Effect of Sodium Sulfate on Preparation of Ferronickel from Nickel Laterite by Carbothermal Reduction

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In this study, the effect of sodium sulfate on preparation of ferronickel from nickel laterite by carbothermal reduction was investigated. The thermodynamic analysis showed that the addition of sodium sulfate can effectively enlarge the region of liquid slag in the phase diagram. The experimental results of carbothermal reduction revealed that sodium sulfate was capable of enhancing the reduction of nickel laterite, as well as promoting the aggregation and growth of nickel-iron particles considerably. Both the size of ferronickel particles and the grade of Ni in the magnetic material increased with increase in the dosage of sodium sulfate. The Ni grade and its recovery ratio were only 2.4 mass% and 58.1% when the raw material was reduced in the absence of sodium sulfate. However, with addition of 8.0 mass% sodium sulfate, the grade of Ni in magnetic material and the recovery of Ni reached up to 9.7 mass% and 89.1%, respectively. The contents of S, P, C and Si in the magnetic materials was also discussed. In addition, the reaction mechanisms of reduction in the presence of sodium sulfate was revealed by investigating the phase transformation, growing character of ferronickel as well as TG and evolved gas analysis. The effective utilization coefficient of nickel (E_{Ni}) which is a new characterization method of normalization was proposed to compare different studies on preparation of ferronickel from various nickel laterite.

KEY WORDS: nickel laterite; sodium sulfate; ferronickel; carbothermal reduction; effective utilization coefficient.

1. Introduction

As an industrial important metal, the nickel is mainly used in the production of stainless steel and high temperature alloys.1–5) At present, nickel is mainly extracted from sulfide and laterite type nickel ores, which account for approximately 36% and 64% of the worldwide nickel reserves respectively.6) In recent years, the world annual demand for nickel has increased tremendously due to soaring stainless steel production, particularly in China. As sulfide ores and high-grade nickel resources are exhausted gradually, much attention has been paid recently to recovery of nickel from low-grade nickel laterite ore.7–13) However, the extraction of nickel from laterite ore is relatively difficult because of the low nickel content and isomorphic substitution in goethite or serpentine.14–16)

Recently, many researchers have studied direct reduction of laterite ore by adding additives to improve the reduction and metal-slag magnetic separation. Li et al.17) and Rao et al.18) investigated the beneficiation of nickelferrous laterite (Ni: 1.9 mass%, T·Fe: 22.1 mass%) by reduction roasting in the presence of sodium sulfate. They obtained a ferronickel alloy with 9.5 mass% Ni and 79.3 mass% Fe, which was prepared by reduction roasting at 1 100°C for 60 min with addition of 20.0 mass% sodium sulfate followed by wet magnetic separation. Jiang et al.21) have recovered nickel from laterite ore (Ni: 1.5 mass%, T·Fe: 34.7 mass%) by selective reduction with addition of sodium sulfate (10.0 mass%) at 1 200°C for 50 min. A ferronickel concentrate with Ni grade of 9.9 mass% and nickel recovery of 90.9% was obtained after wet magnetic separation. Lu et al.14) studied the effect of sodium sulfate on the hydrogen reduction process of nickel laterite ore. The maximum nickel content of 5.6 mass% and nickel recovery of 83.6% could be obtained from the reduction of nickel laterite ore at 800°C for 220 min in the presence of 20.0 mass% sodium sulfate at a total gas flow rate of 5.6×10⁻³ m³/s (V_{H2}:V_{N2}=7:3). Zhu et al.13) investigated the reduction of low-grade nickel laterite at 1 100°C for 60 min with addition of 6.0 mass% calcium
sulfate and 5.0 mass% reductant coal. The results showed a nickeliferous concentrate containing 6.0 mass% Ni with nickel recovery of 92.1% was obtained by wet magnetic separation. Liu et al. \cite{22} have prepared ferronickel at 1 400°C with different basicity by semi-molten state reduction of nickel laterite (Ni: 1.8 mass%, T·Fe: 17.9 mass%). They found that when the basicity ((CaO+MgO)/(SiO2+Al2O3)) is 0.60, the nickel content could reach 11.5 mass% in the alloy nugget and the recovery ratio of nickel was 98.6%, while the grade and recovery ratio of Fe was 84.2 mass% and 68.7%, respectively. In conclusion, adding additives especially sodium sulfate is efficient to increase the grade of nickel in ferronickel concentrate as well as nickel recovery. However, the recovery ratio of Fe was restrained in the above studies and excessive dosage of additives were added during reduction which will cause serious corrosion of furnace lining and indirect increase of the production cost.

