

Two-stage reduction for the preparation of ferronickel alloy from nickel laterite ore with low Co and high MgO contents

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Abstract: The preparation of ferronickel alloy from the nickel laterite ore with low Co and high MgO contents was studied by using a pre-reduction–smelting method. The effects of reduction time, calcination temperature, quantity of reductant and calcium oxide (CaO), and pellet diameter on the reduction ratio of Fe and on the pellet strength were investigated. The results show that, for a roasting temperature >800 °C, a roasting time >30 min, 1.5wt% added anthracite coal, 5wt% added CaO, and a pellet size of ~10 mm, the reduction ratio of Fe exceeds 70% and the compressive strength of the pellets exceeds 10 kg per pellet. Reduction smelting experiments were performed by varying the smelting time, temperature, quantity of reductant and CaO, and reduction ratio of Fe in the pellets. Optimal conditions for the reduction smelting process are as follows: smelting time, 30–45 min; smelting temperature, 1550°C; quantity of reductant, 4wt%–5wt%; and quantity of CaO, 5wt%; leading to an Fe reduction ratio of 75% in the pellets. In addition, the mineral composition of the raw ore and that during the reduction process were investigated by process mineralogy.

Keywords: pre-reduction; smelting; ferronickel alloy; nickel laterite ore

1. Introduction

An increasing number of studies have focused on the pyrometallurgical and hydrometallurgical processing of nickel laterite ores, and many approaches have been presented. Pyrometallurgical processes include pre-reduction–smelting [1], direct reduction [2–3], semi-molten state reduction [4], and coal-based self-reduction [5], whereas hydrometallurgical processes include the Caron process [6], reduction roast leaching [7–8], atmospheric and high pressure acid leaching [9–12], and chlorinated water leaching [13]. Thus, debate continues regarding which treatment is best suited for processing high-MgO nickel laterite ores [14].

Several methods for processing low-grade nickel laterite ores with a high MgO content have been investigated. Li *et al.* [15] used a solid-state deoxidation technique to obtain Ni by reducing low-grade nickel laterite ores. Jiang *et al.* [16] produced a high-Ni-grade ferronickel from laterite ores us-

ing the selective-reduction wet-magnetic separation process, with the addition of sodium sulfate. Valix *et al.* [17] adopted a biological leaching method to recover Ni and Co from nickel laterite ores. Finally, Lee *et al.* [18] proposed an electrochemical leaching method to extract Ni from low-grade laterites containing less than 2wt% Ni.

The nickel laterite ore from Tagaung Taung, Myanmar, has high moisture and high MgO content and its Ni content can reach an average level of ~2wt%. Because of the low Co content of this ore, Co recovery via pyrometallurgy is not required. Given the process reliability, the flexibility of the raw material, the management of production, and the investment returns, the rotary-kiln-electric-furnace (RKEF) smelting [19–20] has proven very feasible for processing the Ni ore from Tagaung Taung. Fig. 1 shows a flow chart for this process. The RKEF process offers the following advantages: (1) it is a mature, short-flow, and convenient technology; (2) it is feasible for and applicable to different types of materials; (3) the smelting conditions are controlla-

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ble and economical and offer high metal recovery; (4) the flue gas contains essentially no SO₂ and little soot and is therefore easily processed; (5) construction is rapid and efficient, thereby requiring less investment.

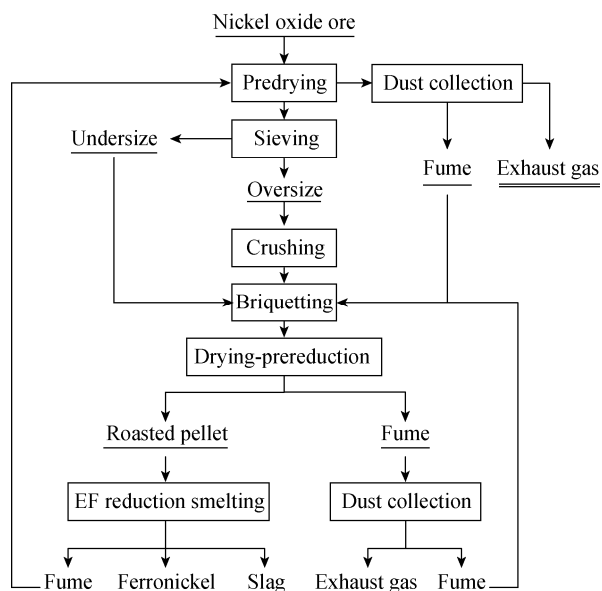


Fig. 1. Flow chart for processing the nickel laterite ore from Tagaung Taung, Myanmar.

In this work, to determine an optimum treatment for processing high-MgO nickel laterite ores, we used a pre-reduction smelting method to obtain ferronickel alloy

from the nickel laterite ore from Tagaung Taung. Furthermore, we investigated how the conditions of the pre-reduction–smelting method affect the process.

2. Experimental

2.1. Raw materials

The Tagaung Taung nickel laterite ores (Ni content: 1wt%–2wt%) were crushed using a jaw crusher and then screened, resulting in a very uniform Ni distribution with no Ni segregation. Thus, the Ni grade in the ores could not be improved by the tail removal method, although all of the ores were subjected to furnace smelting. Anthracite coal and coke were used as reductants for the pre-reduction and reduction smelting processes, respectively. Tables 1 and 2 give the chemical composition of the nickel laterite ore, reductant, and flux used in this study.

2.2. Experimental setup

The pre-reduction process was typically carried out in an 8-kW muffle furnace equipped with a silicon carbide heating element and a Pt–10wt%Rh/Pt thermocouple for monitoring the temperature. The pre-reduction reaction was conducted in homemade stainless steel crucibles ($\phi 50$ mm \times 100 mm and $\phi 150$ mm \times 300 mm) under lidded and sealed conditions at 700–900°C.

