

Article

Preparation of Nickel–Iron Concentrate from Low-Grade Laterite Nickel Ore by Solid-State Metalized Reduction and Magnetic Separation

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Abstract: In this paper, the process of solid-state metalized reduction and magnetic separation was investigated for preparation of nickel–iron concentrate from a low-grade laterite nickel ore. The effects of reduction temperature, reduction time, amount of dosages, and magnetic field strength on grades and recoveries of nickel and iron were studied. The results showed that nickel–iron concentrate with a nickel grade of 7.32%, nickel recovery of 81.84%, iron grade of 78.74%, and iron recovery of 69.78% were obtained under the conditions of a reduction temperature of 1200 °C, reduction time of 120 min, calcium fluoride addition of 12%, ferric oxide addition of 10%, coal addition of 12%, and magnetic field strength of 170 kA/m.

Keywords: laterite nickel ore; solid-state metalized reduction; magnetic separation; nickel–iron concentrate



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1. Introduction

Nickel (Ni) is widely used in chemical, metallurgical, petroleum, mechanical manufacturing, aerospace, and other fields due to its excellent physical and chemical properties, such as magnetic conductivity, plasticity, and corrosion resistance [1–3]. Global nickel production has continued to rise over the past one hundred years, especially after the year 2000. In recent years, the production capacity of laterite nickel ore in new global nickel mining projects has exceeded 50%, which indicates that laterite nickel ore has become an important direction for the utilization of nickel ore resources [4].

The utilization processes of laterite nickel ore could be generally divided into two types, i.e., hydrometallurgical process and pyrometallurgical process [5–11]. The typical hydrometallurgical processes include reduction-roasting–ammonia-leaching process and pressure-acid-leaching process [6,9], while the typical pyrometallurgical process is the rotary-kiln–electric-furnace-reduction-smelting process. The latter is widely used in laterite nickel ore smelters, and the pyrometallurgical process is primarily designed for high-grade laterite nickel ore [2]. However, the utilization of low-grade laterite nickel ore resources are receiving attention with the continuous consumption of laterite nickel ore resources, and the treatment processes of low-grade laterite nickel ore have been extensively studied [12–18], primarily including direct-reduction–magnetic-separation, reduction-sulfide-roasting–magnetic-separation and chlorination-separation–magnetic-separation. Huang et al. investigated a direct-reduction–magnetic-separation process to

obtain ferronickel granules from laterite nickel ore with 1.59% Ni and 16.86% Fe [19]. The ferronickel granules with the grades of 9.4% Ni and 87.5% Fe were obtained at the conditions of the roasting temperature 1350 °C, the C/O molar ratio 1.4, the roasting time 60 min, the limestone amount 20%, and the recoveries of Ni and Fe were 93.8% and 84.8%, respectively. Rao et al. investigated the reduction/sulfidation behaviors of a laterite nickel ore in the presence of sodium sulfate; the results showed that sodium sulfate was of benefit to the selective reduction of nickel, and the addition of sodium sulfate led to an increased nickel metallization ratio under the same roasting temperature and time [20]. Li et al. investigated direct-reduction–magnetic-separation process to obtain ferronickel particles from laterite nickel ore with 1.91% Ni and 22.1% Fe, and a ferronickel alloy with 9.48% Ni and 79.3% Fe was prepared by reduction roasting at 1100 °C for 60 min in the presence of 20 wt.% sodium sulfate followed by wet magnetic separation; the corresponding recoveries of Ni and Fe were 83.01% and 56.36%, respectively [3]. It was found that the addition of sodium sulfate could liberate iron and nickel from Ni/Fe-substituted lizardite, as well as increase the size of ferronickel particles considerably, and the roasting temperature was reduced to 1100 °C. Ma et al. studied the solid-state metalized reduction process to obtain nickel–iron concentrate from laterite nickel ore with 0.8% Ni and 10.9% Fe; the addition of calcium fluoride (CaF₂) dramatically improved the beneficiation of nickel and iron, and the grades of nickel and iron in the concentrate were increased from 2.5% and 62.6% to 6.9% and 71.4%, respectively [21]. The results suggested that the addition of CaF₂ could effectively promote the migration and polymerization of newly generated alloy particles, which improved the beneficiation of nickel and iron by magnetic separation.

In this paper, a solid-state metalized reduction and magnetic separation process was proposed to enrich Ni and Fe from a low-grade laterite nickel ore with Ni 0.98% and Fe 6.99%. The different parameters on the recovery rates of Ni and Fe and the grades of Ni and Fe in nickel iron concentrate were investigated in detail.