In order to obtain a low cost and high efficiency process for recovering ferronickel from nickel laterite, carbothermic reduction of nickel laterite with less addition of sodium sulfate, and then followed by dry magnetic separation was researched. The X-ray diffraction (XRD), and the results in Table 1 indicate that the laterite ore is mainly composed of CaAl2Si2O8(H2O)4, (Mg,Al)3(Si,Fe)2O5(OH)4 and Fe2O3. The nickel laterite used in this study was obtained from Philippines. The main chemical composition of the raw nickel laterite is shown in Table 1. The content of Ni and total iron grade (T·Fe) was 1.8 mass% and 17.9 mass%, respectively. It can be observed that the sample has a high content of silica, magnesia, alumina and water (includes: free water, crystal water and hydroxy group). The mineralogical analysis of the sample was investigated by X-ray diffraction (XRD), and the results in Fig. 1 indicate that the laterite ore is mainly composed of CaAl2Si2O8(H2O)4, MgSi2O5(OH)4, (Mg,Al)3(Si,Fe)2O5(OH)4 and Fe2O3.

Table 1. Chemical composition of nickel laterite ore in this study (mass%).

<table>
<thead>
<tr>
<th>Ni</th>
<th>T·Fe</th>
<th>Cr2O3</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>CaO</th>
<th>MgO</th>
<th>P</th>
<th>S</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>17.9</td>
<td>0.5</td>
<td>35.0</td>
<td>4.8</td>
<td>1.5</td>
<td>13.5</td>
<td>0.005</td>
<td>0.06</td>
<td>17.4</td>
</tr>
</tbody>
</table>

2. Experimental

2.1. Material

2.1.1. Nickel Laterite

The nickel laterite used in this study was obtained from Philippines. The main chemical composition of the raw nickel laterite is shown in Table 1. The content of Ni and total iron grade (T·Fe) was 1.8 mass% and 17.9 mass%, respectively. It can be observed that the sample has a high content of silica, magnesia, alumina and water (includes: free water, crystal water and hydroxy group). The mineralogical analysis of the sample was investigated by X-ray diffraction (XRD), and the results in Fig. 1 indicate that the laterite ore is mainly composed of CaAl2Si2O8(H2O)4, MgSi2O5(OH)4, (Mg,Al)3(Si,Fe)2O5(OH)4 and Fe2O3.

2.1.2. Reducing Coal

Pulverized coke was used as reductant whose particles size was smaller than 1 mm. The industry analysis of coke is presented in Table 2.

2.1.3. Additive

Sodium sulfate used in the study was of analytical reagent (AR) grade.

2.2. Methods

2.2.1. Experimental Procedure

The as-received nickel laterite was dried at 120°C for 2 hours in an oven and ground to 60 mass% of the particles passing 0.074 mm. The ground sample was mixed to homogeneity with pulverized coke and powdery sodium sulfate. The mixture was then briquetted into a cylinder (Φ30 mm×10 mm) by powder tablet press machine with the pressure of 15 MPa (nothing was used as a binder for the briquetting process). The additive of sodium sulfate was varied from 0 to 8.0 mass% and the molar ratio of C/O (oxygen in iron oxide and nickel oxide) in mixtures was set at 0.8 in order to improve the grade of Ni in magnetic material.