Table 1. Chemical composition of the nickel laterite ore

wt%

Ni	Fe	Cu	Zn	Co	SiO ₂	CaO	MgO	Al ₂ O ₃	Mn	C	S
2.12	13.38	0.008	0.031	0.036	43.90	0.46	17.73	1.71	0.21	0.088	0.0058

Table 2. Chemical composition of the reductant and flux

wt%

Reductant	Ash	Volatile matter	Moisture	S	C	Bomb calorific value / (MJ·kg ⁻¹)
Coke	20.41	9.67	0.30	0.70	71.27	27.30
Coal	12.68	1.06	0.38	0.70	85.88	28.91
Flux	Al ₂ O ₃	CaO	SiO ₂	Fe	MgO	
Lime	1.36	92.59	0.92	0.23	0.52	

The reduction smelting experiments were conducted in a 12-kW high-temperature Si–Mo resistance furnace with an Si–Mo rod as the heating element. A lidded zirconia crucible (80 mm \times 170 mm) was used for reduction smelting without atmosphere protection at 1500–1550°C.

2.3. Experimental scheme

The pellet ores were prepared from a given mass of nickel laterite ore to which corresponding amounts of anthracite coal and analytically pure calcium oxide (CaO) were added. The pellets were then oven dried at 70°C for 12 h. To com-

plete the reduction reaction, the dried pellets were maintained for a certain time at the target temperature. Next, the crucible was removed and immediately quenched with water, thereby avoiding re-oxidation of Fe²⁺ in the pellets. After cooling to room temperature, the pellets were removed from the crucible and weighed.

Five pellets were selected at random for the measurement of their compressive strength and drop strength; the averages of these measurements were considered as the strength indices of this batch of pellets (kg per pellet). The drop strength was determined by repeatedly dropping a pellet

from a height of 0.5 m onto a 15-mm thick steel plate and repeating the dropping until the pellet cracked or ruptured. The drop strength is given as the number of such drops before the pellet fractured. Next, the pellets were ground completely and a portion was sampled to analyze the total Fe (T_{Fe}) and Fe^{2+} , with the pre-reduction indices being $w(Fe^{2+})/w(TFe)$ (degree of Fe reduction in pellets).

An appropriate quantity of pellets (or nickel laterite ore) was weighed and combined with a certain amount of coke

powder. The mixture was placed in a zirconia crucible, which was lidded and placed in an Si–Mo furnace. After the mixture was heated to the predefined temperature, thermal smelting was continued for a specified period, after which the material was allowed to cool naturally to room temperature. The crucible was then removed and weighed. The slag was ground completely, and the alloy was dissolved in aqua regia. The components of the slag and the alloy were subsequently analyzed (see Fig. 2).

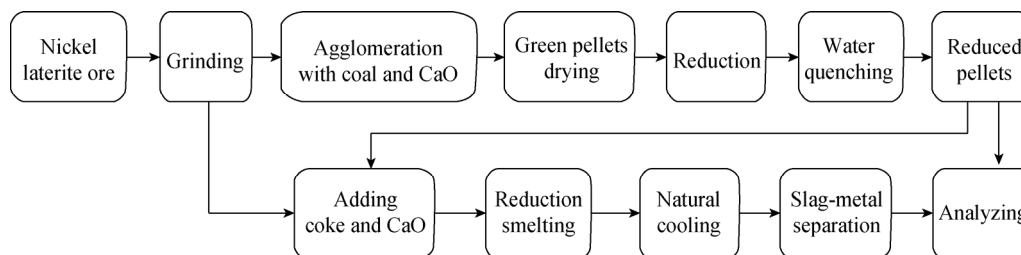


Fig. 2. Experimental procedure.

3. Results and discussion

3.1. Characterization of nickel laterite

The mineral composition was characterized by optical microscopy, X-ray powder diffraction (XRD), and scanning electron microscopy (SEM). Fig. 3 shows the XRD pattern of the nickel laterite ore from Tagaung Taung, Myanmar. The diffraction patterns clearly indicate that these ores are composed mainly of serpentines, talc, quartz, and montmorillonite along with minor amounts of illite and Fe minerals. Other minerals were not detected because they were present in trace amounts or were poorly crystallized.

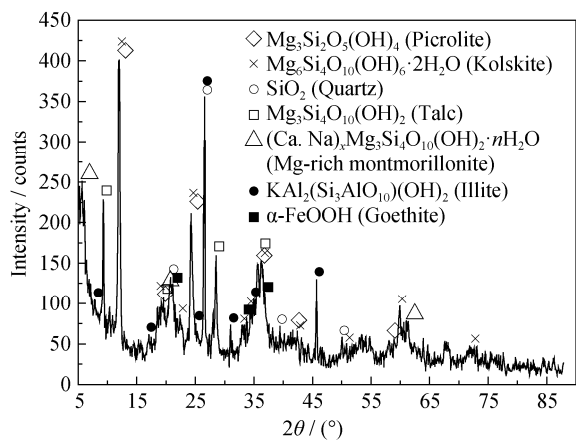


Fig. 3. XRD pattern of the nickel laterite ore from Tagaung Taung, Myanmar.

In addition to the aforementioned minerals, optical mi-

croscopy reveals various amounts of magnetite, chromite, limonite, and psilomelane as well as trace amounts of pyrite, chalcopyrite, nicopyrite, molybdenite, and copper in different ore samples. In many nuggets, substantial amounts of magnesiochromite or chrompicotite are detected in chromite structures. A portion of chrompicotite is irregularly shaped and separately embedded in serpentine. A small amount of sulfide in the form of granules (<0.043 mm diameter) fills the gangue fissures or crystal boundaries, and some chrompicotite resides in limonite. These sulfides generally exist separately but may react metasomatically with nicopyrite, molybdenite, or Cu to form co-occurring structures. Magnetite is mostly idiomorphic, whereas the semi-idiomorphic crystals are embedded in Mg grunerite, talc, and serpentine. The grain sizes are very non-uniform, ranging from 0.10 to 0.043 mm. Fig. 4 shows the microstructure of the major minerals in the ores. Clearly, the minerals consist mostly of coarse-grain dissemination.

