

Experimental Study on Utilization of Low-Grade Complex Ore through Direct Reduction- Melting and Separation

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Abstract. The direct reduction-melting and separation combined process was the metallurgical processing route, where the iron oxide was reduced with pulverized coal at the solid state. Then, the metallic Fe and the slag were melted and separated at high temperature liquid state. The experiments of this direct reduction-melting and separation combined process were conducted with vanadic titanomagnetite, nickel-laterite ores and copper tailings as raw materials. The experimental results demonstrated that the process could contribute to the comprehensive utilization of the low grade complex iron ore, which is suitable for commercialization.

1. Introduction

The reserves of low-grade iron ore account for a high proportion of all iron ore resources in the world. For example, the low-grade ore (Fe content ≤ 33 wt. %) reserves exceeded 90% of all the proved iron ore reserves in China [1], where more than a third of all the proved iron ore reserves are associated to one or more other elements, namely, low-grade complex ore. These low-grade complex ore resources should not only be the important raw material of the steel industry, but also the indispensable raw material to the non-ferrous metals and the rare metals industry. As the social demand for metal minerals increased, the rich iron ore reserves have gradually been exhausted. The comprehensive utilization of the low grade complex ore has consequently become an important subject.

In order to fully utilize the low grade complex iron ore, the researchers conducted a high amount of research work. The research works demonstrated that the combined process of direct reduction-melting and separation with hot delivery and hot charge has apparent advantages, such as short flow, flexible production and low pollution [2-3]. The combined process was the metallurgical processing route where the iron oxide was reduced by pulverized coal to the solid state in a direct reduction furnace. Following, the metalized pellets were hot delivered and hot charged in the electric arc furnace. Finally, the metallic Fe and the slag were melted and separated in the electric arc furnace at the molten state. The distinctive feature of the process was that the primary energy non-coke coal was the main energy medium consumed in the material heating and reduction, and the secondary energy medium was the electrical energy consumed in the material melting and separation. This energy medium consumption structure improved the energy efficiency and reduced the total energy consumption. Through the process not only the direct reduced iron was got, but also the recyclable elements in the



slag were enriched. As an example, with the $\text{TiO}_2 \geq 55.3$ wt.% vanadium titanomagnetite as the raw material, the pig iron containing vanadium and the rich titanium slag of 82.5 wt % in TiO_2 were obtained; with the nickel-laterite ores as the raw material, the ferronickel with of 8.73% in Ni and the slag were obtained; with the Fe of 41.0 wt% copper tailings as the raw material, the iron direct reduction and the enriched precious metal slag were obtained. The experimental study through the direct reduction-melting and separation process was conduct with the three kinds of polymetallic ore respectively.