The reduction process was carried out at 1 400 and 1 420°C in a resistance furnace with the roasting temperature controlled within ±2°C. The schematic diagram of experimental apparatus is presented in Fig. 2. Argon was passed through the furnace to expel the air when it was preheated to the required temperature. Then the graphite crucible loading the briquettes was introduced to the hot zone of the furnace. After roasting for a time period of 60 min under argon atmosphere, the crucible was taken out of the furnace and quenched rapidly to ambient temperature. Finally, the reduced sample was crushed to less than 3 mm and prepared for dry magnetic separation.

Table 2. Industry analysis of pulverized coke (mass%).

<table>
<thead>
<tr>
<th>Fixed carbon</th>
<th>Ash</th>
<th>Volatile</th>
<th>P</th>
<th>S</th>
<th>Heating quantity of bomb cylinder (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.1</td>
<td>10.7</td>
<td>13.2</td>
<td>0.08</td>
<td>0.4</td>
<td>24 717</td>
</tr>
</tbody>
</table>
2.2.2. Characterization

The phase composition of different samples was determined by X-ray diffraction using a diffractometer (XRD, RIGAKU D/Max 2500PC, Japan) under the conditions as follows: Cu Kα, tube current and voltage: 250 mA, 40 kV, scanning range: 10°–90° (2θ), step size: 0.02° (2θ) and scanning speed: 8°/min. A scanning electron microscope equipped with an energy diffraction spectrum analyzer (SEM-EDS, TESCAN VEGA 3 LMH, Czech Republic) was used for microstructure analysis. The thermogravimetry (TG) experiments were conducted using a Setaram Evo TG-DTA 1750 thermal analyzer at 0.3 K/s with graphite as reductant and flowing argon, and the evolved gas was detected in real time by TILON LC-D200 mass spectrometer.

2.2.3. Evaluation Indexes

The recoveries of Ni and Fe in each experiment was calculated according to the formulas (1) and (2), respectively.

\[
\eta_{\text{Ni}} = \frac{M \times X_{\text{Ni}}}{M_0 \times X_{\text{Ni}}^0} \times 100\% \quad \text{(1)}
\]

\[
\eta_{\text{Fe}} = \frac{M \times X_{\text{Fe}}}{M_0 \times X_{\text{Fe}}^0} \times 100\% \quad \text{(2)}
\]

Where \(\eta_{\text{Ni}}\) is the recovery of Ni (%), \(\eta_{\text{Fe}}\) is the recovery of Fe (%), \(M\) is the mass of magnetic fraction (g), \(X_{\text{Ni}}\) is the grade of Ni in the magnetic fraction (mass%), \(X_{\text{Fe}}\) is the grade of Fe in the magnetic fraction (mass%), \(M_0\) is the mass of raw laterite nickel in reduction sample (g), \(X_{\text{Ni}}^0\) is the content of Ni in the nickel laterite. \(X_{\text{Fe}}^0\) is the content of Fe in the nickel laterite.

3. Thermodynamic Analysis

The Ellingham diagram of the iron and nickel oxides that existed during the reduction process was calculated by FactSage 6.2 software and shown in Fig. 3. It can be concluded that the order of stability of these oxides from high to low is FeO, Fe₃O₄, NiO and Fe₂O₃. The nickel oxide is predicted to possess higher reducibility than hematite. Thus, it is feasible to thoroughly reduce nickel oxide while keeping part of iron oxides being reduced by adding insufficient reducing agent (molar ratio of C/O is set at 0.8). As a result, the nickel content in the ferronickel material can be improved.

The phase diagram of SiO₂–MgO–Al₂O₃–Na₂O at 1400°C with different proportion of Na₂O are calculated by FactSage 6.2 software and shown in Fig. 4, the value of Z: 0, 0.0164, 0.0328, 0.0492, 0.0656 is corresponding to 0 mass%, 2.0 mass%, 4.0 mass%, 6.0 mass%, 8.0 mass% Na₂SO₄, respectively. It can be seen from Fig. 4 that the liquid phase region are gradually enlarged with the increase of Na₂O (Na₂SO₄), which indicated that the melting point of the slag can be effectively decreased in the presence of sodium sulfate.