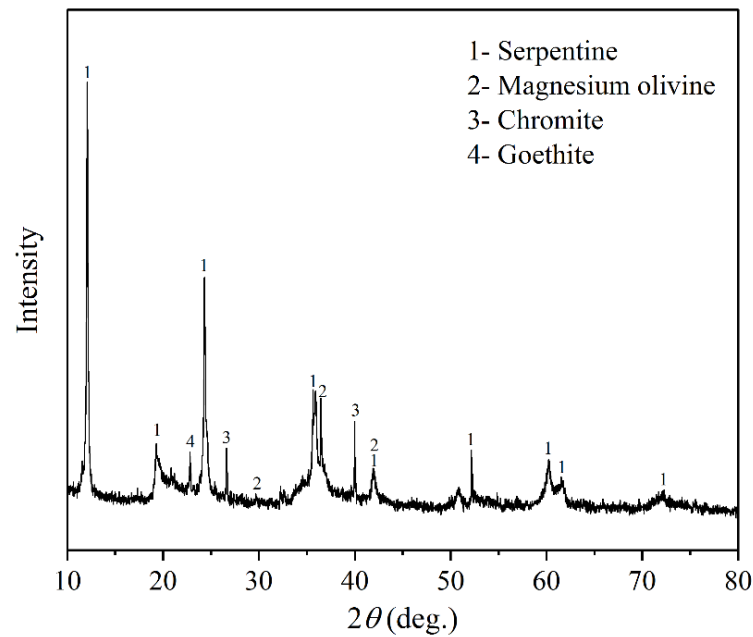
2. Materials and Methods

2.1. Materials and Reagents

The low-grade laterite nickel ore used in this study was obtained from Zimbabwe, and the major metal elements of the sample are listed in Table 1. From Table 1, we can see that the content of Ni and Fe in the low-grade laterite nickel ore are 0.98% and 6.99%, respectively, which clearly suggests that the nickel content of the sample is low, and the iron content is significantly lower than previous literature reported [3,19–21]. Therefore, it is needed to investigate how to recover Ni from the low-grade laterite nickel ore with low Fe content. The mineral composition was determined via XRD; the XRD pattern is shown in Figure 1, and the main mineral compositions are shown in Table 2. As can be seen from Table 2, the major mineral phases are serpentinite ((Mg,Fe,Ni)₃Si₂O₅(OH)₄), magnesium olivine (Mg₂(SiO₄)) and chromite ((Fe,Mg)Cr₂O₄), the contents of which are 64.4%, 19.3%, and 6.4%, respectively. And the goethite (FeOOH), hornblende ((Ca,Na)₂(Mg,Fe,Al)₅[(Al,Si)₈O₂₂](OH)₂) and quartz (SiO₂) are minor mineral phases with contents of 3.4%, 3.4%, and 1.4%, respectively. The embedding particle size of the main minerals were analyzed with MLA analysis, as shown in Table 3. From Table 3, we can see that the particle size of serpentinite and magnesium olivine in the sample are mainly distributed below 150 µm and uniformly distributed in different particle size ranges. The particle size of chromite in the sample is mainly distributed in the particle size of 38 µm and 150 µm. The reductant used in this study was coking coal, with the calorific value of 7193 kcal/kg, and the chemical analysis of the coal is given in Table 4. The calcium fluoride (CaF₂) and iron oxide (Fe₂O₃) were obtained from Sinopharm Chemical Reagent Co., Ltd., Shanghai, China. The CaF₂ was an analytical reagent, and the content of CaF₂ was higher than 98.5%. The Fe₂O₃ was an analytical reagent, and the content of Fe was between 69.8% and 70.1%.

Table 1. Main chemical compositions of nickel laterite ore (wt.%).

Ni	SiO ₂	MgO	TFe	Cr	Co	Cu
0.98	39.65	32.45	6.99	0.26	0.013	0.01
CaO	Al ₂ O ₃	MnO	TiO ₂	K ₂ O	S	P
0.18	0.066	0.099	0.11	0.0049	0.050	0.0039

**Figure 1.** XRD pattern of nickel laterite ore.**Table 2.** Main mineral compositions of nickel laterite ore (wt.%).

Serpentinite	Magnesium Olivine	Chromite	Hornblende
64.4	19.3	6.3	3.4
Goethite	Quartz	Others	
3.4	1.4	1.2	

Table 3. The embedding particle size of the main minerals of nickel laterite ore (wt.%).

Granularity (μm)	Serpentinite and Magnesium Olivine	Chromite	Goethite	Hornblende
150–300	5.75	2.04	0.3	0
75–150	18.96	53.15	3.96	0.76
38–75	21.04	29.47	13.17	4.72
20–38	20.94	7.94	15.01	4.79
10–20	15.93	3.37	22.3	30.85
<10	17.36	4.04	45.26	58.9

Table 4. Chemical compositions of coal (wt.%).

Fixed Carbon	Volatile Matter	Ash	Moisture	S
78.51	8.96	10.43	2.10	0.36

2.2. Methods and Equipment

The main parameters affecting solid-state metalized-reduction tests in this study are roasting temperature, roasting time, coal content, CaF_2 content, and Fe_2O_3 content. Five groups of tests were designed to investigate the effects of these factors on Ni and Fe recoveries. The solid-state metalized reduction tests were performed in a muffle furnace (DC-B15/16, Beijing Du Chuang Ke Ji, Co., Ltd., Beijing, China), and the roasting temperature was controlled by a programmable control cabinet with a precision of $\pm 2^\circ\text{C}$. Firstly, the ore was ground using a ball mill (XMQ-350 $\times$ 160, Wuhan Exploration Machinery, Co., Ltd., Wuhan, China) to -0.074 mm, accounting for 70%, and the coal was ground using a vibration mill to -0.074 mm, accounting for 80%. Secondly, the pulverized ore sample was mixed evenly with pulverize coal, CaF_2 , and Fe_2O_3 in the preset proportion, and the coal, CaF_2 , and Fe_2O_3 addition percentages represent the percentages of weight of coal, CaF_2 , and Fe_2O_3 addition to the weight of the original ore, respectively. Thirdly, the 200 g of mixed sample was weighed and placed into a silicon carbide graphite crucible (the volume was 226 cubic centimeters) with a tight-fitting lid. When the temperature in the muffle furnace reached the preset temperature, the crucible was placed into the muffle furnace, and the timing was initiated after shutting the door of the muffle furnace. The type of atmosphere in the muffle furnace was not adjusted during the reduction-roasting process. After being held at the preset temperature for a definite time, the crucible was taken out and quenched in water to prevent the reoxidation of the reduction product. The cooled reduction product was filtered and dried at 80°C . Fourthly, the reduction product was ground with a small amount of water using an XZM-100 laboratory vibratory mill (Wuhan Exploration Machinery Co., Ltd., Hubei, China) to 85%, passing -0.045 mm. Finally, the as-received product was subjected to wet magnetic separation through a CXG- $\phi 50$ magnetic tube (Wuhan Exploration Machinery Co., Ltd., Hubei, China) to obtain the nickel-iron concentrate.

$$\eta_N = \frac{m \times \gamma^1}{M \times \gamma^0} \times 100\% \quad (1)$$

The recovery of Ni was calculated as Equation (1), where η_N is the recovery of Ni; m is the weight of nickel-iron concentrate, g; M is the weight of nickel laterite ore, g; γ^1 is the grade of Ni in nickel-iron concentrate, %; and γ^0 is the grade of Ni in nickel laterite ore, %.

$$\eta_F = \frac{m \times \gamma_F^1}{M_F \times 0.7 + M \times \gamma_F^0} \times 100\% \quad (2)$$

The recovery of Fe was calculated as Equation (2), where η_F is the recovery of Fe; m is the weight of nickel-iron concentrate, g; M is the weight of nickel laterite ore, g; M_F is the weight of Fe_2O_3 addition, g; γ^1 is the grade of Fe in nickel-iron concentrate, %; γ^0 is the grade of Fe in nickel laterite ore, %.