Some nuggets are rich in silicate minerals (e.g., Ni-rich serpentine, psilomelane, népouite, and Ni-rich talc) and nickel sulfides (e.g., Ni-sufficient psilomelane and small amounts of nicopyrite and heazlewoodite). However, in addition to these Ni-rich carrier minerals or other low-Ni nuggets, different amounts of Ni often appear in gangue minerals such as serpentine, Ni grunerite, and chlorite. In general, these minerals contain 1wt%–3wt% Ni. Although this content is far less than that in Ni-rich minerals, these low-Ni minerals are also major Ni carriers in the ores. Despite the low-Ni content in limonite, dissemination of Ni is substantial because it is a product of sulfides oxidation. In the ores,

Ni mainly occurs in silicates, psilomelane, limonite, and sulfides, and the silicates contain a far higher Ni content compared to the other minerals. In fact, the majority of Ni in the ores occurs in the main body of the gangue formed by serpentine, talc, chlorite, and cummingtonite. The second type of carrier consists of hydrous oxides such as psilomelane

and limonite. Because of their low contents, Ni-rich sulfides are not major Ni carriers. Psilomelane contains abundant Ni and a substantial amount of Co, making it a major Co carrier. Moreover, psilomelane and Ni-rich talc contain some Fe, indicating that dissemination of iron is common during the ore formation.

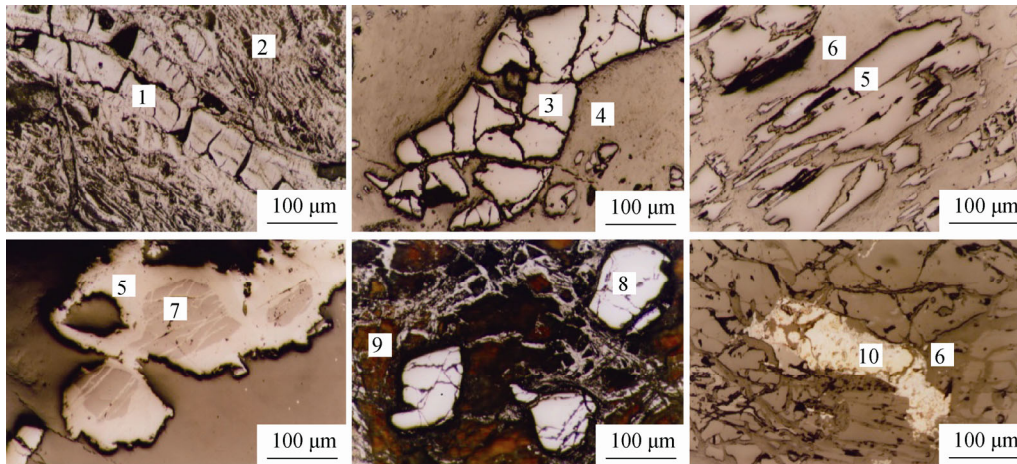


Fig. 4. Microstructure of various minerals in raw ores. 1—picrolite; 2—kolskite; 3—montmorillonite; 4—talc; 5—chromite; 6—gangue; 7—magnesiochromite; 8—magnetite; 9—grunerite; 10—sulfide.

Dissemination of iron is very evident in the ores, and the majority of minerals contain abundant Fe. The types of Fe include Fe-rich minerals (magnetite, chromite, limonite, pyrite, magnetic pyrite, and nicopyrite) and iron-bearing minerals (serpentine, talc, chlorite, amphibole, picrite, illite, spinel, and psilomelane). Except for a few Fe-free minerals (quartz, népouite), nearly all of the minerals present are iron carriers. Magnetite, chromite, and picotite are basically Ni-free. Because Cr and Mg are closely correlated, chromite and magnesiochromite usually contain Mg, and chromite appears with small amounts of Si, Al, and Mg. Although the ores contain substantial amounts of Fe-rich oxidized minerals, the Fe contents of these minerals are far lower than the Fe contents in silicates. These abundant iron-containing silicates are the major Fe carriers in the ores, and Fe-rich oxidized minerals are the only Fe carriers. Despite the high Fe content, sulfides are not major Fe carriers because of the trace Fe contents in sulfur-containing minerals.

3.2. Pre-reduction

3.2.1. Optimization of the pre-reduction process

Fig. 5 shows how the roasting time affects the Fe reduction ratio and the compressive strength of pellets. Under the test conditions, the roasting time does not strongly affect the Fe reduction ratio, but slightly affects the compressive strength. To guarantee sufficient strength, we used a roasting

time longer than 45 min. The roasting temperature substantially affects both the Fe reduction ratio and the compressive strength of the pellets. After 1 h of roasting at 700°C, the Fe reduction ratio was only 40% and the compressive strength was only 4 kg per pellet. To guarantee an Fe reduction ratio greater than 60%, we used a roasting temperature higher than 800°C. The reductant dosage strongly affects the Fe reduction ratio but has essentially no effect on compressive strength or drop strength. Anthracite coal combined with 1.5wt% original ore qualifies for Fe reduction. The dosage of CaO has essentially no effect on Fe reduction or drop strength, but slightly affects the compressive strength. The compressive strength of pellets was enhanced with an increase in CaO dosage. The requirements of furnace smelting dictate a minimum of 5wt% original ore. The pellet size of pellets has no effect on Fe reduction or drop strength, but slightly affects the compressive strength.

These test conditions enable easy drying during the pre-reduction of the Tagaung Taung nickel ore. With a roasting temperature greater than 800°C, a roasting time longer than 30 min, the addition of 1.5wt% anthracite coal (m_r) and 5wt% CaO (m_{CaO}) (with respect to the weight of the original ore), and a pellet size of ~10 mm, excellent pellets were prepared, with an Fe reduction ratio exceeding 70%, a compressive strength greater than 10 kg per pellet, and a drop strength exceeding 10 times.