4. Results and Discussion

4.1. Ferronickel Preparation by Carbothermal Reduction

4.1.1. The Grade of Ni and Fe in the Magnetic Material

The morphology of the samples reduced at 1400 and 1420°C with different Na₂SO₄ dosages is plotted in Fig. 5. It can be observed that the cylindric briquettes were changed to spherical pellets, this is mainly attributed to the melting of the slag during reduction. By increasing the content of sodium sulfate from 0 to 8.0 mass%, the melting degree of
ronickel reached up to centimeter-level, which was much larger than that of previous studies.\textsuperscript{1,14,17,21} As a result, the separation of ferronickel particles from the slag was expected to be intensified dramatically.

**Figure 6** shows the relationship between the grade of Ni in the magnetic material and the dosage of sodium sulfate when reducing at 1 400 and 1 420°C for 60 min. The results in Fig. 6(a) revealed that the grade of Ni in the magnetic material increased distinctly with the addition of sodium sulfate. The Ni grade is only 2.4 mass% when reduced in the absence of sodium sulfate. As 2.0 mass% of sodium sulfate was added, the Ni grade increased obviously to 8.4 mass%, and then raised gradually to 9.3 mass% with sodium sulfate of 8.0 mass%. It can be concluded that the grade of Ni in the magnetic material can be effectively improved by adding sodium sulfate. Compared with the results in Figs. 6(a) and 6(b), it is observed that the content of Ni obtained at 1 420°C was relatively higher than that at 1 400°C.

To evaluate the reduction of ferric oxide during roasting, the grade of Fe in magnetic material as a function of sodium sulfate dosage is shown in **Fig. 7**. It is ascertained that the Fe grade was greatly improved even in the presence of 2.0 mass% sodium sulfate, however, it remained almost constant after that. With regard to the reduction temperature at 1 420°C, the Fe grade was slightly lower than that obtained at 1 400°C. This is mainly ascribed to the fact that more nickel was enriched in the magnetic material and the carburization phenomenon was enhanced at higher temperature.

### 4.1.2. The Recoveries of Ni and Fe in the Magnetic Material

The effect of sodium sulfate dosage on the recovery of Ni in the magnetic fraction is given in **Fig. 8**. It is found that the Ni recovery was greatly improved by increasing the dosage of sodium sulfate from 0 to 2.0 mass%. As the sodium sulfate was continuously increased, the recovery of Ni increased slightly after that. The Ni recovery reached 89.1% when the reduction temperature and dosage of sodium sulfate was 1 420°C and 8.0 mass%, respectively.

The relationship between the recovery of Fe in the magnetic material and the dosage of sodium sulfate was also investigated. The results in **Fig. 9** indicate that the recovery of Fe was similar with that of Ni. When the dosage of...
sodium sulfate increases from 0 to 2.0 mass%, the recovery of Fe was increased from 58.1% to 88.1% correspondingly at the reduction temperature of 1400°C. Thus, adding sodium sulfate during reduction roasting also facilitated the recoveries of both Ni and Fe.

4.1.3. The Content of Impurity Element in the Magnetic Material

The contents of S and P in the magnetic material are also examined and the results are shown in Fig. 10. As the dosage of sodium sulfate was increased, the content of S in the magnetic fraction was linearly increased. This is mainly due to that S would combine with metallic iron to form FeS, and then exists in the form of Fe–FeS in the magnetic material. According to the previous study, the metallic Ni and C can decrease the melting point of the iron metal. Therefore, the low melting point substance of FeS and Ni–Fe will be melted at 1400°C and aggregated to larger particles. The content of P in the magnetic material was relative lower, which increased firstly and then remained almost unchanged after that. In addition, the variation trend of S and P content in the magnetic material is observed to be similar at the experimental temperatures.