The chemical components of products were analyzed by Atomic Absorption Spectrometer ICE3500 (ThermoScientific, Waltham, MA, USA). X-ray diffraction (XRD) data collection was performed with a Rigaku D/Max-1200 (20 mA, 40 kV; the scanning rate of $10^\circ/\text{min}$) from 3° to 80° , with 0.02° increments). The microscopic photos were observed by electron microscope (ZEISS Axioskop 40, ZEISS, Oberkochen, Germany). The elemental composition of the particular regions was analyzed by scanning electron microscopy, combined with energy-dispersive spectroscopy and electron probe (Shimadzu EPMA-1720, Shimadzu Corporation, Kyoto, Japan). The embedding particle size of the main minerals were analyzed by MLA (FEI MLA650F, FEI Company, Hillsboro, OR, USA).

2.3. Thermodynamic Basis

The description of the carbothermic reactions of laterite nickel ore has been investigated [12,20–22], and the carbothermic reactions of chromite pellets have also been investigated by Li, J.C. et al. [23]. The related reactions and the corresponding values of standard Gibbs free energy change are presented in Table 5. From Table 5, the NiO could be reduced

to metallic Ni at the lowest temperature, 435 °C; the Fe₂O₃ would be reduced to Fe₃O₄ at the lowest temperature, 798 °C; the Fe₃O₄ would be reduced to FeO at the lowest temperature, 880 °C; the FeO could be reduced to metallic Fe at the lowest temperature, 596 °C; the chromite (FeO·Cr₂O₃) could be reduced to metallic Fe at the lowest temperature, 909 °C. The softening point of magnesium-rich nickel oxide ore was higher than 1350 °C [21]. The above analysis shows that the solid-state metalized reduction in this laterite nickel ore using coal as reductant is thermodynamically feasible.

Table 5. $\Delta G_T^0 - T$ of iron and nickel oxides reduction by solidstate carbon.

Chemical Equation	$\Delta G_T^0 - T$ (J/mol)	
$\text{NiO}_{(s)} + \text{C}_{(s)} = \text{Ni}_{(s)} + \text{CO}_{(g)}$	122,207–172.83 T	(1)
$\text{NiO}_{(s)} + \text{CO}_{(g)} = \text{Ni}_{(s)} + \text{CO}_{2(g)}$	−37,600–11.8 T	(2)
$\text{C}_{(s)} + \text{CO}_{(s)} = \text{CO}_{2(g)}$	170,700–174.5 T	(3)
$3\text{Fe}_2\text{O}_{3(s)} + \text{C}_{(s)} = 2\text{Fe}_3\text{O}_{4(s)} + \text{CO}_{(g)}$	237,700–222 T	(4)
$3\text{Fe}_2\text{O}_{3(s)} + \text{CO}_{(g)} = 2\text{Fe}_3\text{O}_{4(s)} + \text{CO}_{2(g)}$	−52,130–41.0 T	(5)
$\text{Fe}_3\text{O}_{4(s)} + \text{CO}_{(g)} = 3\text{FeO}_{(s)} + \text{CO}_{2(g)}$	35,380–40.2 T	(6)
$\text{Fe}_3\text{O}_{4(s)} + \text{C}_{(s)} = 3\text{FeO}_{(s)} + \text{CO}_{(g)}$	262,350–179.7 T	(7)
$\text{FeO}_{(s)} + \text{CO}_{(g)} = \text{Fe}_{(s)} + \text{CO}_{2(g)}$	−10,556.2–17.69 T	(8)
$\text{FeO} \cdot \text{Cr}_2\text{O}_{3(s)} + \text{C}_{(s)} = \text{Fe}_{(s)} + \text{Cr}_2\text{O}_3 + \text{CO}_{(g)}$	163,755–138.49 T	(9)

3. Results

3.1. Effect of Reduction Temperature

Many studies have proven that the reduction temperature has a significant impact on the nickel–iron concentrate for laterite nickel ore treated by pyrometallurgical process. Therefore, the effect of different reduction temperatures on the nickel–iron concentrate in the range of 1100 °C to 1300 °C was investigated under the conditions of reduction time 90 min, coal addition 10%, CaF₂ addition 12%, Fe₂O₃ addition 10%, and magnetic field strength 170 kA/m, and the results are shown in Figure 2. As shown in Figure 2, the recoveries of nickel and iron display a parabolic trend, reaching a maximum value at 1225 °C, and this variation is similar to the solid-state metalized reduction for the nickel oxide ore from Yunnan Province, China [21]. The increase in recoveries of nickel and iron suggests that the migration and aggregation behavior of nickel and iron were significantly enhanced by increasing the temperature from 1100 °C to 1225 °C. The XRD patterns of the reduction product at 1200 °C and 1250 °C are shown in Figure 3. As shown in Figure 3, the characteristic peaks of [Fe,Ni] proved that nickel and iron had been metalized and generated alloys at the solid-state temperature of 1200 °C. From Figure 3, we also found that characteristic peaks of katophorite ($\text{Na}_2\text{Ca}(\text{Mg},\text{Fe}^{(2+)})_4(\text{Al},\text{Fe}^{(3+)})[\text{Si}_7\text{AlO}_{22}](\text{OH},\text{F})_2$) and riebeckite ($\text{Na}_2\text{Fe}_3^{(2+)}\text{Fe}_2^{(3+)}[\text{Si}_4\text{O}_{11}]_2(\text{OH})_2$) at 1250 °C are stronger than 1200 °C, and the characteristic peaks of tremolite ($2\text{CaO} \cdot 5\text{MgO} \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$) are weaker than 1200 °C, which implied that a part of Fe is converted into katophorite and riebeckite when the reduction temperature was higher than 1250 °C. This might result in the decreasing of recoveries of nickel and iron. As the temperature increases from 1100 to 1200 °C, the nickel grade increases from 1.69% to 7.31%, reaching a maximum at 1200 °C and no longer changing as the temperature increases. Similarly, the Fe grade in nickel–iron concentrate increases from 43.03% to 80.06% with the temperature increasing from 1100 °C to 1200 °C. However, after 1200 °C, the grade of Fe in nickel–iron concentrate shows a downward trend. It should be noted that the reduction product exhibits a melting phenomenon when the reduction temperature is higher than 1225 °C, which is not conducive to the industrial application of this process in rotary kiln systems. The above results show that the temperatures ranging from 1200 °C to 1225 °C are optimal.

