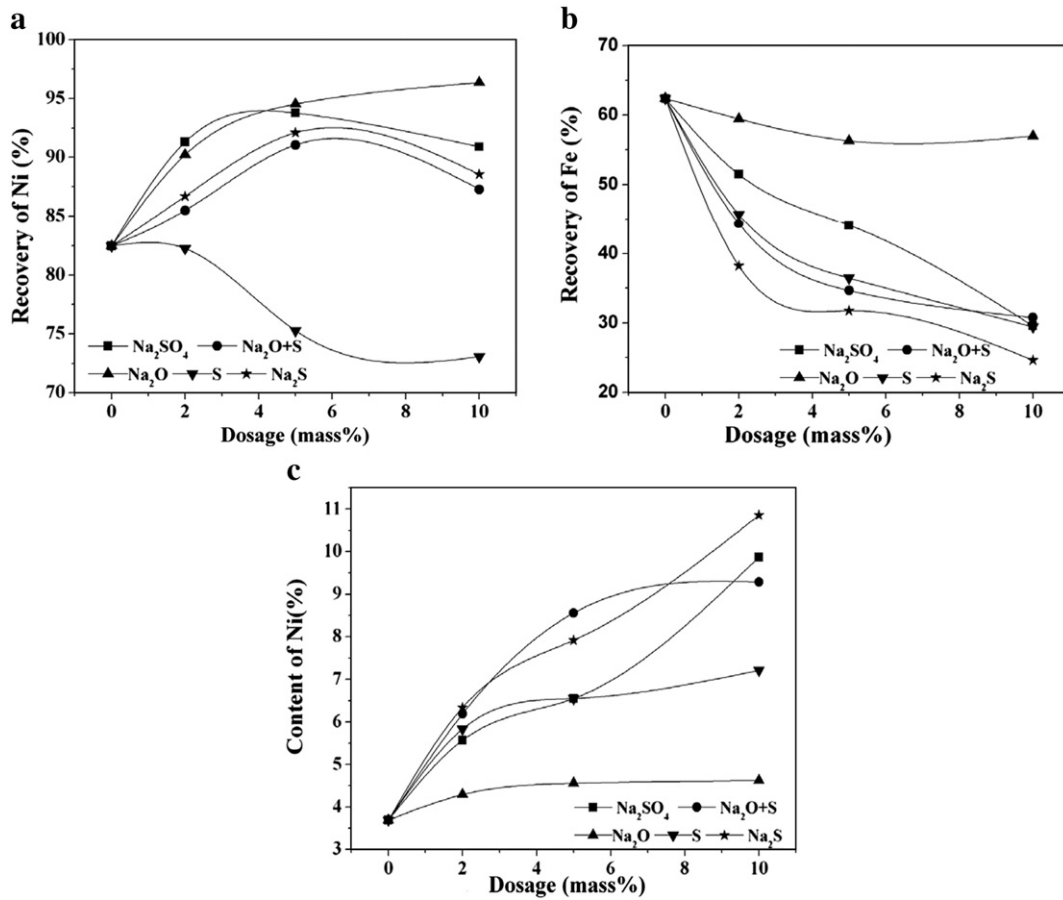


Fig. 1. Effect of different additives on grade and recovery of nickel and iron in ferronickel concentrate: (a) nickel recovery, (b) iron recovery, (c) nickel grade.

iron recovery decreased from 62.39% to 56.98%. Thus, Na<sub>2</sub>O increases nickel recovery.

The results in Fig. 1 also show that the variation trend of the grade and the recovery of nickel and iron with the addition of Na<sub>2</sub>O and S mixture is similar to that with Na<sub>2</sub>S and Na<sub>2</sub>SO<sub>4</sub>, respectively. When the Na<sub>2</sub>S and Na<sub>2</sub>SO<sub>4</sub> dosages were increased to 10%, the nickel grade increased to 9.87% and 9.29%, nickel recovery were 90.90% and 87.29%, and iron recovery decreased to 29.55% and 30.76%, respectively.

Therefore, a high nickel grade ferronickel concentrate can be produced from high iron grade laterite ore using the reduction roasting and magnetic separation processes, in the presence of Na<sub>2</sub>S, Na<sub>2</sub>SO<sub>4</sub>, or the mixture of Na<sub>2</sub>O and S.