The effect of sodium sulfate addition on the contents of C and Si in the magnetic material is shown in Fig. 11. It is evident that the content of C in magnetic material firstly increased and then decreased with increase in the sodium sulfate dosage. Thermodynamic analysis indicated that the
addition of sodium sulfate is favorable to decrease the melting point of slag, which improved the fluidity and facilitated the carburization in the metal. However, sodium sulfate would also react with carbon, the carbon used to reduce the oxides was decreased when continuously increasing the sodium sulfate dosage. Therefore, the content of C in the magnetic material firstly increased and then decreased. It can be seen from Fig. 11 that, the content of Si was as high as 20.5 mass% in the magnetic material when reduced at 1400 °C in the absence of sodium sulfate. This is because part of silica was reduced to elemental Si, and then combined with metallic iron. The nickel bearing ferrosilicon turned into the magnetic material after magnetic separation. As sodium sulfate was added in the reduction process, the sodium salt will react with silica to form silicates. In addition, more liquid slag was formed which significantly promoted the growth of ferronickel and slag-metal separation. Consequently, the content of Si in the magnetic material was substantially decreased.

4.2. Mechanisms on Intensifying Reduction of Laterite Ore

4.2.1. Phase Transformation of Laterite Ore during Reduction

Sodium sulfate can greatly improve the reduction and slag-metal separation during roasting of nickel laterite. To find out the function of sodium sulfate on phase transformation, XRD analysis was carried out to reveal the difference between the briquettes reduced in the absence and presence of sodium sulfate. It can be seen from Fig. 12(a) that, metallic iron was still detected in the non-magnetic material when reduced without sodium sulfate, while it disappeared after adding 8.0 mass% sodium sulfate, which indicated that the addition of Na2SO4 was beneficial to separating iron from slag. The minerals including magnetite (Fe3O4), greigite (Fe3S4) and forsterite (Mg2SiO4) were observed in the non-magnetic material with Na2SO4. Sodium was not detected in the XRD pattern because of its low content or amorphous state.

Regarding the XRD results of magnetic material in Fig. 12(b), the iron mainly existed as metallic iron (Fe), iron nickel and kamacite (Fe–Ni). A small amount of greigite (Fe3S4) as well as magnetite (Fe3O4) were also observed under the condition of 8.0 mass% Na2SO4. However, other impurities including clinoenstatite ((Mg, Fe)SiO3) and enstatite (MgSiO3) were obviously mixed in the magnetic material without sodium sulfate. It indicated that sodium sulfate is beneficial to the aggregation and growth of ferronickel particles, and the slag-metal separation was also improved, which is consistent with the results shown in Figs. 6 and 7.

4.2.2. Growing Character of Ferronickel Particles

The microstructure of the reduced briquettes were studied by using SEM-EDS analysis to characterize the growing character of ferronickel particles during reduction roasting. The results obtained at 1400°C with roasting time of 60 minutes are given in Fig. 13.

As can be seen from Fig. 13(A), the ferronickel particles have not been well aggregated. Most of the particles were
smaller than 20 μm, which was adverse to magnetic separation. The main chemical composition of ferronickel particles is Fe, Ni together with Si, and Si was mainly existed in the form of elemental silicon. Figures 13(B) and 13(C) represent the microstructure of slag and ferronickel obtained from the roasted briquettes in the presence of 8.0 mass% sodium sulfate. Figure 13(B) shows that there are few ferronickel particles in the slag because the separation of metal and slag is relatively thorough (shown in Fig. 5). The gangue minerals as well as sodium were detected in the EDS results of slag (point 4). The SEM images in Fig. 13(C) reveal that there are two main phases in the ferronickel particle, namely ferronickel alloy (point 5) and Fe–Ni–S eutectoid (point 6). The eutectoid formed in the experimental temperature was melt due to its low melting point and precipitated between the ferronickel grains during solidification. It demonstrated that the addition of sodium sulfate not only improved the formation of liquid slag, but also facilitated generating low
melting eutectoid. Thus, both the growth and separation of ferronickel particles were promoted.