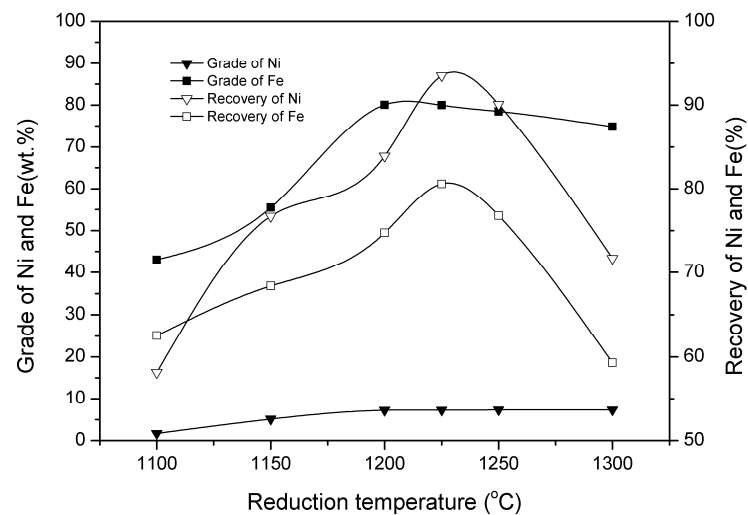


Figure 2. Effect of reduction temperature on grades and recoveries of Ni and Fe.

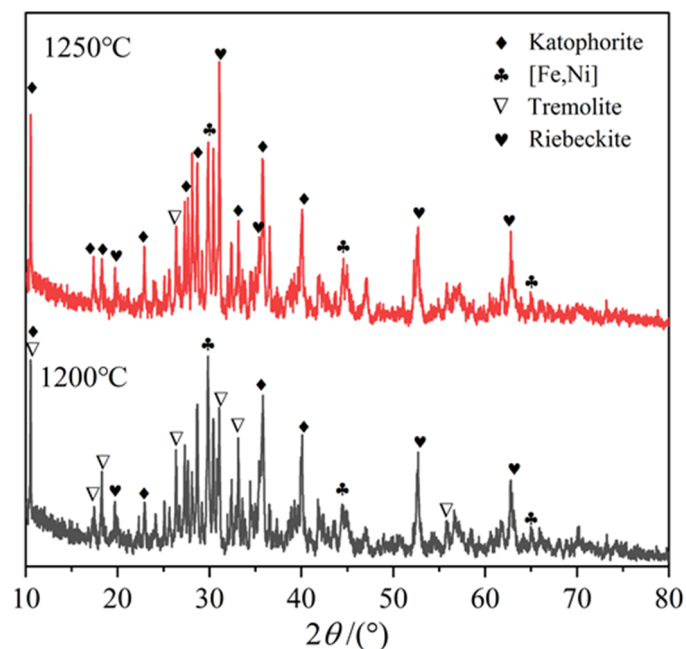


Figure 3. XRD pattern of the reduction product at 1200 °C and 1250 °C.

3.2. Effect of Reduction Time

Under the conditions of reduction temperature 1200 °C, coal addition 10%, CaF_2 addition 12%, Fe_2O_3 addition 10%, and magnetic field strength 170 kA/m, the effect of reduction time on the nickel–iron concentrate was examined, and the results are shown in Figure 4. As shown in Figure 4, the grades of Ni and Fe in nickel–iron concentrate changed insignificantly with increasing reduction time from 60 min to 240 min, but the recoveries of Ni and Fe in nickel–iron concentrate iron increased gradually from 60 min to 120 min and decreased gradually when the reduction time exceeds 150 min. The reason might be that the ferro-nickel granules generated would become more tightly bound to surrounding minerals with the increasing roasting time. Therefore, the reduction time varying between 120 min and 150 min is optimal.

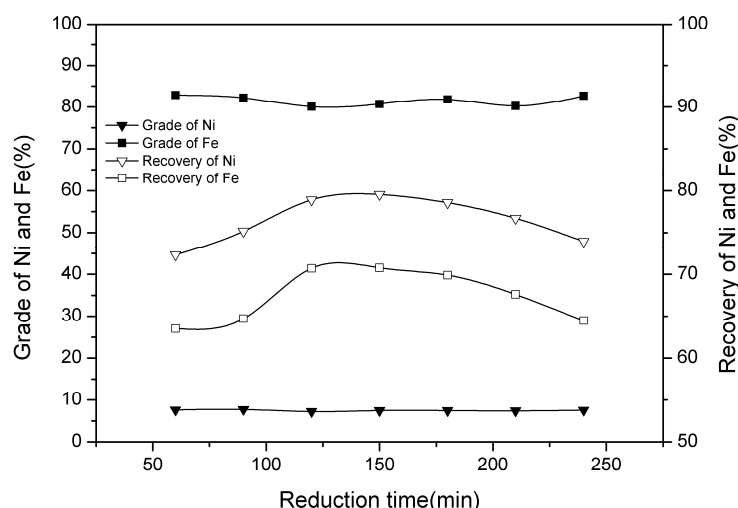


Figure 4. Effect of reduction time on grades and recoveries of Ni and Fe.