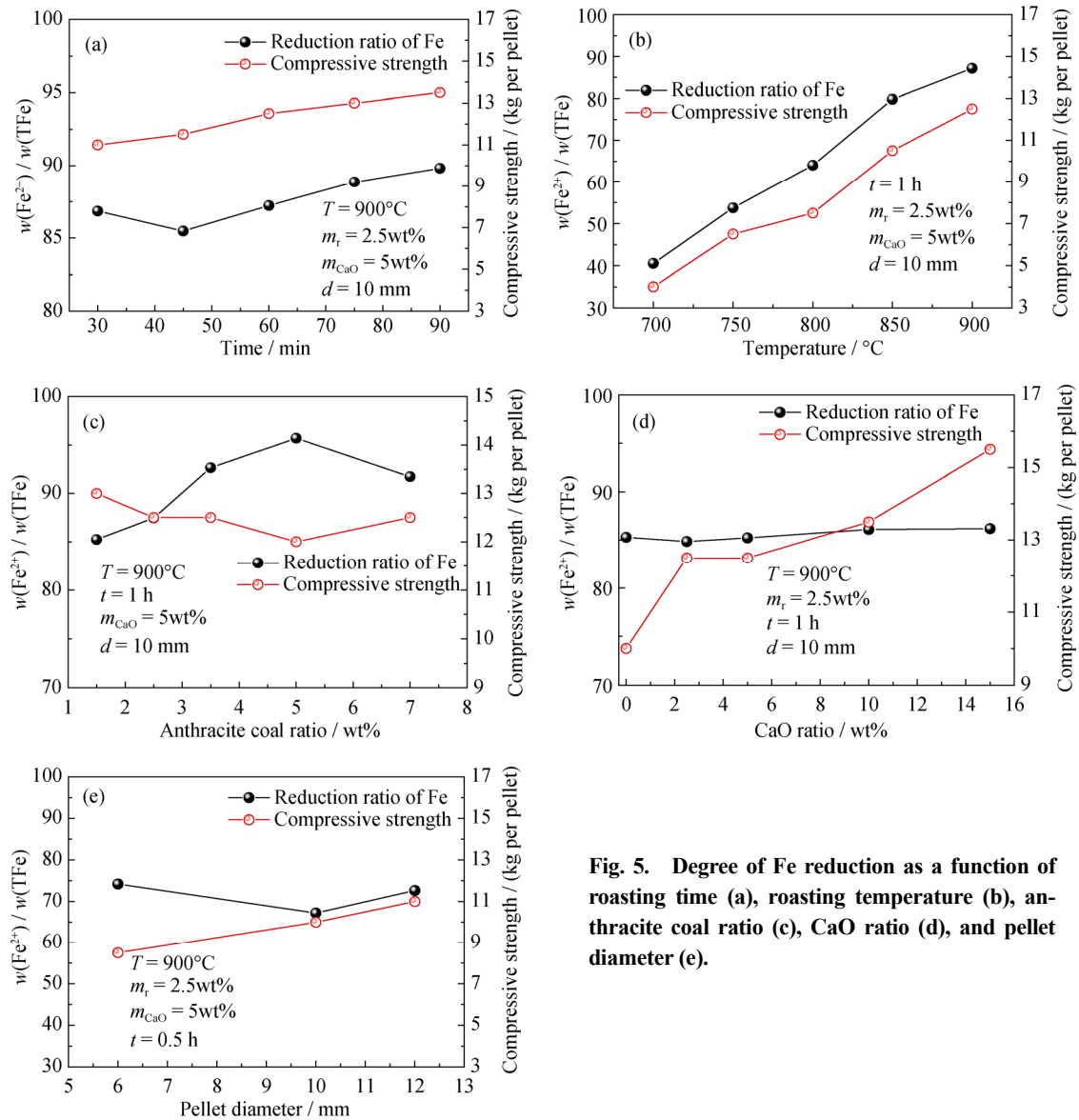


Fig. 5. Degree of Fe reduction as a function of roasting time (a), roasting temperature (b), anthracite coal ratio (c), CaO ratio (d), and pellet diameter (e).

3.2.2. Mineralogy of the pre-reduction process

Fig. 6 shows the main mineral composition of the reduced roasted pellets. Clearly, applying the pre-reduction process to nickel laterite ore completely converts the hydrous serpentine, talc, montmorillonite, and illite into anhydrous picrite and olivine. In particular, high-Mg serpentine is transformed into forsterite, whereas low-Mg talc is transformed into enstatite or clinoenstatite. In addition, hydrous limonite and psilomelane are transformed into magnetite or hausmannite. Since chrompicotite is anhydrous, it does not change during pre-reduction.

Note that the main mineral in roasted pellets is quartz (Fig. 6). By comparing the quartzose diffraction intensity in Fig. 6 with that from the raw material in Fig. 3, we find that

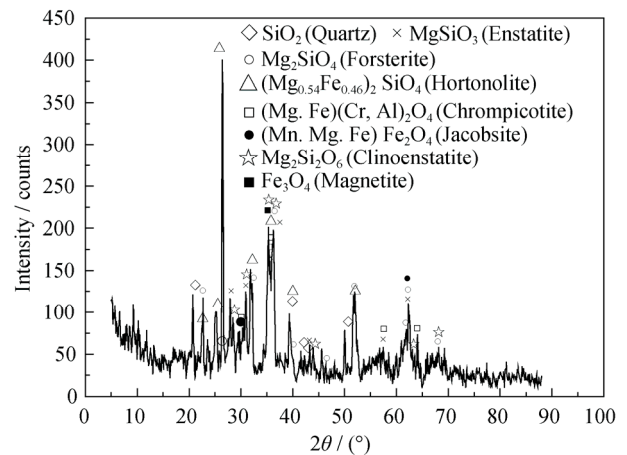


Fig. 6. XRD pattern of the reduced roasted pellets.

quartzose is substantially enriched after roasting, mainly because the number of anhydrous minerals increases after dehydration. This process is also associated with a considerable increase in the amount of chrompicotite. Conversely, after dehydration, the newly formed picrite and olivine exhibit low crystallinities, which leads to relatively strong diffraction lines from quartz and spinel whose phase do not change.

Optical microscopy shows that no sulfides occur in the

roasted pellets, which indicates that they are oxidized during roasting and reduced to magnetite or alloy. Fig. 7 shows the microstructure of the reduced pellets. Clearly, magnetite, spinel, and quartz without a phase change are completely crystallized into coarse particles. Because the original minerals (serpentine, talc, illite) are abrasive, the newly formed picrite and olivine englobe the magnetite, spinel, and quartz, and are under the action of sintering, resulting in the formation of loose and porous aggregates.