2. Experimental study of vanadic titanomagnetite

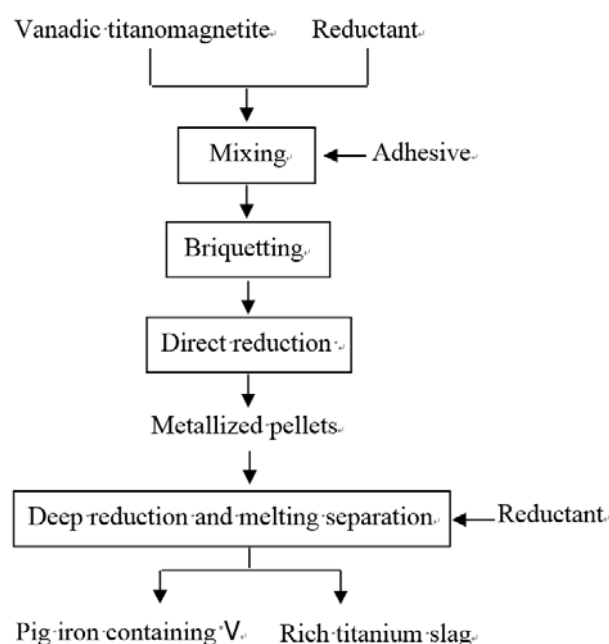


Figure 1. Process Flow Diagram of Vanadic titanomagnetite

Vanadic titanomagnetite is an important type of polymetallic complex ore that is closely associated to $\text{FeTiO}_3 \cdot \text{Fe}_3\text{O}_4$, $\text{FeO} \cdot \text{TiO}_2$, $2\text{FeO} \cdot \text{TiO}_2$ and other compounds. The Ti element mainly existed in the form of TiO_2 . Due to the low Fe content, the complex mineral structure and the smelting technology limitations, through the existing processes the three elements of Fe, V and Ti could not be recycled [4-6]. Through the traditional blast furnace-converter smelting processes only Fe and V could be extracted from vanadium titanomagnetite, whereas the Ti was discharged as waste. Through the wetting process producing titanium oxide (titanium white), only Ti could be extracted from vanadium titanomagnetite, whereas the Fe and V of the vanadium titanomagnetite were discharged as waste.

In order to recycle the three elements of Fe, V and Ti at the same time; the vanadic titanomagnetite experiment was carried out through the direct reduction-melting and separation process. The direct reduction- melting and separation process was designed as follows: the vanadic titanomagnetite, the coal powder and the adhesive were mixed according to a certain ratio; the mixtures were pressed into carbon-containing pellets with the briquetting machine; and consequently, the carbon-containing pellets were placed into the dryer. Following drying, the mixtures were placed in the high temperature furnace for direct reduction. The carbon-containing pellets were turned into metallized pellets subsequently to reduction. The metallized pellets were directly sent to the melting electric arc furnace. Since the FeO of vanadic titanomagnetite was hard to be reduced, the coal powder reductant was added to the melting electric arc furnace in the melting procedure, for the deep reduction of FeO to be achieved. The metallized pellets melted and the FeO was deep reduced in the melting electric arc furnace. The different densities of the molten iron and titanium slag led to natural separation in the

molten pool. The final products following metal tapping and slagging were found to be rich in titanium slag and molten pig iron containing vanadium. The process flow diagram is presented in figure 1.

The vanadium titanomagnetite studied in the paper, was titanium placer concentrate following ore dressing from Indonesia. The compositions of the vanadium titanomagnetite are presented in table 1. The compositions of reductant coal are presented in table 2. It could be observed from table 1 that the total Fe content was 22.4~24.5% and the TiO₂ content was 55.3%~57.0%. The Vanadium titanomagnetite, the coal powders of 80% in C and the organic adhesive were mixed. The cane molasses (sugar by-products) were used as the adhesive in the experiments.

The briquetting parameters of the raw material were as follows, in details. The briquetting machine pressure was 350 KN and the diameter of the carbon containing pellet was 30 mm. The drying temperature was 200°C and the drying duration was 120 minutes. Through many experiments, the optimal reduction parameters were discovered as follows: carbon mass fraction of 13%, reduction temperature of 1350°C and reduction duration of 30 minutes. The smelting duration in the melting electric arc furnace was 30min.

Table 1. Composition of vanadium titanomagnetite

Item	TFe	FeO	Fe ₂ O ₃	TiO ₂	SiO ₂	Al ₂ O ₃	CaO	MgO	V ₂ O ₅	P	S
Mass fraction	22.4~	12.5~	19.0~	55.3~	2.5~	1.5~	0.2~	2.2~	0.04~		
wt. %	24.5	14.5	20.5	57.0	3.0	2.2	0.5	3.5	0.1	0.03	0.01

Table 2. Composition of Coal (Dry basis)

Item	Fixed carbon	Ash	Volatile	S
Mass fraction wt. %	80.0	13.0	5.0	0.2

Table 3. Fluctuation range of Direct Reduced Molten Iron Compositions

Item	Fe	C	S	P	Si	V
Mass fraction wt. %	≥97	2.0~4.0	0.01~0.10	0.10~0.20	0.1~0.2	0.06~0.10