3.3. Effect of Coal Addition

Coal has been applied in many metal reduction processes to improve the reduction rate. The effect of coal addition on the nickel–iron concentrate was investigated under the conditions of reduction temperature 1200 °C, reduction time 120 min, CaF_2 addition 12%, Fe_2O_3 addition 10%, and magnetic field strength 170 kA/m, and the results are shown in Figure 5. As shown in Figure 5, the grades of Ni and Fe in nickel–iron concentrate increase gradually with increasing coal addition, and the grade of Fe increases more obviously when the coal addition is less than 10%. The recoveries of nickel and iron show parabolas and reach the maximum values at coal addition 10%. This phenomenon is primarily owing to the increasing coal addition providing a more comprehensive reduction atmosphere and increasing the effective surface area of the reaction when the coal addition is less than 10% [2]. However, the excessive coal addition at high temperatures would accelerate the reduction in ferrocarburizing, which would reduce the metallization rate of the reduction product. Therefore, the coal addition 10% is optimal.

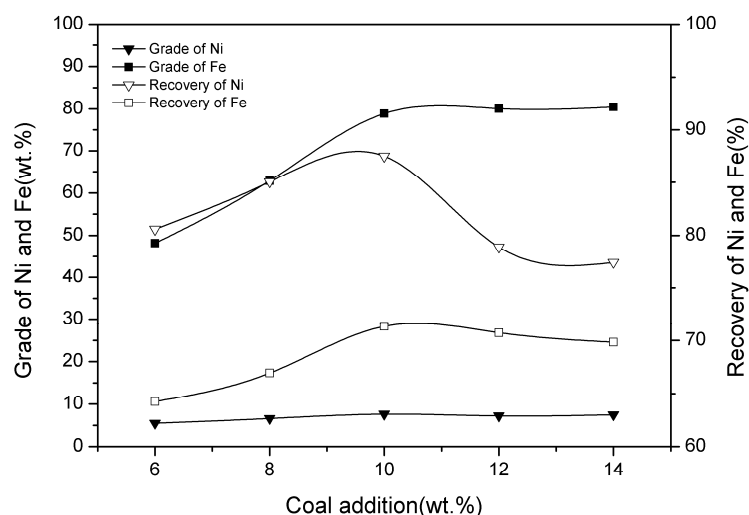


Figure 5. Effect of coal addition on grades and recoveries of Ni and Fe.

3.4. Effect of CaF_2 Addition

Ma et al. reported a method “solid-state metalized reduction of magnesium-rich low-nickel oxide ore”, and the results showed that CaF_2 addition could reduce the surface tension of ferronickel alloy particles, which resulted in nickel and iron, and could metalize

and aggregate as banded solid solution below the molten temperature [19]. In this test, the effect of CaF_2 addition on the nickel–iron concentrate was investigated under the conditions of reduction temperature 1200°C , reduction time 120 min, coal addition 10%, Fe_2O_3 addition 10%, and magnetic field strength 170 kA/m, and the results are shown in Figure 6. As shown in Figure 6, the grades and recoveries of Ni and Fe in nickel–iron concentrate increase constantly with the increasing CaF_2 addition, which indicates that CaF_2 can promote the generation of ferronickel and improve the aggregation of ferro-nickel granules (bright white particles). And the microscope photos (Figure 7) show a significant increase in the number and particle size of alloy particles after the addition of CaF_2 . However, the reduction product exhibits a melting phenomenon (the reduction product was fused together) when the CaF_2 addition exceeded 12%, which is disadvantageous for the industrial application of this process in rotary kiln systems. Therefore, the 12% CaF_2 addition is optimal.

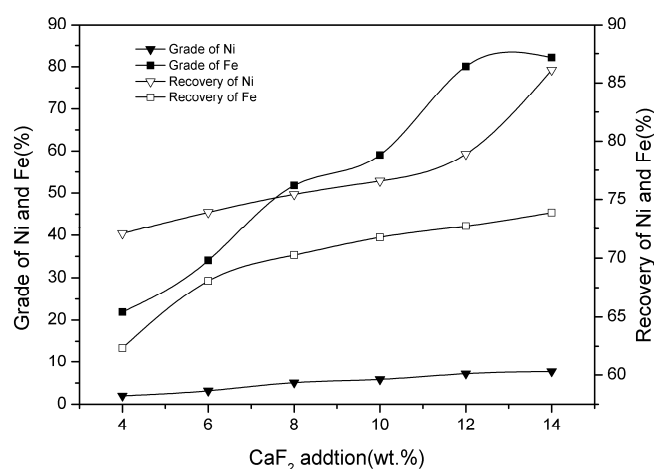


Figure 6. Effect of CaF_2 addition on grades and recoveries of Ni and Fe.

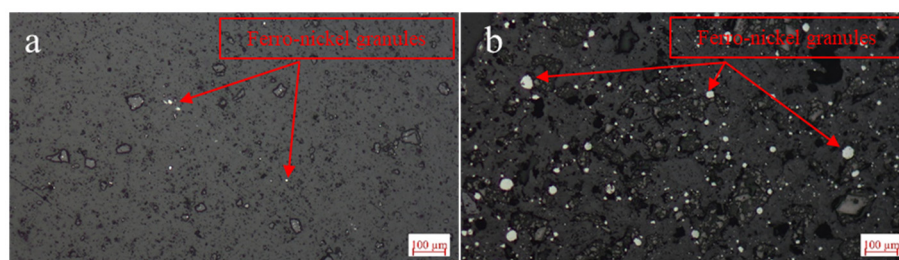


Figure 7. Microscopic photos: absence of CaF_2 (a) and presence of CaF_2 (b). The bright white particles represent ferro-nickel granules.

