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# Effect of additives on growth of ferronickel grains and metal-slag separation behavior

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Abstract: Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub>, FeO, FeS and carbon were used to regulate the properties of slag or metal fractions, and their effects on metal growth and metal–slag separation behavior were investigated. The growth of ferronickel grains can be enhanced by adding these additives, and Na<sub>2</sub>S was the most effective. Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub> and FeO mainly affected the properties of slag, while carbon and FeS affected the metal fraction. The onset temperature of metal–slag separation was 1297 °C for the sample without additive, which was decreased to 1123 and 1101 °C after adding 3.30 wt.% Na<sub>2</sub>S and 4.47 wt.% Na<sub>2</sub>CO<sub>3</sub>, respectively. The onset temperature of metal–slag separation was mainly controlled by the slag fraction. The average apparent activation energy of metal grain growth was 125.32 kJ/mol without additive, and it decreased obviously after adding different additives. Na<sub>2</sub>S also had the most remarkable effect on the decrease in activation energy.

Key words: nickel laterite ore; slag properties; metal growth; metal-slag separation; kinetics

# **1** Introduction

Nickel is one of the most important metals and is widely used to produce stainless steel, highperformance alloy, electroplating and batteries, etc. Global nickel production of 2020 has reached about  $2.5 \times 10^6$  t, and more than 50% was consumed in China [1]. About 85% of nickel was used in the stainless-steel industry, while electroplating and batteries consumed 6% and 5%, respectively [2]. Nickel is supplied from both sulfide and laterite ores [3,4], and laterite ore has become the main source of nickel production.

To date, many techniques have been applied to extracting nickel from laterite ore [5,6]. Hydrometallurgical process is mainly available for limonite-type or transition layer ores [7,8]. Pyrometallurgical processes, such as blast furnace (BF) smelting, rotary kiln-electric furnace smelting (RKEF), Krupp-Renn (Nipon Yakin Oheyama) and direct reduction-magnetic separation, have become the main technologies for saprolite-type ore [9-12]. BF smelting process can only produce low-nickel pig iron, and agglomeration is indispensable before smelting in BF. RKEF has achieved large-scale production, and high-nickel products can be obtained. However, RKEF process generally consumes a lot of electricity. Krupp-Renn process is a semi-molten smelting process, which has certain advantages in terms of energy consumption. Nevertheless, this method has strict requirements on operation and process conditions, otherwise, formation of ring in rotary kiln will be easily caused [11].

In recent years, many scholars have conducted

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a lot of research on the direct reduction-magnetic separation process. Since the reduction procedure was carried out at a relatively low temperature, the energy consumption can be saved [13]. However, in order to promote the magnetic separation of ferronickel, it is necessary to enhance the reduction process as well as the aggregation and growth of ferronickel grains. Formation of regional liquid phase has been proved to be effective for metal growth and preliminary metal-slag separation [14,15].

The method of generating regional liquid phase is classified as adjusting the properties of slag or metal fractions by adding different additives. For example, Na<sub>2</sub>CO<sub>3</sub>, CaF<sub>2</sub>, CaO and CaSO<sub>4</sub> can be used to adjust the properties of the slag fraction [16-18]. In the Krupp-Renn process, iron oxide was partially reduced to FeO [11], and the formed FeO would enter into the slag fraction and decrease its melting temperature [19]. Sulfur is a surfactant element which could reduce the surface tension of ferronickel particles; therefore, the aggregation and growth of ferronickel can be enhanced [20,21]. When carbonaceous reductant was used in the reduction process, carburization of ferronickel was also favorable to decrease the melting temperature and promote the growth of ferronickel grains [22]. By adding sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>) to the reduction process, the properties of both slag and metal fractions can be adjusted [23-25].

Previous studies have proved that forming regional liquid phase in either slag or metal fractions was beneficial to the aggregation and growth of ferronickel grains. However, the effect of different additives on the metal growth and metal-slag separation behavior has not been systematically investigated and compared. In this study, the effect of various additives on the growth of ferronickel grains and metal-slag separation behavior was investigated. Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub> and FeO were used to adjust the properties of slag fraction, and FeS and carbon were used to adjust the properties of metal fraction. The effect of these additives on the metal growth was investigated by using optical microscope observation and the image processing software of ImageJ Pro. The metal-slag separation behavior was also compared based on the in situ observation by using high temperature confocal scanning laser microscopy (CSLM).