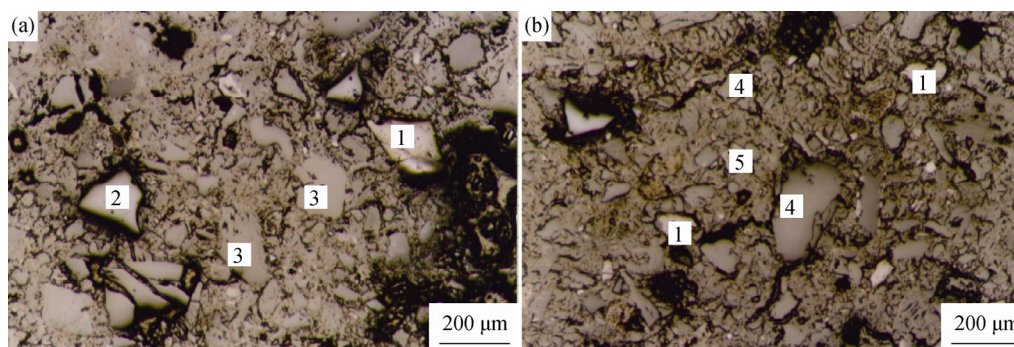


Fig. 7. Microstructure of various minerals in the pre-reduced pellets. 1—magnetite; 2—chrompicotite; 3—silicate; 4—quartz; 5—Mn-rich phase.

Given the special geographical environment and climate conditions in Tagaung Taung, the nickel ore should be processed by dried pre-reduction, which ensures the normal progression of furnace reduction smelting, conserves power, and increases the amount of ore processed. The optimal conditions for dried pre-reduction of the Tagaung Taung nickel ore are as follows: roasting temperature $>800^{\circ}\text{C}$, roasting time >30 min, 1.5wt% anthracite coal, and 5wt% CaO. The resulting pellets exhibit an Fe reduction ratio $>70\%$, a compressive strength >10 kg per pellet, and a drop strength >10 times. During reduced roasting, Ni essentially does not migrate; it remains in the product after the phase change.

3.3. Smelting

To investigate the feasibility of furnace reduction smelting for the Tagaung Taung nickel ore, we varied the factors that influence the smelting process for a 12-kW Si–Mo furnace (CaO dosage, dosage of reducer, reduced smelting temperature, smelting time, Fe reduction ratio in pellets). To guarantee the accuracy of the results and to ensure that the slag composition was not modified, we used a zirconia crucible.

3.3.1. Smelting time

At an appropriate smelting temperature, prolonging the reduction smelting time not only ensures the complete reduction of valuable metals but also facilitates the complete sedimentation of metal phases in the slag, which facilitates

metal recovery. However, an excessively long smelting time increases energy consumption, reduces the amount of ore processed by the equipment, and aggravates soak erosion to the slag. Thus, using an appropriate reduction smelting time improves production efficiency and conserves power. As shown in Fig. 8, at a reduction smelting temperature of 1550°C , the smelting heat preservation time does not substantially affect the Ni recovery ratio, which remains greater than 99%. We suggest an optimal smelting time of 30–45 min.

3.3.2. Smelting temperature

The reduction smelting temperature plays multiple roles. First, the temperature increase accelerates the reduction of metallic oxides, decreases the slag viscosity, and promotes the aggregation and sedimentation of metal phases, which is favorable for slag–metal separation and slag–alloy emission. However, an excessively high smelting temperature increases energy consumption, aggravates the soaked erosion that coats the furnace, and accelerates the dissolution of alloy in the slag, all of which hinder metal recovery.

The Ni–Fe alloy produced via furnace reduction smelting of the nickel laterite ore features a high melting point and a high smelting temperature. Thus, we conducted smeltings at 1450 , 1500 , and 1550°C .

Fig. 9 shows that, at 1450°C , the Ni content in the slag decreases to 0.1wt% and the Ni recovery exceeds 97%. At 1450 or 1500°C , however, the resulting smelt slag is needle

shaped and some of the Ni–Fe alloy particles appear in the slag, indicating that Ni–Fe alloy aggregation is incomplete, most likely because of the high slag viscosity (~ 1.4 Pa·s). At

1550°C, the Ni–Fe alloy aggregation is complete, with obvious slag–metal separation. Thus, the appropriate reduction smelting temperature is at least 1550°C.

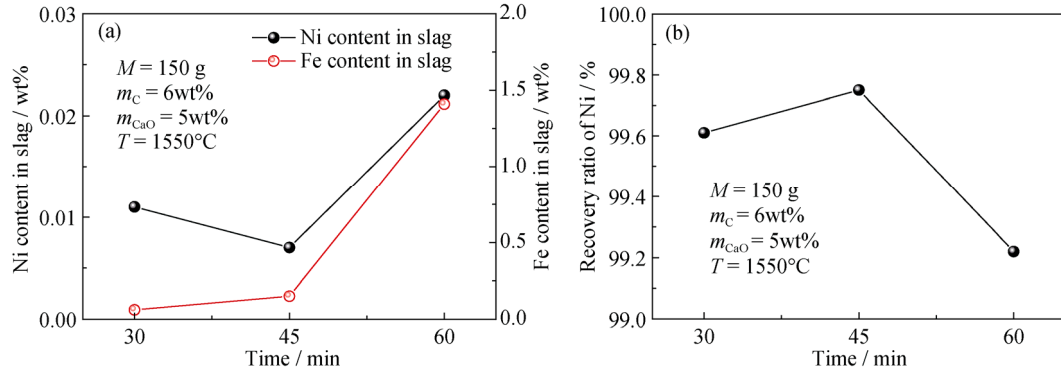


Fig. 8. Ni and Fe contents in the slag and alloy against reduction time.