4.2.3. TG and Evolved Gas Analysis

The thermogravimetry analysis and ion current curves of evolved gases are shown in Figs. 14 and 15, respectively. Compared with the carbothermal reduction of nickel laterite without adding sodium sulfate, the initial reaction temperature decreased significantly after adding sodium sulfate. This is mainly due to the reduction of sodium sulfate by carbon at around 850–900°C, and the mainly chemical equations were shown as follows:

\[ \text{Na}_2\text{SO}_4 + 4C = \text{Na}_2\text{S} + 4\text{CO} \]  
\[ \text{Na}_2\text{SO}_4 + 4\text{CO} = \text{Na}_2\text{S} + 4\text{CO}_2 \]  
\[ \text{Na}_2\text{SO}_4 + 3\text{CO} = \text{Na}_2\text{O} + \text{S} + 3\text{CO}_2 \]

Moreover, the mass loss stage corresponding to the reduction of nickel and iron oxides also shifted forward by about 100°C. The gases of CO and CO\(_2\) which was generated from the reactions between sodium sulfate and C are beneficial to boudouard reaction as well as further reduction of nickel laterite. In addition, sodium ion can enhance the reactivity of graphite and improve the amorphous state of carbon. Therefore, adding sodium sulfate can effectively decrease the initial temperature of carbothermal reduction of nickel laterite.

According to the results in Fig. 15, the peak value of CO and CO\(_2\) ion intensity was observed at 1 200–1 250°C in the absence of sodium sulfate, while the corresponding peaks were obtained at 1 100–1 150°C after adding sodium sulfate. The relative ion intensity ratio of CO\(_2\)/CO with sodium sulfate is higher than that without adding sodium sulfate. It indicated that the utilization efficiency of reducing agent is higher in the presence of sodium sulfate. Besides, the peak value of CO and CO\(_2\) ion intensity was observed at 1 300–1 400°C. In the reduction process, the intermediate product FeO would react with SiO\(_2\) to generate Fe\(_2\)SiO\(_4\). The reduction of Fe\(_2\)SiO\(_4\) was difficult and will occur between 1 300°C and 1 400°C. Thus, the ion current of CO was formed in the temperature range of 1 300–1 400°C. It can be seen from Fig. 15 that the ion intensity of CO is smaller than that without sodium sulfate, this is because the formed Fe\(_2\)SiO\(_4\) is less than that without sodium sulfate. As sodium sulfate can improve the dynamic conditions and increase the reduction rate during roasting, more iron oxides would be reduced to Fe. Moreover, the sodium salts will react with SiO\(_2\), this also led to generating less content of Fe\(_2\)SiO\(_4\). In addition, no sulfurous gases were detected by the mass spectograph, it may be due to the sulfurous gas was very slight. In conclusion, adding sodium sulfate can also improve the dynamic conditions of chemical reaction and increase the reduction rate during roasting.

4.3. Comparison of the Present Study with Previous Studies

In this study, the product of ferronickel was prepared from nickel laterite by reductive roasting at 1 400 and 1 420°C with a relative small dosage of sodium sulfate. The addition of sodium sulfate in this study was lower than other studies and the experimental temperature was lower than the conventional smelting temperature in RKEF process. Moreover, although the Fe recovery was distinctly higher than the
other studies, the Ni grade in the magnetic material was still closed to 10.0 mass%. It indicated that both nickel and iron can be recovered in the present study. In order to describe the effective utilization coefficient of nickel ($E_Ni$) in different studies with respect to various nickel laterite ores, a new characterization method of normalization was proposed. The equation to calculate the effective utilization coefficient of nickel ($E_Ni$) can be expressed as follows:

$$E_Ni = \frac{G_{Nim}}{G_{Ni} \times R_{Fe} + G_{Nim}} \times 100\% \quad (6)$$

where $E_Ni$ is the effective utilization coefficient of nickel, %; $G_{Nim}$ is Ni grade in the raw material, mass%; $G_{Fe}$ is Fe grade in the raw material, mass%; $R_{Fe}$ is recovery ratio of Fe, %; $G_{Nim}$ is the Ni grade in magnetic material, mass%.