3.5. Effect of Fe_2O_3 Addition

Our preliminary experimental results showed that the addition of iron could improve the recovery of nickel; the reason might be that the addition of iron could promote the generation of ferronickel, which could improve the ability to capture nickel. In this test, the effect of Fe_2O_3 addition on the nickel–iron concentrate was investigated under the conditions of reduction temperature 1200°C , reduction time 120 min, coal addition 10%, CaF_2 addition 12%, and magnetic field strength 170 kA/m, and the results are shown in Figure 8. As shown in Figure 8, the grades of Ni and Fe in the nickel–iron concentrate display a parabolic shape and reach the maximum values at a 10% Fe_2O_3 addition; the reason might be due to the fact that an appropriate amount of iron addition could promote the generation of ferro-nickel granules, while excessive iron can lead to a higher iron content in ferro-nickel granules, which results in a decrease in nickel grade. And the microscope photos (Figure 9) also show a significant increase in the particle size of ferro-

nickel granules (bright white particles) after the addition of Fe_2O_3 . The recoveries of Ni and Fe in nickel–iron concentrate increased constantly with the increased Fe_2O_3 addition, and when the Fe_2O_3 addition was 10%, the recoveries of Ni and Fe reach the maximum values and then almost level off. Therefore, in this test, the 10% Fe_2O_3 addition is optimal.

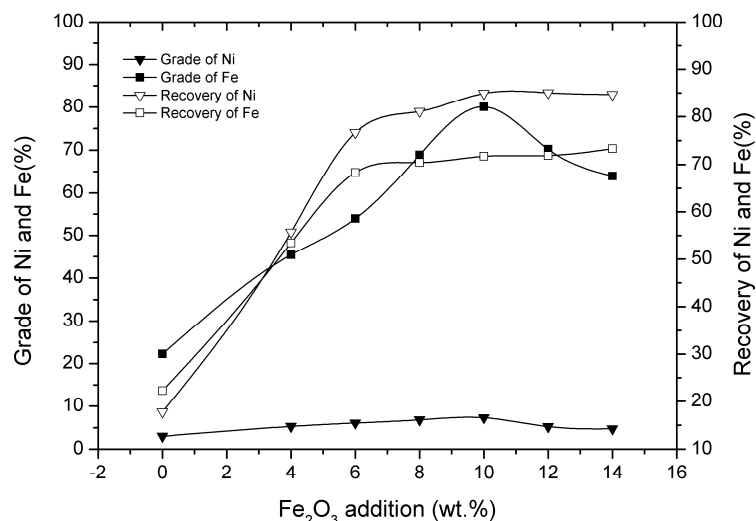


Figure 8. Effect of Fe_2O_3 addition on grades and recoveries of Ni and Fe.

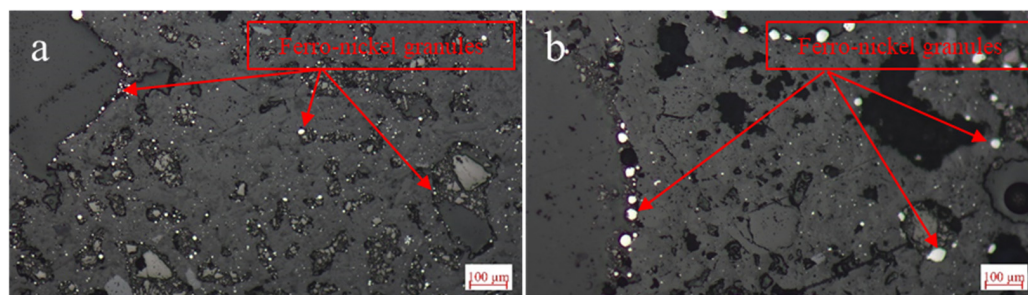


Figure 9. Microscopic photos absence of Fe_2O_3 (a) and presence of Fe_2O_3 (b). The bright white particles represent ferro-nickel granules.

3.6. Elemental Composition of the Particular Regions in Reduction Product

In this test, the elemental composition of the particular regions in reduction product was analyzed. The results of SEM image and EDS elemental analysis are shown in Figure 10, and the results of electron probe analysis are shown in Tables 6–8. The SEM images showed a mass of bright white particles generated and embedded in the charcoal gray matrix. The EDS analysis results show that reduction product are mainly composed of nickel–iron particles, tremolite-like minerals, and talc-like minerals. As shown in Table 6, the electron probe analysis show that the elemental composition of nickel–iron particles are Fe, Ni, Si, and Co, and the contents are 84.05%, 12.92%, 0.35%, and 0.32%, respectively. As shown in Table 7, the elemental composition of the tremolite-like mineral is SiO_2 and MgO , and the contents are 60.00% and 37.28%, respectively. As shown in Table 8, the elemental composition of the talc-like mineral is SiO_2 and MgO , and the contents are 54.52% and 20.84%, respectively.

Table 6. The elemental compositions of nickel–iron particles.