### 3.2. Phase transformation and microstructure of the roasted ore

Laterite ore was mixed with reductant and additives, as were listed in Table 3. The reduction roasting process of the mixture was described as Section 2.2. And then the roasted ores were prepared for XRD analysis and microscopic analysis. To illustrate the mineral components and the

Table 3  
Composition of the ore mixtures with different additives (wt.%).

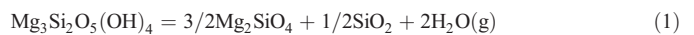
Symbol	Laterite ore	Coal	Additives			
			Na <sub>2</sub> O	S	Na <sub>2</sub> S	Na <sub>2</sub> SO <sub>4</sub>
(a)	100	2	–	–	–	–
(b)	100	2	10	–	–	–
(c)	100	2	–	10	–	–
(d)	100	2	10	10	–	–
(e)	100	2	–	–	10	–
(f)	100	2	–	–	–	10

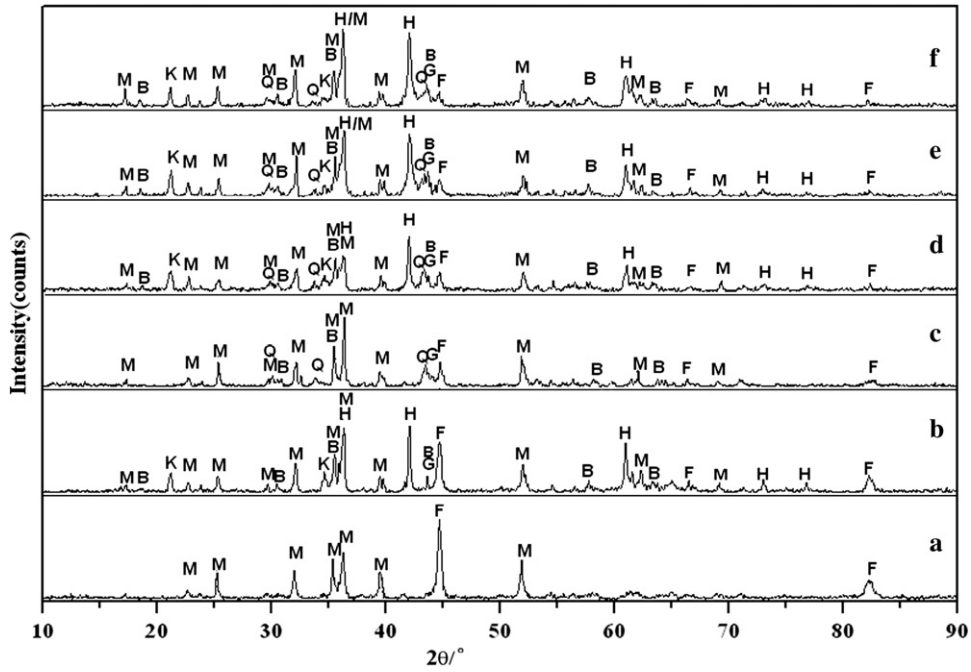
mineralogical phase transformation of laterite ore in the reduction roasting, the roasted ores were ground to 38 μm for XRD analysis. And for the microscopic analysis of roasted ores, the roasted ores were set in an epoxy resin mount and polished. All the polished samples were coated with a 30 nm thick carbon film prior to SEM-EDS analysis.

#### 3.2.1. XRD analysis of the roasted ore with different additives

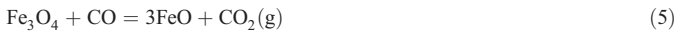
The XRD spectra of roasted ores obtained with the addition of different additives are shown in Fig. 2. The different kinds and dosages of additives in Fig. 2(a to f) correspond to those in Table 3 (a to f).