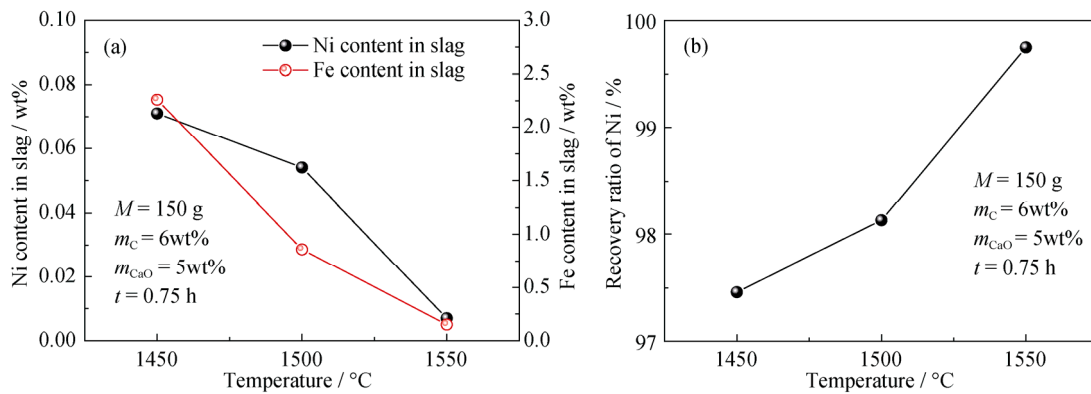


Fig. 9. Ni and Fe contents in the slag and alloy against smelting temperature.

3.3.3. Reductant quantity

The results show that, to guarantee high Ni recovery, more than 5wt% coke powder should be added. Moreover, when pre-reduced pellets are used as the raw material instead of nickel laterite ore without pre-reduction, less coke is required.

The test results indicate that the Ni and Fe contents in the slag and the Ni content in the Ni–Fe alloy depend on the dosage of the reducer (Fig. 10). Clearly, a dosage of coke powder greater than 5wt% stabilizes the downward trend of Ni content in the slag; however, the Fe content in the slag decreases substantially. In addition, the Ni content in the alloy decreases dramatically because of intensive reduction. That is, the Ni in nickel laterite ore is more reducible than iron; the iron therefore starts to be strongly reduced when Ni reduction terminates. To improve both the Ni recovery and the Ni content in the alloy, we recommend a coke powder dosage of 5wt%–6wt%.

3.3.4. Quantity of calcium oxide

The slag shape experiments show that the addition of a

slight amount of CaO only slightly reduced the slag melting point, whereas it significantly increased the viscosity and soak erosion. However, because of the addition of excessive CaO, reduction smelting of the Tagaung Taung nickel ore is not recommended; CaO can not only excessively decrease the slag melting point but can also cause furnace accidents and increase the amount of processing materials required, leading to increases in power consumption and the Ni content in the slag.

The results indicate that reduction smelting of the Tagaung Taung nickel ore is very easy and Ni recovery in the slag is as high as 98%. We also observed that the slag with natural basicity features low alloy aggregation and incomplete slag–metal separation, which is attributable to the high slag viscosity.

Fig. 11 shows how the Ni and Fe contents in the slag and the Ni content in the Ni–Fe alloy vary with cinder basicity. When the slag basicity is 0.5–0.6, the Ni content is $<0.01\text{wt}\%$ and the Ni content in the Ni–Fe alloy is $\sim 18\text{wt}\%$. Comprehensive considerations suggest that the addition of 5wt% CaO and a slag basicity of 0.5 are appropriate.

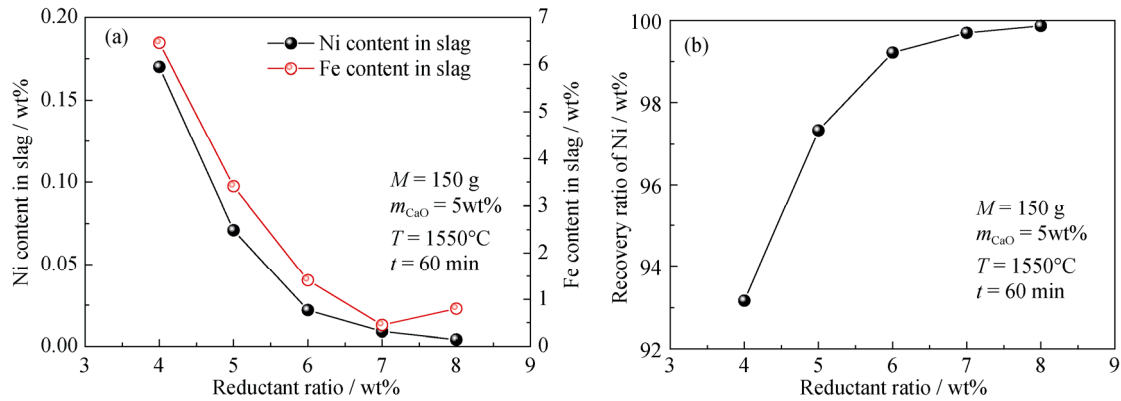


Fig. 10. Ni and Fe contents in the slag and alloy plotted against the quantity of the reductant.

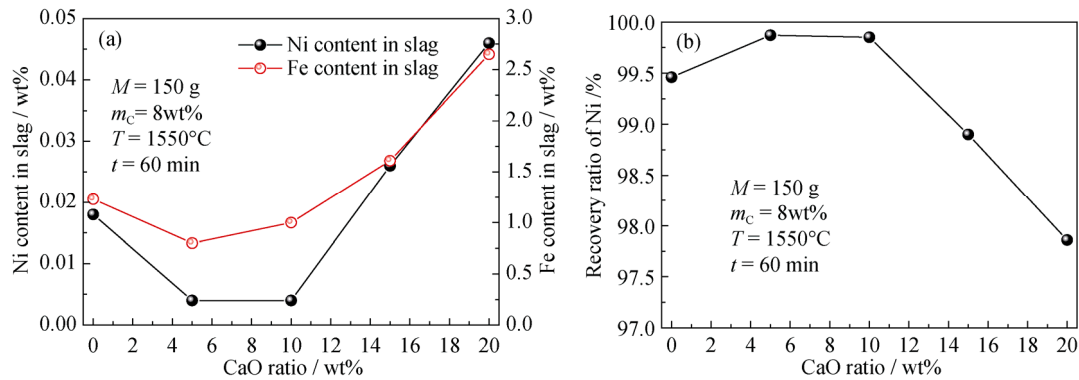


Fig. 11. Ni and Fe contents in the slag and alloy as a function of the CaO ratio.