Co	Fe	Si	Ni	S	Total
0.32	84.06	0.35	12.92	0.02	97.67

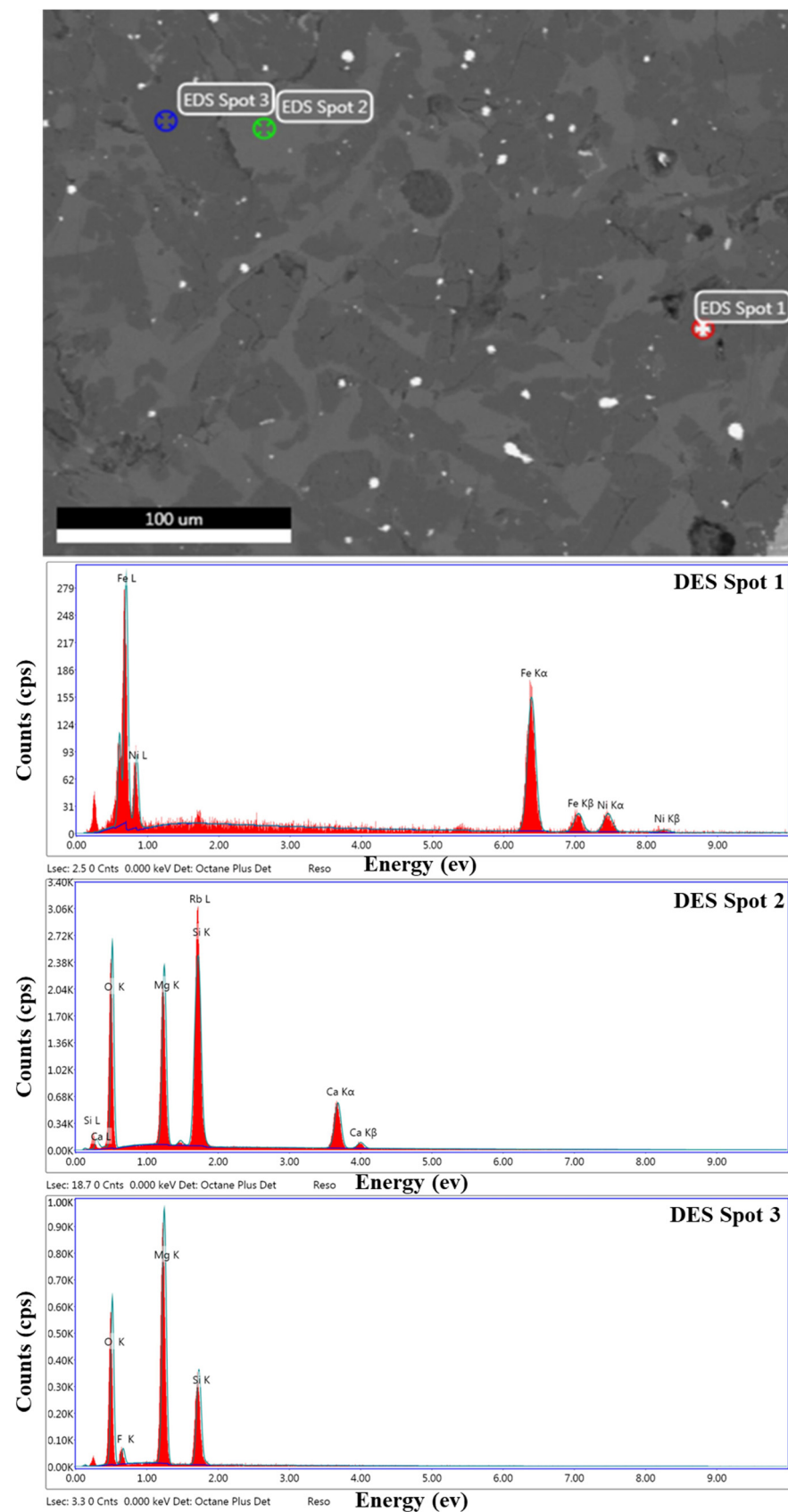


Figure 10. SEM image and EDS elemental analysis of the solid-state metalized-reduction product (fixed conditions: reduction temperature 1200 °C, reduction time 120 min, coal addition 10%, CaF₂ addition 12%, Fe₂O₃ addition 10%).

Table 7. The elemental compositions of the tremolite-like minerals.

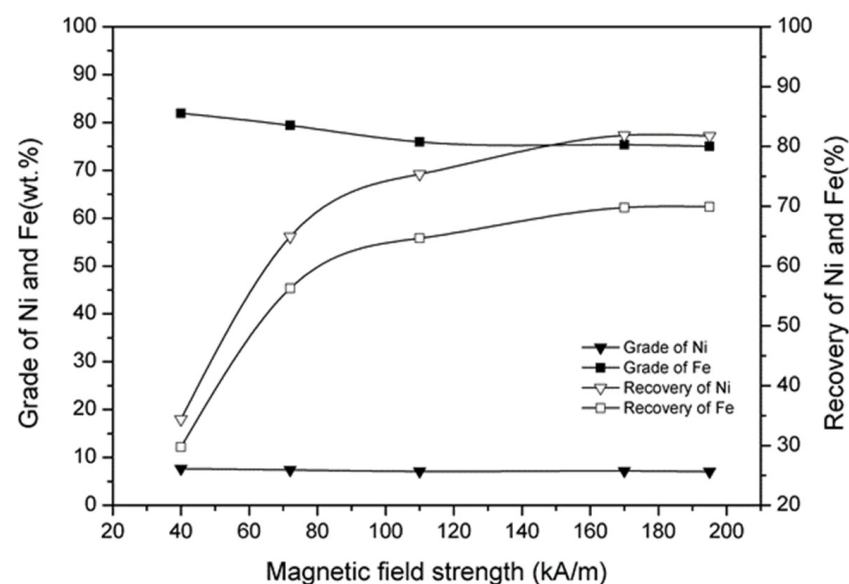
F	MnO	TiO ₂	SiO ₂	Na ₂ O	Fe ₂ O ₃	Cr ₂ O ₃
0.086	0.11	0.004	60.00	0.01	1.74	0.32
P ₂ O ₅	MgO	NiO	CaO	Al ₂ O ₃	Total	
0.004	37.28	0.005	0.61	0.18	100.34	

Table 8. The elemental compositions of the talc-like minerals.

F	MnO	TiO ₂	SiO ₂	Na ₂ O	Fe ₂ O ₃	Cr ₂ O ₃
1.421	0.098	0.02	54.52	0.018	0.20	0.25
P ₂ O ₅	MgO	NiO	CaO	Al ₂ O ₃	Total	
0.021	20.84	0.009	17.97	2.12	97.48	

3.7. Effect of Magnetic Separation

The magnetic field strength and grinding fineness are the main factors affecting the magnetic separation results. In this test, the effect of magnetic field strength and grinding fineness on the nickel–iron concentrate were also investigated, and the results are shown in Figures 11 and 12. As shown in Figure 11, the grades of Ni and Fe in nickel–iron concentrate decrease slightly with the magnetic field strength increasing, and the grade of Fe decreases more significantly. The recoveries of Ni and Fe in nickel–iron concentrate increase constantly with the magnetic field strength increasing, and when the magnetic field strength is 170 kA/m, the recoveries of Ni and Fe reach the maximum values and then almost level off. Therefore, the magnetic field strength 170 kA/m is optimal. As shown in Figure 12, the grades of Ni and Fe in the nickel–iron concentrate increase slightly with the grinding fineness increasing. However, the recoveries of Ni and Fe in the nickel–iron concentrate decrease gradually with the grinding fineness increasing. Therefore, the grinding fineness -0.045 mm accounted for 80% is optimal.