The XRD pattern of the roasted ore without additives exhibited high content of kamacite and forsterite, as shown in the Fig. 2(a). This result is caused by the dehydroxylation of lizardite [(Mg,Fe)<sub>3</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>] and the recrystallization of silicate minerals (Li et al., 2011). Moreover, the goethite [FeOOH] and pecoraite [Ni<sub>3</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>] were reduced to kamacite in the roasting process. The results illustrate that the ferronickel obtained from the roasted ore without additive has a high iron recovery. According to literatures report (Rao, 2010; Lu, 2012) and analyzing the roasted ore mineral composition and phase transformation, it was also reported that the reduction of iron and nickel oxide by carbon occurs through the gaseous intermediates CO and CO<sub>2</sub> blew about 1200 °C (Fruehan, 1977). Therefore, the reactions equation could be represented by





**Fig. 2.** XRD patterns of the roasted ores with different additives at a dosage of 10% F-kamacite ([Fe,Ni]), G-taenite ([Fe,Ni]), H-wustite (FeO), M-forsterite ((Mg,Fe)<sub>2</sub>SiO<sub>4</sub>), P-spinel (MgFe<sub>2</sub>O<sub>4</sub>), Q-troilite (FeS), K-nepheline (Na<sub>3</sub>MgAl(SiO<sub>4</sub>)<sub>2</sub>).



The mineralogical composition of the roasted ore with the addition of Na<sub>2</sub>O are wustite [FeO], nepheline [Na<sub>3</sub>MgAl(SiO<sub>4</sub>)<sub>2</sub>], kamacite, and taenite [Fe,Ni], is shown in Fig. 2(b). The proportion of the wustite is higher than that of other mineralogical composition. These results indicate that Na<sub>2</sub>O could react with silicate minerals to form low melting point nepheline, and could exchange with nickel oxide and iron oxide from silicate minerals in reduction roasting (Watanabe et al., 1987). And the main reaction with the addition of Na<sub>2</sub>O can be represented by

$$\text{Na}_2\text{O} + 2\text{Fe}_2\text{SiO}_4 = 4\text{FeO} + \text{Na}_2\text{Si}_2\text{O}_5 \quad (9)$$

The reduction atmosphere was weaker in the molten ore because the diffusion rate of reductive gas was decreased by the formation of low molten point minerals. Moreover, the thermodynamic calculations showed that nickel oxide is reduced prior to iron oxide, thus the step of wustite further reducing the metallic iron could be suppressed in a weak reduction atmosphere. Only a small amount of wustite was reduced to kamacite. This result could explain the increase of nickel recovery with a corresponding decrease of iron recovery in Fig. 1(b).

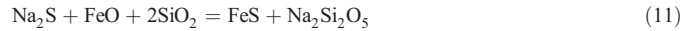
The diffraction peaks of kamacite, taenite, forsterite, and FeS were observed in the XRD pattern of the roasted ore with addition of S in

Fig. 2(c). The peak intensity of kamacite has a sharp decrease, in contrast to the XRD pattern of the roasted ore with the addition of Na<sub>2</sub>O in Fig. 2(b). These results illustrate that S could react with metallic iron to form FeS (Nagata and Bolsaitis, 1986; Okajima, 1987), and the reaction was expressed as follows:

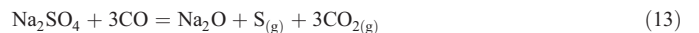


FeS is non-magnetic, so the formation of FeS is in accordance with the sharp decrease of iron recovery and significant increase of nickel grade as S dosage increases in Fig. 1(c).

The roasted ore of the mixtures in Table 3 (d, e, f) has a similar phase transform, as shown in Fig. 2(d, e, f). Kamacite, taenite, forsterite, FeS, and nepheline were observed in the XRD pattern. The XRD analysis of the roasted ore with Na<sub>2</sub>S demonstrates that Na<sub>2</sub>S could react with ferrous minerals to form FeS (Li et al., 2012a,b).