The results by comparing different studies are shown in Table 3. It can be seen that the effective utilization coefficient of nickel in this study is obviously higher than the previous studies.

5. Conclusions

In this study, the effect of sodium sulfate on preparation of ferronickel from nickel laterite by carbothermal reduction was investigated. The conclusions are drawn as follows:

1) A ferronickel product with 9.7 mass% Ni and 86.3 mass% Fe was prepared by reductive roasting at 1420°C for 60 min in the presence of 8.0 mass% sodium sulfate followed by dry magnetic separation. The corresponding recoveries of Ni and Fe reached up to 89.1% and 86.0%, respectively.

2) The content of sulfur in magnetic material increased gradually while that of silicon decreased remarkably with increase in the sodium sulfate dosage. The effective utilization coefficient of nickel was as high as 92.1% which was much higher than the previous studies.

3) The role of sodium sulfate can be summarized as: 1) improve the gasification of carbon and decrease the beginning temperature for reduction of nickel laterite; 2) more iron and nickel were liberated because of the reaction between sodium salt and silica; 3) the aggregation and growth of ferronickel particles as well as the slag-metal separation were enhanced due to the formation of low melting point of slag and ferronickel metals.

Acknowledgements

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REFERENCES


Table 3. Comparison of the present study with previous studies.

<table>
<thead>
<tr>
<th>Ni grade (raw material)</th>
<th>Reduction temperature</th>
<th>Additive, content</th>
<th>Reductant (magnetic material)</th>
<th>Recovery ratio (Ni)</th>
<th>Recovery ratio (Fe)</th>
<th>Theoretical Ni grade</th>
<th>$E_Ni$</th>
<th>Ferronickel size</th>
<th>Reference</th>
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<tbody>
<tr>
<td>1.8%</td>
<td>1420°C</td>
<td>NaSO₄, 8.0 mass%</td>
<td>coal</td>
<td>9.7%</td>
<td>89.1%</td>
<td>86.0%</td>
<td>10.5%</td>
<td>92.1%</td>
<td>This study</td>
</tr>
<tr>
<td>1.9%</td>
<td>1100°C</td>
<td>NaSO₄, 20.0 mass%</td>
<td>coal</td>
<td>9.5%</td>
<td>83.0%</td>
<td>56.4%</td>
<td>13.3%</td>
<td>71.3%</td>
<td></td>
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<tr>
<td>1.5%</td>
<td>1200°C</td>
<td>Na₂S, 10.0 mass%</td>
<td>coal</td>
<td>10.9%</td>
<td>88.6%</td>
<td>24.6%</td>
<td>14.9%</td>
<td>73.1%</td>
<td></td>
</tr>
<tr>
<td>1.5%</td>
<td>1200°C</td>
<td>Na₂SO₄, 10.0 mass%</td>
<td>coal</td>
<td>9.9%</td>
<td>90.1%</td>
<td>29.6%</td>
<td>12.7%</td>
<td>77.8%</td>
<td></td>
</tr>
<tr>
<td>1.5%</td>
<td>1200°C</td>
<td>Na₂O and S, 10.0 mass%</td>
<td>coal</td>
<td>9.3%</td>
<td>87.3%</td>
<td>30.8%</td>
<td>12.3%</td>
<td>75.9%</td>
<td></td>
</tr>
<tr>
<td>1.4%</td>
<td>800°C</td>
<td>H₂, 5.6%</td>
<td>coal</td>
<td>6.0%</td>
<td>92.1%</td>
<td>–</td>
<td>–</td>
<td>16.1 μm</td>
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<tr>
<td>1.4%</td>
<td>1100°C</td>
<td>CaSO₄, 6.0 mass%</td>
<td>coal</td>
<td>6.0%</td>
<td>92.1%</td>
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<td>16.1 μm</td>
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