**Figure 11.** Effect of magnetic field strength on grades and recoveries of Ni and Fe.

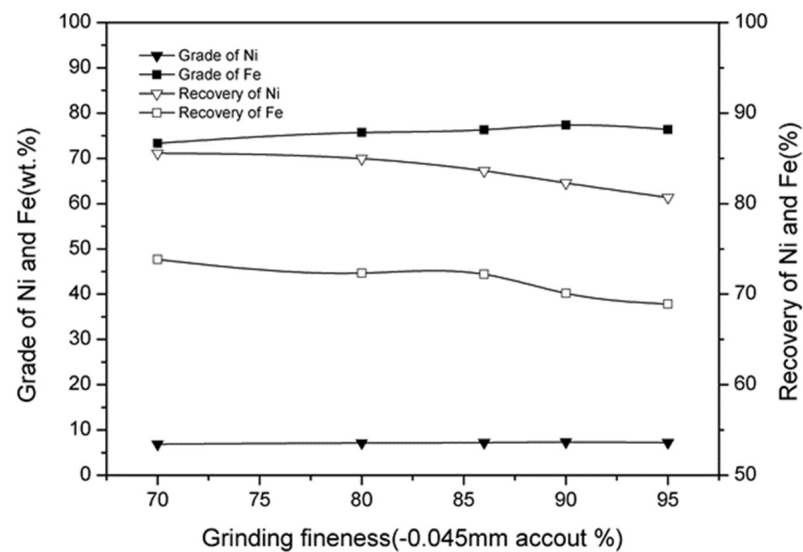


Figure 12. Effect of grinding fineness on grades and recoveries of Ni and Fe.

4. Discussion

Based on the above-mentioned results, a solid-state metalized reduction and magnetic separation process is presented for preparation of nickel–iron concentrate from low-grade laterite nickel ore, as shown in Figure 13. Firstly, the pulverized ore was mixed with pulverize coal, CaF_2 , and Fe_2O_3 in the preset proportion evenly. Secondly, the mixed sample was reduction-roasted in the muffle furnace. After reduction, the cooled reduction product was ground to 80%, passing -0.045 mm. Finally, the nickel–iron concentrate was obtained by magnetic separation. The nickel–iron concentrate with nickel and iron grades of 7.32% and 78.74%, respectively, was obtained, and the recoveries of nickel and iron were 81.84% and 69.78%, respectively. The main chemical compositions and XRD analyses of nickel–iron concentrate are shown in Table 9. As shown in Table 9, nickel and iron are effectively enriched, and the nickel–iron concentrate meets the FeNi7.5 grade II standard for pig iron containing nickel GB/T 28296-2012. Table 9 also suggests that the chromium (Cr), copper (Cu), and cobalt (Co) are enriched in nickel–iron concentrate, the Cr content is enriched from 0.26% to 0.86%, the Co content is enriched from 0.013% to 0.098%, and the Cu content is enriched from 0.01% to 0.082%.

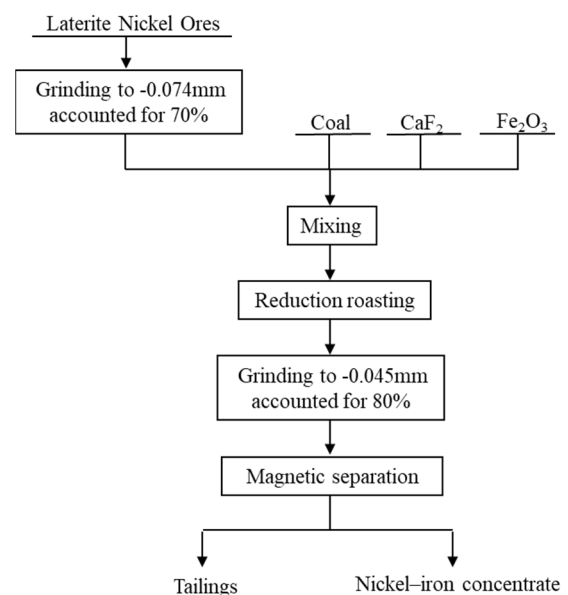


Figure 13. The process chart of the recovery of Ni from a low-grade laterite nickel ore.

Table 9. Main chemical compositions of nickel–iron concentrate (wt.%).

Ni	TFe	Si	Cr	Co
7.32	78.74	4.18	0.86	0.098
Cu	C	S	P	
0.082	0.78	0.21	0.008	

5. Conclusions

A feasible process was employed for preparation of nickel–iron concentrate from low-grade laterite nickel ore from Zimbabwe by solid-state metallized reduction and magnetic separation. Our experiments lead to the following conclusions:

1. The serpentinite, magnesium olivine, and chromite were the major constituent minerals in the laterite nickel ore investigated in this study, and the content of Ni and Fe were 0.98% and 6.99%, respectively. The particle size of serpentinite and magnesium olivine were mainly distributed below 150 μm and uniformly distributed in different particle size ranges. The particle size of chromite in the sample was mainly distributed between 38 μm and 150 μm , and the particle size of goethite was mainly distributed below 38 μm .
2. The addition of CaF_2 for the solid-state metallized reduction could dramatically improve the beneficiation of nickel and iron. When the addition of CaF_2 was 12 wt.% of laterite nickel ore, the grades of nickel and iron in the nickel–iron concentrate increased from 2.01% and 21.92% to 7.32% and 78.74%, respectively; meanwhile, the recoveries of nickel and iron increased to 81.84% and 69.78%, respectively.
3. Appropriate amounts of Fe_2O_3 addition for the solid-state metallized reduction could promote the generation of ferro-nickel granules. When the addition of Fe_2O_3 was 10 wt% of laterite nickel ore, the grade and recovery of nickel in the nickel–iron concentrate increased from 3.02% and 17.79% to 7.32% and 81.84%, respectively.
4. A nickel–iron concentrate with a nickel grade of 7.32%, nickel recovery of 81.84%, iron grade of 78.74%, and iron recovery of 69.78% was obtained under the conditions of a reduction temperature of 1200 $^\circ\text{C}$, reduction time of 120 min, calcium fluoride addition of 12%, ferric oxide addition of 10%, coal addition of 12%, and magnetic field strength of 170 kA/m.

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