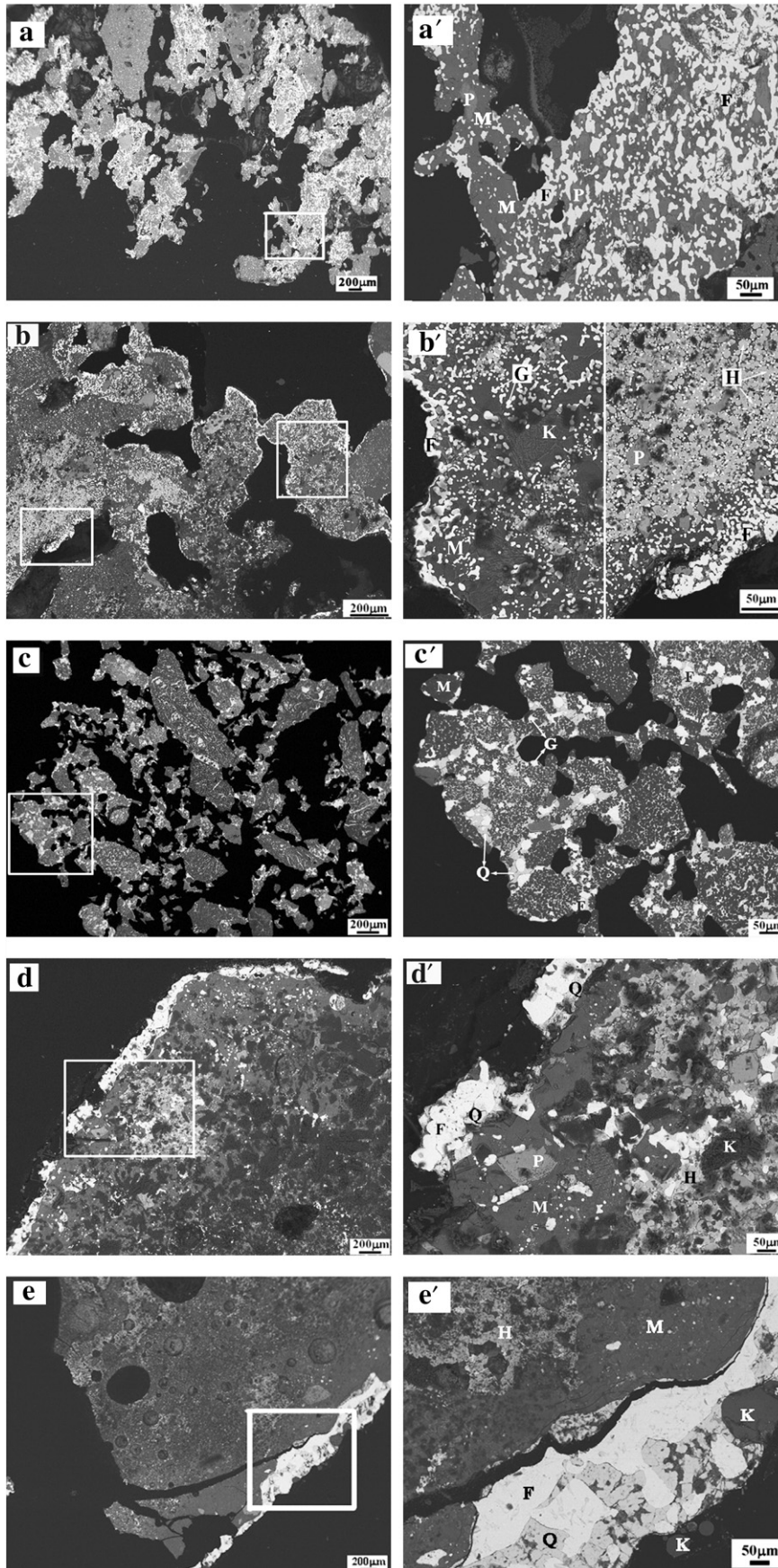


However, the thermal decomposition and reducing reaction equation of Na<sub>2</sub>SO<sub>4</sub> (Li et al., 2012a,b; Meng et al., 2012; Hou, 1981; Rao, 2010) were represented as follows:



Therefore, Na<sub>2</sub>SO<sub>4</sub> could decompose to Na<sub>2</sub>O and S in a reducing atmosphere; Na<sub>2</sub>SO<sub>4</sub> was also reduced to Na<sub>2</sub>S. And then the products of thermal decomposition and reducing reaction of Na<sub>2</sub>SO<sub>4</sub> reacted with the mineralogical composition of the laterite ore. Na<sub>2</sub>O improves nickel recovery, whereas S and Na<sub>2</sub>S are beneficial for nickel enrichment through magnetic separation because of the formation of FeS. Thus, a significant increase in nickel grade and recovery of ferronickel concentration can be obtained from magnetic separation under the synergic action of Na<sub>2</sub>O, S, and Na<sub>2</sub>S. Moreover, the effect of selective reduction on iron-bearing minerals and nickeliferous minerals is efficient.