# 2 Experimental

## 2.1 Materials

Chemical reagents, including SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO and MgO with a purity greater than 99.99%, were used to synthesize a primary slag sample. These reagents were proportioned at 64wt.%SiO<sub>2</sub>-9wt.%Al2O3-3wt.%CaO-24wt.%MgO and premelted. Ferronickel mixture containing 10 wt.% Ni and 90 wt.% Fe was uniformly mixed and used as the metal fraction. The mixture was milled to size below 10 µm by using a high energy ball mill. Other reagents, such as FeS, Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub>, graphite and FeO with a purity greater than 99.99%, were employed to regulate the properties of slag and metal fractions. Carbon was only used as carburizing agent and there were no other reductants. The mass ratio of metal (ferronickel) to primary slag was fixed at 26.44:73.56, which was determined according to the chemical composition of a nickel laterite ore [26].

#### 2.2 Methods

2.2.1 Roasting experiment

The roasting experiment was carried out to study the influence of additives on the growth behavior of ferronickel grains. The metal and slag fractions prepared in Section 2.1 were added with different additives. After adding additive, the mixture was uniformly mixed and briquetted to a cylinder ( $d30 \text{ mm} \times 10 \text{ mm}$ ) under the pressure of 15 MPa. The cylinder was then roasted at 1300 °C for 60 min under Ar atmosphere. A horizontal tube furnace was used for the roasting experiment. The roasted briquette was then cooled and polished for microstructure analysis. The amount of additive was based on the element balance of Na or S. For example, when 6.00 wt.% Na<sub>2</sub>SO<sub>4</sub> was added to the reduction roasting of nickel laterite, assuming element of S was completely converted to Na2S or FeS, their corresponding proportions were 3.30 wt.% and 3.72 wt.%, respectively.

2.2.2 Microstructure observation and image processing

Optical microscope was used to observe the microstructure of samples after roasting (as shown in Fig. 1(a)), and the image processing software of ImageJ Pro was used to count the area and number of metallic particles in the micrograph. Based on



**Fig. 1** Microstructure of roasted briquette (a) and selected metallic phase by ImageJ software (b)

the micrograph taken by optical microscope, it was dimensioned and gray-scale transformed by ImageJ Pro software. The metallic particles (shown as white in Fig. 1(a)) were marked in red (Fig. 1(b)). Then, the area and number of the red area were counted by the same software. Thirty different micrographs were chosen for each sample. Since the metallic particles had different size and irregular shape, the particles and the cross section were assumed to be spherical and circle, respectively. Thus, the average area (S) of the particles can be obtained when the total area and number of the particles were known. The average diameter (d) of the particles was calculated by the following formula:

$$d = 2\sqrt{S/\pi} \tag{1}$$

#### 2.2.3 In situ observation

In situ observation using confocal scanning laser microscopy (CSLM) was carried out to observe the metal-slag separation behavior [27]. The CSLM is composed of a microscope (Lasertec, VL2000DX, vender: Yonekura MFG. Co., Ltd.) and an infrared heating high temperature furnace (model: VL2000DX). The schematic diagram of CSLM is shown in Fig. 2. The inner cavity of the heating furnace is oval, and the halogen lamp is located at the bottom of the heating furnace. The heat derived from the lamp can be reflected and focused for fast heating the sample. The mixture of synthetic slag, ferronickel powder and additive were loaded in an alumina crucible with a height of 3.5 mm and an inner diameter of 7 mm. The crucible was then placed on the platinum sample holder of the heating furnace. Subsequently, the furnace was sealed and vacuumed. Dehumidified and deoxygenated argon gas (>99.999 vol.%) was introduced into the furnace. Finally, the furnace was heated under three stages: from room temperature to 200 °C at 50 °C/min, 200-1000 °C at 500 °C/min, and 1000-1550 °C at 60 °C/min, respectively.