3.3.5. Reduction ratio of pellets

The reduction of Ni–Fe oxide is endothermic, ensuring that a greater reduction ratio of Fe and Ni before the addition of roasted sand to the furnace for reduction smelting would reduce the power consumed during furnace smelting. Industrial tests indicate that the Fe reduction ratio of roasted sand strongly affects the consumption of smelting power. Another advantage is that pre-reduction of roasting sand reduces the amount of coke required for reduction smelting.

With the use of pre-reduced pellets and the addition of 5wt% coke (approximately 4.35wt% of the original ore), the Ni recovery remained as high as 99%. The results show that the Ni and Fe contents in the slag and the Ni content in the Ni–Fe alloy all depend on the reduction ratio of Fe in the pellets (Fig. 12).

During smelting, when the coke dosage is constant, the Ni and Fe contents in the slag and the Ni content in the alloy all decrease gradually with the increase of the reduction ratio of Fe in the pellets; however, the recovery ratio of Fe increases substantially. Compared with the effects of the reducer dosage, when the reduction ratio of Fe in the pellets is set to ~80%, the amount of coke powder required

may decrease to ~4wt% (i.e., approximately 3.5wt% of the original ore).

The results show that the reduction smelting of the Tagaung Taung nickel ore is very easy. For a smelting temperature of 1550°C, the smelting time is 30–45 min. With 5wt% CaO added and under appropriate coke conditions, the slag contains <0.02wt% Ni and ~1wt% Fe, whereas the resulting alloy contains ~20wt% Ni and the recovery ratio of Ni exceeds 98%. To further validate these conditions, we designed the following comprehensive experiments for the original nickel ore and pre-reduced pellets.

The following conditions were fixed: a reduction smelting temperature of 1550°C, a coke dosage of 4wt% for the pre-reduced pellets and 6wt% for the original nickel ore, a CaO dosage of 5wt%, a smelting time of 45 min, and a raw material dosage of 150 g. The results of these comprehensive experiments on reduction smelting of the original nickel ore and pre-reduced pellets thoroughly validate the aforementioned conditions: the Ni content in the slag was less than 0.02wt%, and the recovery ratio of Ni exceeded 99%. For the pre-reduced pellets with an Fe reduction ratio of approximately 75%, the addition of coke as a reducer with

4wt% pellets (approximately 3.5wt% of the original nickel ore) is completely feasible for reduction smelting.

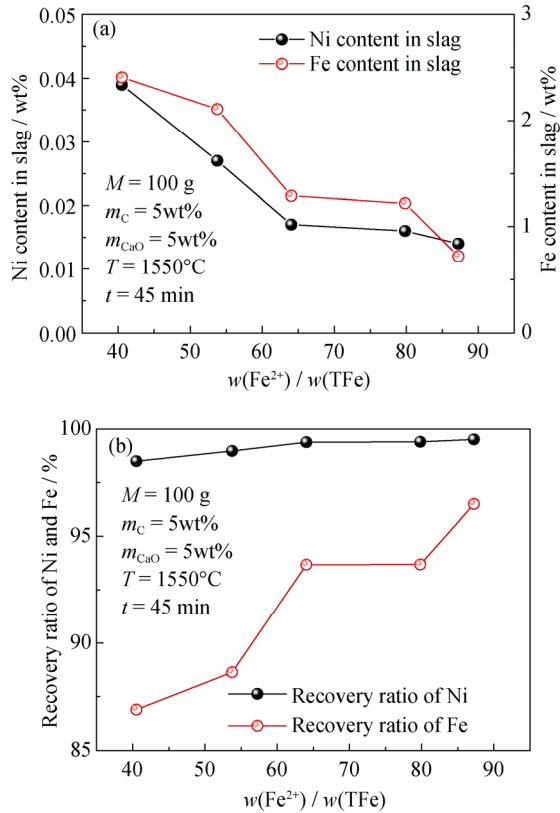


Fig. 12. Ni and Fe contents in the slag and alloy plotted against the reduction ratio of Fe in pellets.

3.3.6. Mineral composition of the slag

Fig. 13 shows the main mineral composition of the reduction smelting pellets. Clearly, the main minerals in this slag are picrites, followed by anorthite and small amounts of olivine, chropicotite, and baddeleyite. In particular, diopside and hedenbergite form from reduction smelting, whereas enstatite, hypersthene, and small amounts of olivine and chropicotite are common products from the pre-reduction pellets. Although they remain in the slag, they also undergo melt-out crystallization. The baddeleyite originates from the furnace coating.

Comparing the main mineral components in the reduced pellets reveals that abundant free quartz, forsterite, magnetite, jacobsite, and Mn and Fe oxides disappeared and were replaced by Ca-rich limestone. These results suggest that, in real smelting, the addition of abundant lime and forsterite facilitates a reaction to form tremolite; furthermore, the lime also reacts with quartz and magnetite to form hedenbergite, and the added alumina reacts with the lime to form anorthite.

Fig. 14 shows the microstructure of various minerals in

the slag. Microscopy reveals essentially no metal minerals in the reduction smelting slag or in the fine-grain Ni-Fe alloy, indicating that metal precipitation is ideal. In addition to chrompicotite, the slag is also composed of low-reflectivity silicates.

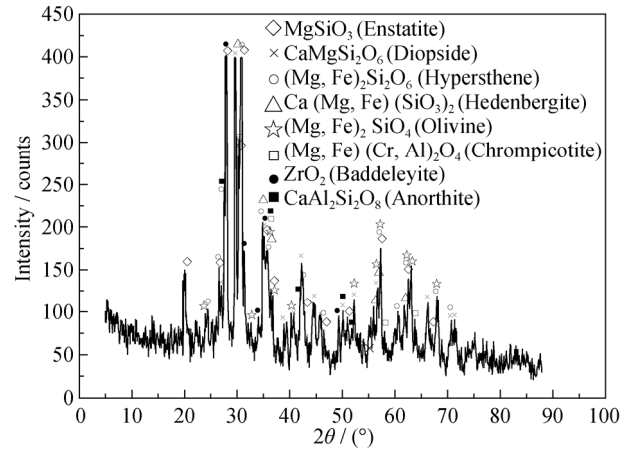


Fig. 13. XRD pattern of the reduction smelting slag.