**Fig. 3.** SEM images (backscattered electron images) of the roasted ores with different additives: (a) – (f) general overview of microstructure of minerals particles and (a') to (f') enlarged view marked areas F-kamacite, G-taenite, H-wustite, M-forsterite, P-spinel, Q-troilite, K-nepheline.

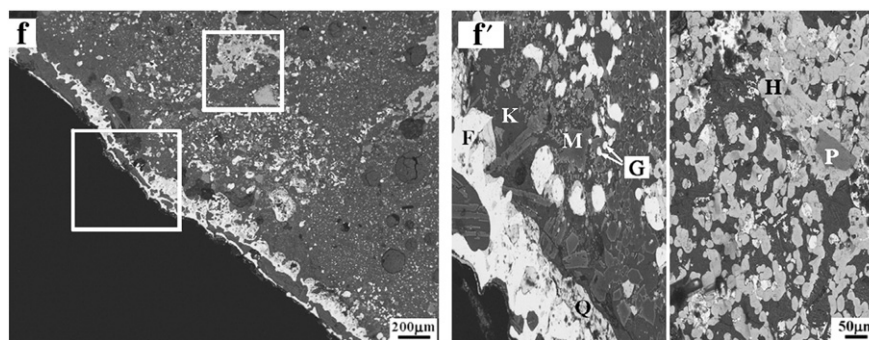


Fig. 3 (continued).

### 3.2.2. SEM-EDS analysis

The microstructure of the roasted ore and the mode of occurrence of the main elements were analyzed by SEM coupled with EDS. Fig. 3 presents the microstructures and elemental composition of the roasted ore listed in Table 3 (a to f). The Figures from (a') to (f') are the magnified view of the marked areas in the Figures from (a) to (f), respectively.

The coarse bright phase (spot F), light black phase (spot M), and gray areas (spot P) observed by the EDS analysis in Fig. 3(a') and the XRD analysis in Fig. 2 are kamacite, forsterite, and spinel, respectively. The observations of grayish binder phase (spot H), black areas (spot K), and fine bright phase (spot G) in Fig. 3(b') indicate that these spots occur as wustite, nepheline, and taenite. The grayish white phase (spot Q) around kamacite in Fig. 3(c') is FeS. The phases observed in Fig. 3(d') include kamacite, taenite, forsterite, spinel, wustite, nepheline, and FeS. The composite mineral phases in Fig. 3(e') and (f') have similar characteristics to that observed in Fig. 3(d').

Fig. 3(a–f) shows the general microstructure of the roasted ores. The structure of the roasted ore mixing without additive is loose, and kamacite is observed scattering and embedding in forsterite and spinel, as shown in Fig. 3(a). Meanwhile, the roasted ore with added  $\text{Na}_2\text{O}$  exhibits a compact structure in Fig. 3(b). The roasted ore surface is saponaceous, which illustrates that the roasted ore is molten in the reduction roasting process with the addition of  $\text{Na}_2\text{O}$ . The molten structure of the roasted ore accelerated the migration rate of metallic particle, which was beneficial for the growth of the metallic particles.

Meanwhile, the reduction of ferrous minerals was suppressed by decreasing the diffusion rate of the reductive gas in the molten structure. Thus, several wustite are formed. The result is accordance with the XRD analysis of the roasted ore with the addition of  $\text{Na}_2\text{O}$ . The wustite phase interlinks with the metal particles and forsterite because of the strong migration ability of the newly generated wustite grain (Okajima, 1987).

The general structure of the roasted ore with added S is loose in Fig. 3(c), and the metallic particles are enclosed by FeS. The observation illustrates that S can be enriched in the metallic particle surface and react with metallic iron to form FeS. Thus, S could reduce the surface tension and make the metal particle size grow (Nagata and Bolsaitis, 1986; Li et al., 2012a,b); some particle size could grow up to 50  $\mu\text{m}$ . The mutual connection of metallic particles is inhibited in the loose structure of the roasted ore, thus these metallic particles are single and independent. The results could explain the significant increase of nickel grade and the sharp decrease of nickel and iron recovery of the ferronickel concentrate obtained from the magnetic separation with the addition of S.