Fig. 2 Schematic diagram of confocal scanning laser microscopy

# **3** Results and discussion

#### 3.1 Grain growth behavior

#### 3.1.1 Effect of Na<sub>2</sub>S

During the practical direct reduction process, Na<sub>2</sub>SO<sub>4</sub> will be first reduced by CO to Na<sub>2</sub>S, and Na<sub>2</sub>S would react with FeO and SiO<sub>2</sub> to form FeS and silicate [20]. Thus, Na<sub>2</sub>S was chosen to adjust the properties of slag fraction. The effect of Na<sub>2</sub>S on the metal growth was investigated by maintaining the roasting temperature at 1300 °C. The results in Fig. 3 indicate that as the content of Na<sub>2</sub>S (based on the slag fraction) was increased from 0% to 3.30%, the average diameter of ferronickel particles increased from 16.68 to 35.55 µm. The addition of Na<sub>2</sub>S is advantageous to increase the liquid phase content of slag, which would promote the migration of ferronickel grains and enhance their growth. The liquid phase content in slag was calculated by FactSage 8.0 and the results are also plotted in Fig. 3. By increasing the Na<sub>2</sub>S content from 0% to 3.30%, the liquid phase content increased distinctly from 25.55% to 47.86%. The change trend of average diameter and liquid content is almost the same, demonstrating that generating more liquid phase is conducive to the aggregation and growth of ferronickel grains. The study by RAO et al [15] revealed that the mean particle size of ferronickel increased from 7.4 to 48.6  $\mu$ m with the addition of 20 wt.% Na<sub>2</sub>SO<sub>4</sub> when nickel laterite ore was reduced at 1100 °C for 60 min. It indicated that Na<sub>2</sub>SO<sub>4</sub> was effective to promote the growth of ferronickel grains.



Fig. 3 Effect of Na<sub>2</sub>S content on metal growth

#### 3.1.2 Effect of Na<sub>2</sub>CO<sub>3</sub>

Sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) has also been used to enhance the reduction process of nickel laterite ore. Na<sub>2</sub>CO<sub>3</sub> cannot be reduced by CO but will combine with SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> to form silicate aluminosilicate  $(Na_2CO_3+SiO_2=Na_2SiO_3+$ or  $CO_{2(g)}$  [16]. The generated  $CO_2$  could promote the Boudouard reaction (C+CO<sub>2(g)</sub>=2CO<sub>(g)</sub>). Hence, Na<sub>2</sub>CO<sub>3</sub> was used to adjust the properties of slag fraction, and the actual active component was Na<sub>2</sub>O when Na<sub>2</sub>CO<sub>3</sub> was decomposed. The average diameter of ferronickel particles and liquid phase content as a function of Na<sub>2</sub>CO<sub>3</sub> content (based on the slag fraction) was given in Fig. 4. It can be observed that the average diameter increased from 16.68 to 25.46 µm as the Na<sub>2</sub>CO<sub>3</sub> content increased from 0% to 4.47%. The liquid phase content increased from 25.55% to 40.73%, correspondingly. However, when Na<sub>2</sub>CO<sub>3</sub> content was added from 2.98% to 4.47%, the average diameter remained almost unchanged and the liquid phase increased slightly. Compared to the results in Fig. 3, the effect of  $Na_2CO_3$  was worse than that of  $Na_2SO_4$ . As reported by ZHOU et al [16],  $CO_2$  gas derived from  $Na_2CO_3$  decomposition would result in volume expansion of the pellet. As a result, the ferronickel particles were dispersed and the growth of ferronickel may be inhibited.



Fig. 4 Effect of Na<sub>2</sub>CO<sub>3</sub> content on metal growth

#### 3.1.3 Effect of FeO

FeO is an important component used to adjust the properties of slag fraction [10,19]. The content of FeO during the reduction process can be controlled by adjusting the ratio of reductant. The effect of FeO was investigated by varying its content from 0% to 6% (based on the slag fraction). The results in Fig. 5 indicate that the average diameter of ferronickel particles increased from 16.68 to 21.90 µm as FeO content was increased. The corresponding liquid phase content increased from 25.55% to 36.15% when FeO content was increased from 0% to 6%. FeO in the slag not only promotes the growth of ferronickel grains, but also improves the interfacial behavior among slag, metal and carbon phases. Previous studies [28,29] indicated that molten FeO-bearing slag was favorable to shorten the distance between the metal phase and carbon, which made the metal carburizing more easily. The slag containing FeO has a positive effect on the mass transfer of carbon and promotes the metal to melt. In addition, the wettability of FeO-bearing slag on metallic iron is better than that without FeO, which indicates that metal-slag separation can be improved after FeO is reduced.