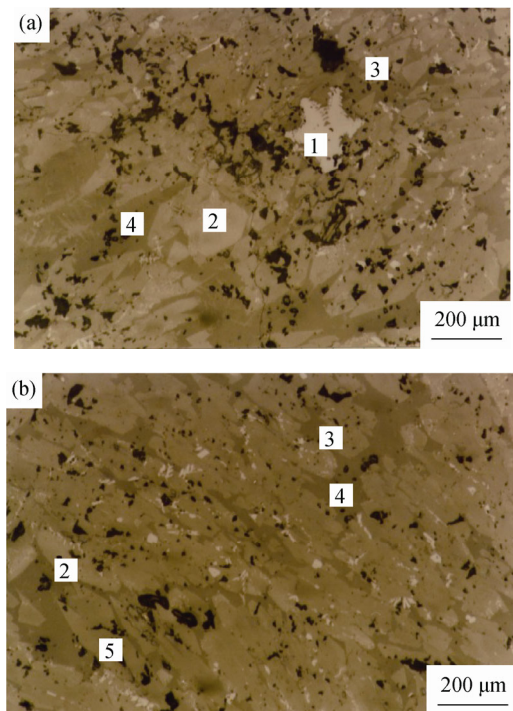


Fig. 14. Microstructure of various minerals in the slag. 1—chropicotite; 2—diopside; 3—anorthite; 4—enstatite; 5—hedenbergite.

3.3.7. Alloy structures and the characteristics of impurities

Microscopy shows that the alloy after reduction smelting contains a small amount of fine particle sulfurized impurities and smaller amounts of silicate impurities (which are mostly spherically and irregularly massive, stripe-shaped or

star-shaped, and uniformly distributed in the alloy). Silicate impurities are mostly columnar or irregular and massive and are scattered in the alloy. Fig. 15 shows the microstructure of sulfide impurities and silicate impurities in the alloy. Clearly, these sulfide impurities have uniform particle sizes that range from 0.070 mm in a small section of coarse parti-

cles to 0.010 mm in fine particles. The silicate impurities are coarser, and almost no fine particles occur.

Table 3 shows the chemical composition of the ferronickel alloy. The Ni content reaches 17.5wt%, and the Fe content is 79.5wt%. The C and Si contents in the alloy are 1.57wt% and 0.3wt%, respectively.

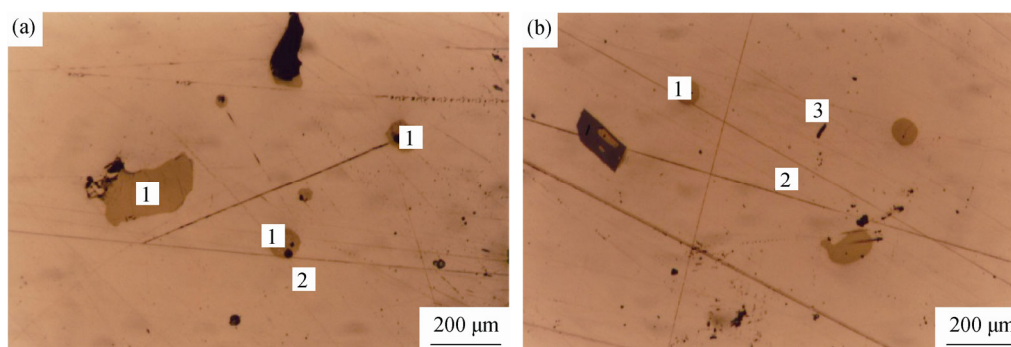


Fig. 15. Microstructure of various minerals in the alloy. 1—pyrrhotite; 2—ferronickel alloy; 3—silicate.

Table 3 Chemical composition of the ferronickel alloy

											wt%
Ni	Fe	Cu	Co	Cr	Mg	Na	Si	C	S	P	Other
17.5	79.5	0.13	0.55	0.05	0.05	0.079	0.3	1.57	0.024	0.053	<0.2

4. Conclusions

(1) The nickel laterite ore from Tagaung Taung has a high MgO content and a low Co content. The main minerals in the Tagaung Taung nickel ore are serpentine, talc, montmorillonite, and quartz, followed by illite, chlorite, various amphiboles and picrites as well as a small amount of spinel.

(2) The optimal conditions for pre-reduction of the Tagaung Taung nickel ore are as follows: roasting temperature >800°C, roasting time >30 min, 1.5wt% anthracite coal, and 5wt% CaO. The resulting pellets have an Fe reduction ratio of 70%, a compressive strength >10 kg per pellet, and a drop strength >10 times. Process mineralogical experiments show that, during pre-reduction, serpentine transforms into forsterite, talc transforms into hard enstatite, psilomelane transforms into hausmannite, and limonite transforms into impure magnetite. Furthermore, Ni does not migrate but remains in the product after the phase change.

(3) The optimal conditions for reduction smelting of the Tagaung Taung nickel ore are as follows: a reduction smelting temperature of 1550°C, a coke powder dosage of 4wt%–5wt% of the original nickel ore, a CaO dosage of 5wt%, a reduction smelting time of 30–45 min, and an Fe reduction ratio of 75% in the pellets. The Ni recovery ratio

can exceed 95%, and the Ni content in the Ni–Fe alloy is ~20wt%. The main minerals in the reduced smelt slag are enstatite, diopside, hedenbergite, hypersthene, and chrompicotite. No Ni is detected in silicates or oxides in the slag. Small amounts of sulfide impurities and silicate impurities occur in the alloy.

(4) Given the local climate and substantial moisture in the ore, we suggest a process of pre-drying → screening → crushing → rotary kiln pre-reduction → electric furnace smelting. In the final production of the alloy, the Ni content may reach 17.5wt% when the Fe content in the slag is maintained at 3wt%–4wt%. At this point, the Ni content in the slag is 0.05wt%–0.1wt%, and the recovery ratio of Ni exceeds 97%.

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