The roasted ores have a closed microstructure, as shown in Fig. 3(d to f). The metallic particles grow up obviously and form a metallic shell with a grain size about 100  $\mu\text{m}$ , covering the surface of the roasted ore. The results demonstrate that the reduced ores were molten in the roasting process. The molten structure and generation of FeS can promote the size of grown metallic particle. The growth

of metallic particles is beneficial for exacting ferronickel from non-magnetic gangue by grinding-magnetic separation. This evidence supports the previous conclusion based in Fig. 1 that the magnetic separation of ferronickel from gangue is more effective with the addition of  $\text{Na}_2\text{SO}_4$ ,  $\text{Na}_2\text{S}$ , or the mixture of  $\text{Na}_2\text{O}$  and S.

According to the XRD analysis and SEM-EDS analysis of the roasted ore with  $\text{Na}_2\text{SO}_4$ , the mechanism of  $\text{Na}_2\text{SO}_4$  in promoting the selective reduction of laterite was that parts of  $\text{Na}_2\text{SO}_4$  decomposed to  $\text{Na}_2\text{O}$  and S under reducing atmosphere. Meanwhile, some of the  $\text{Na}_2\text{SO}_4$  was also reduced to  $\text{Na}_2\text{S}$ . Sulfur could enrich in the surface of metallic particle and react with metallic iron to form FeS. And sulfur could reduce the surface tension and make the metal particles size growing. Moreover,  $\text{Na}_2\text{S}$  reacts with ferrous minerals to form FeS and  $\text{Na}_2\text{O}$ .  $\text{Na}_2\text{O}$  reacts with silicate to form low melt point minerals and melt the reduced ore, which could accelerate the transport rate of metallic particles in the molten ore, and then the metallic particles could connect for growth.

## 4. Conclusions

- (1) According to the experimental results with different additives,  $\text{Na}_2\text{O}$  improved the nickel recovery, and S significantly affected the increase in nickel grade. The variation trend of the grade and the recovery of nickel and iron of the ferronickel concentrate with the addition of mixture of  $\text{Na}_2\text{O}$  and S was similar to that with  $\text{Na}_2\text{S}$  and  $\text{Na}_2\text{SO}_4$ , separately. When the dosages of  $\text{Na}_2\text{S}$ ,  $\text{Na}_2\text{SO}_4$ , and the mixture of  $\text{Na}_2\text{O}$  and S were increased to 10 wt.%, the nickel grade of the ferronickel concentrate increased to 9.87%, 10.86%, and 9.29%, with nickel recovery of 90.90%, 88.56%, and 87.29%, and iron recovery 29.55%, 24.62%, and 30.76%, respectively. The effect of selective reduction on nickeliferous minerals and ferrous mineral was efficient.
- (2) The XRD analysis of roasted ore and the experimental data with additives indicated that iron recovery in ferronickel concentrate was decreased because of the formation of wustite and FeS. One main reason of this decrease was that the reduction of wustite was suppressed in a weak reduction atmosphere. Another reason was that S reacted with metallic iron to form FeS, which was beneficial for nickel enrichment through magnetic separation.
- (3) The roasted ore with the addition of  $\text{Na}_2\text{SO}_4$  had a closed microstructure. Metallic particles grew up obviously and formed a metallic shell on the surface of the roasted ore. The mechanism of  $\text{Na}_2\text{SO}_4$  in promoting the selective reduction of laterite was that  $\text{Na}_2\text{SO}_4$  could be decomposed to  $\text{Na}_2\text{O}$ , S, and  $\text{Na}_2\text{S}$  in a reducing atmosphere.  $\text{Na}_2\text{O}$ , S, and  $\text{Na}_2\text{S}$  then react with the composition of laterite. Sulphur can be enriched in the surface of metallic particle and can decrease the surface tension of metallic particles to promote the growth of metallic particle size. Moreover,  $\text{Na}_2\text{O}$  reacted with silicate to form low molten point minerals, which could accelerate the migration rate of metallic particles and promote the growth of metallic particles.

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