#### 3.1.4 Effect of carburization

During the reduction of nickel laterite ore, carbonaceous reductant also played an important

role in carburization, which had a favorable effect on the decrease in melting point of metal fraction. The effect of carburization on metal growth was investigated and the results are plotted in Fig. 6. As the carbon content (based on the metal fraction) increased from 0% to 3%, the average diameter of ferronickel particles was increased distinctly from 16.68 to 24.93 µm, then remained almost constant. In this experiment, since the temperature and chemical composition of slag were fixed, the liquid slag content was maintained at 25.55%. Carbon only affected the liquid metal content, which was increased from 0% to 26.44%. According to the Fe-C phase diagram, when the temperature is 1300 °C, the metal fraction will transform to liquid state when the carbon content was greater than 3%. Thus, the liquid metal content was unchanged when the carbon content was 3%-4% [22]. The results of average diameter were in good agreement with the change of liquid phase content.



Fig. 5 Effect of FeO content in slag on metal growth



Fig. 6 Effect of carbon content on metal growth

#### 3.1.5 Effect of FeS

As discussed before,  $Na^+$  in  $Na_2SO_4$  is able to liberate the hosted nickel and iron within lizardite,

while sulfur will react with Fe to form FeS during the reduction process. FeS mainly affects the high temperature properties of metal fraction by forming Fe-FeS eutectic [15]. The average diameter of ferronickel and liquid phase content as a function of FeS content is plotted in Fig. 7. It can be observed that the average diameter of ferronickel particles increased from 16.68 to 24.65 µm as the FeS content increased from 0% to 3.72%. When the temperature was fixed at 1300 °C, the liquid slag content was maintained at 25.55%, while the liquid metal content increased from 0% to 1.86%. The total liquid phase content was increased slightly with the increase in FeS content. Formation of low melting point phase of Fe-FeS eutectic is favorable to the growth of ferronickel grains. Regional liquid phase is like a bridge connecting dispersed ferronickel grains, which can narrow the distance among them [15,20].



Fig. 7 Effect of FeS content on metal growth

#### 3.2 Metal-slag separation behavior

The coal-based reduction of nickel laterite ore consists of several steps: (1) iron/nickel oxides reduction, (2) carburization & melting of reduced ferronickel, (3) slag melting, and (4) metal–slag separation. Here, metal–slag separation is different from molten separation because both metal and slag are not thoroughly melted. To investigate the temperature at which the slag or metal fractions begin to gather, an onset temperature of metal– slag separation was defined as being defocused temperature due to the start of liquid slag or iron droplets coalescence [27]. As shown in Fig. 8, the ferronickel particles were clearly observed before heating (Fig. 8(a)), while they became obscure (Fig. 8(b)) as the temperature was increased.



**Fig. 8** Microstructure of CLSM without additives (Bright area: ferronickel): (a) Initial state; (b) Onset temperature

effect of additives The on the onset temperature of metal-slag separation was investigated and the results are shown in Fig. 9. The temperature for primary slag was 1297 °C; however, it decreased obviously as different additives were added. The results in Fig. 9(a) indicate that Na<sub>2</sub>S or Na<sub>2</sub>CO<sub>3</sub> can exert better effect than FeO. This is because Na<sub>2</sub>S or Na<sub>2</sub>CO<sub>3</sub> acted as a co-solvent on the slag fraction, reducing the melting temperature of the slag. The slag-metal separation behavior was mainly affected by the melting of the slag fraction when Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub> or FeO was added. Although FeO can also reduce the melting temperature of the slag fraction, the onset temperature of metal-slag separation was not distinctly decreased. However, FeO-containing slag has a promoting effect on the carbon mass transfer process, which promotes the carburization in metal phase [27]. According to the average diameter of ferronickel particles, the decrease in onset temperature of metal-slag separation was also favorable to the increase of average diameter.

Similarly, when FeS or carbon was added, the onset temperature of metal-slag separation was also decreased. However, the temperature remained almost constant in the presence of different contents of FeS or carbon. FeS and carbon mainly played a role in decreasing the melting temperature of metal fraction. According to the Fe-FeS and Fe-C phase diagrams, the eutectic temperatures of Fe-FeS and Fe-C are about 988 °C and 1148 °C, respectively, which are obviously lower than the onset temperature of metal-slag separation. Thus, it is inferred that the onset temperature of metal-slag separation may be mainly affected by the slag fraction. Figure 10 shows the theoretical metal or slag melting start temperature under different additives. When the additive was 0%, the metal or slag melting start temperature is 1225 °C. It can be observed that the onset temperature of metalslag separation is higher than the melting start temperature, which indicates that the metal growth does not occur immediately as the metal or slag begins to melt. Higher temperature or enough liquid phase is required for slag-metal separation compared with the melting start temperature.



Fig. 9 Effect of additives on onset temperature of metalslag separation



Fig. 10 Metal or slag melting start temperature with different additives

#### 3.3 Kinetics on growth of ferronickel grains

The model proposed by HILLERT [30] is widely used to investigate the kinetics of grain growth. The rate of grain growth is described as the following equation:

$$U = a_0 V_0 \exp\left(-\frac{Q}{KT}\right) \left[1 - \exp\left(-\frac{\Delta F_{\rm V}}{KT}\right)\right]$$
(2)

where U is the growth rate of crystal nucleus;  $a_0$  is the atomic diameter;  $V_0$  is the vibration frequency of the atom;  $\Delta F_V$  is molar free energy difference between the crystalline and amorphous states; Q is apparent activation energy of nucleus growth; K represents the Boltzmann constant. Generally,  $\Delta F_V \gg KT$ . Therefore, the grain growth can be expressed as follows:

$$d^{n} - d_{0}^{n} = k_{0}t \exp\left(-\frac{Q}{RT}\right) = kt$$
(3)

where *d* and *d*<sub>0</sub> represent the average diameter (µm) of initial grain and the grain after time *t* (min), *n* is the grain growth index,  $k_0$  is the pre-exponential factor, *k* is the rate constant of grain growth (µm<sup>2</sup>/min), *Q* is the apparent activation energy of crystal nucleus growth (kJ/mol), *R* is the gas constant (J/(mol·K)), *T* is the thermodynamic temperature (K), and  $k=k_0\exp[-Q/(RT)]$ .

During the direct reduction of nickel laterite ore, the initial grain size is very small, it means  $d \gg d_0$ . Therefore, Eq. (3) can be simplified as

$$d^{n} = k_{0}t \exp\left(-\frac{Q}{RT}\right) = kt$$
(4)

In the isothermal process (T is a constant), by taking logarithm on both sides of Eq. (4), it can be transformed to the following equation:

$$\ln d = -\frac{1}{n}\ln k + \frac{1}{n}\ln t \tag{5}$$

Based on the relationship between  $\ln d$  and  $\ln t$ , the grain growth index *n* and rate constant of growth *k* can be calculated by the slope (1/n) and intercept  $((\ln k)/n)$  of the regression line.

Similarly, by fixing the reaction time (*t* is a constant), Eq. (6) can be obtained by taking logarithm of Eq. (4). The apparent activation energy (*Q*) of grain growth can be obtained according to the relationship between  $\ln d$  and 1/T.

$$\ln d = \frac{1}{n} \ln k_0 + \frac{1}{n} \ln t - \frac{1}{n} \frac{Q}{RT}$$
(6)

The average diameter of ferronickel particles as functions of duration time (30-129 min) and temperature (1473-1623 K) was investigated, and the experiments were carried out in the absence of additives. The results in Fig. 11(a) indicate that the



Fig. 11 Effect of roasting time on average size of ferronickel grain

average diameter increased continuously within the duration time. By increasing the temperature, the average diameter was also increased. Figure 11(b) shows the relationship between  $\ln d$  and  $\ln t$ . Based on the grain growth model, the grain growth index n was determined as 1.5074. The value of n represents the growth mechanism of ferronickel grains. When n is less than 2, the growth mechanism is grain boundary diffusion. It indicates that the growth of ferronickel grains is controlled by boundary diffusion under the experimental conditions.

The average diameter as a function of temperature and the relationship between  $\ln d$  and 1/T by linear fitting are plotted in Fig. 12. According to the fitting results in Fig. 12(b), the average apparent activation energy (*Q*) is determined as 125.36 kJ/mol in the range of 1473–1623 K. Based on the above results and Eq. (6), the value of  $k_0$  can also be calculated, and its value was  $1.72 \times 10^4$ . Thus, Eq. (4) was transformed to Eq. (7), which can be used to predict the average diameter of



Fig. 12 Effect of roasting temperature on average size of ferronickel particles

ferronickel particles under different conditions. The calculated and experimental average diameters were compared in Fig. 13, and the results were in good agreement.

$$d = \left[1.72 \times 10^4 t \cdot \exp\left(-\frac{125.36 \times 10^3}{RT}\right)\right]^{0.6634}$$
(7)

Similarly, the average activation energy of growth with different additives grain was investigated. The results in Fig. 14 indicate that the activation energy decreased obviously after adding different additives. Among the additives for regulating the properties of slag fraction, Na<sub>2</sub>S had the most remarkable effect on the decrease in activation energy, followed by Na<sub>2</sub>CO<sub>3</sub> and FeO. When the addition of Na<sub>2</sub>S was increased from 0% to 3.30%, the activation energy decreased from 125.32 to 110.40 kJ/mol, correspondingly. Figure 14(b) shows the activation energy for additives that regulated the properties of metal fraction. The results indicate that the activation energy decreased from 125.32 to 117.30 kJ/mol as the carburizing content increased from 0% to 4.00%, and it decreased from 125.32 to 117.61 kJ/mol as the FeS content increased from 0% to 3.30%. The decrease in activation energy is beneficial to aggregation and growth of ferronickel, which is in good agreement with the results of average diameter. However, FeS and carbon played a smaller effect than other additives. This is because the volume of metal fraction was much less than slag fraction, and the ferronickel and additives may be separated by slag.



Fig. 13 Comparison of calculated particle size with measured data



Fig. 14 Effect of additives on the apparent activation energy of ferronickel grain growth

# **4** Conclusions

(1) The growth of ferronickel grains was enhanced by adding Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub>, FeO, carbon and FeS. The average diameter increased from 16.68 to 35.55  $\mu$ m as the Na<sub>2</sub>S content increased from 0% to 3.30%. In the experimental range of additives, Na<sub>2</sub>S was the most effective than other additives.

(2) Regional liquid phase formation was beneficial to the aggregation and growth of ferronickel grains. Na<sub>2</sub>S, Na<sub>2</sub>CO<sub>3</sub> and FeO can affect the liquid phase content of slag fraction, while carbon and FeS affected the metal fraction.

(3) The onset temperature of metal–slag separation was 1297 °C for the sample in the absence of additive, which was decreased distinctly to 1123 and 1101 °C after adding 3.30% Na<sub>2</sub>S and 4.47% Na<sub>2</sub>CO<sub>3</sub>, respectively. The onset temperature of metal–slag separation was mainly controlled by the slag fraction, and it was higher than the metal or slag melting start temperature.

(4) The average apparent activation energy of metal grain growth was 125.32 kJ/mol without additive, and it decreased obviously after adding different additives. Na<sub>2</sub>S also had the most remarkable effect on the decrease in activation energy than among the used additives.

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# 添加剂对金属聚集长大和渣金分离的影响

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摘 要:通过添加 Na<sub>2</sub>S、Na<sub>2</sub>CO<sub>3</sub>、FeO、FeS 和 C 调控渣相或金属相的性能,研究这些添加剂对金属聚集长大和 渣金分离的影响规律。结果表明,加入添加剂可以促进镍铁晶粒的生长,其中 Na<sub>2</sub>S 的促进效果最为显著。Na<sub>2</sub>S、 Na<sub>2</sub>CO<sub>3</sub>和 FeO 主要影响渣相的性能,C 和 FeS 主要影响金属相。无添加剂时,渣金分离起始温度为 1297 ℃,加 入 3.30% Na<sub>2</sub>S 和 4.47% Na<sub>2</sub>CO<sub>3</sub>(质量分数)后,渣金分离起始温度分别降至 1123 和 1101 ℃;渣金分离的起始温度 主要受渣相成分控制。无添加剂时金属晶粒长大的平均表观活化能为 125.32 kJ/mol;添加不同添加剂后,平均表 观活化能明显降低,Na<sub>2</sub>S 对活化能的降低作用也最为显著。

关键词:红土镍矿;渣相性能;金属聚集长大;渣金分离;动力学