Table 4. Fluctuation range of Rich Slag Main Compositions with Coal Injection

Item	TiO ₂	FeO%	MFe	TFe
Mass fraction wt. %	78.0~82.5	6.2~9.0	≤1.0	5.0~7.0

The experimental results were summarized and are presented in tables 2 and 3 from 10 batches of experimental samples. The fluctuation range of direct reduced molten iron compositions is presented in table 2. Table 2 presents that the content of Fe exceeded 97 wt% in the molten iron and the V content was in-between 0.06~0.10 wt%. The molten iron was suitable to produce wear resistance castings or to be used in the converter steelmaking recovery of vanadium. The fluctuation range of the rich titanium slag main composition is presented in table 3. It could be observed that the TiO₂ content in the rich titanium slag was up to 82.5%. The rich titanium slag has many advantages such as high titanium content, good acid solubility and the easily grindability, which is high-quality raw materials to produce titanium white. The experimental study results through the direct reduction-melting and separation process demonstrated that the three elements of Fe, V and Ti could be recovered simultaneously. Also, the comprehensive utilization of vanadic titanomagnetite was achieved.

3. Experimental study of nickel-laterite ores

Nickel is mainly extracted from sulfide ores, which occupy 30% of the global Ni resources. In contrast, the nickel-laterite ores (nickel oxide) which occupy 70% of the global Ni resources have not been large-scale developed for a long time. The Ni content is commonly between 6~8 wt% of the typical

nickel sulfide concentrate and the Ni content is between 1~2 wt% of the nickel-laterite ores. Due to the depletion of nickel sulfide and the increased demand in pure Ni, the exploitation of nickel-laterite ores has received increased attention. At present, the main industrial process of ferronickel production from nickel-laterite ores is the submerged arc furnace smelting process. During the traditional processing, high amounts of time and electric energy were consumed for the submerged arc furnace burden heating, where more than 80% of the total process energy was supplied through electric energy. Consequently, the production efficiency was low and the energy consumption of the process was high. According to literatures reported, the energy consumption was up to an average of 5600~6000 kWh/ton of ferronickel by the traditional submerged furnace process [7].

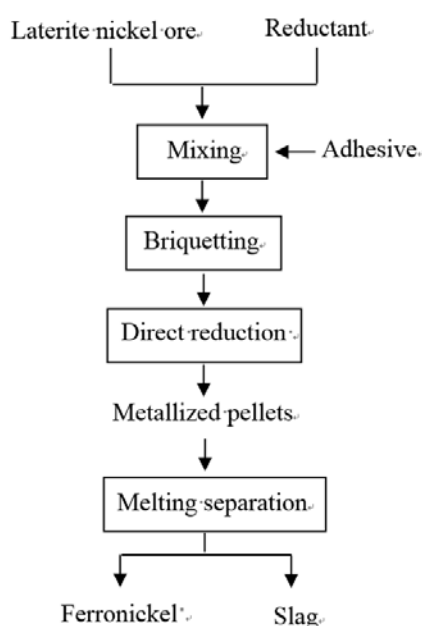


Figure 2. Process Flow Diagram of nickel-laterite ore

The experimental study of nickel-laterite ores was executed through the direct reduction-melting and separation process. The process flow diagram of the nickel-laterite ores is presented in figure 2. Firstly, the nickel-laterite ores were dried; then the coal powder and the adhesive were mixed with nickel-laterite ores dried following the designed ratio. The mixtures were placed in the briquetting machine to be pressed into carbon-containing pellets. Following, the dried pellets were sent to the high temperature furnace to be reduced. The carbon-containing pellets were turned into metallized pellets subsequently to direct reduction in the high temperature furnace. The hot metallized pellets were immediately sent to the melting electric arc furnace. Consequently, the molten ferronickel were obtained. The advantage of process was high energy efficiency and low energy consumption, due to the main energy consumption in the material heating and the reduction from coal, not electricity, as well as the hot delivery and hot charge technology adoption. The reduction reaction of Ni was easier compared to Fe and the Ni reduction exceeded the Fe reduction in value. Therefore, the Ni was completely reduced and the Fe was partially reduced in the process. Compared to the process flow of vanadic titanomagnetite, the deep reduction step was cancelled and the melting separation procedure was executed without a reductant in the electric arc furnace.

The briquetting parameters of the nickel-laterite ores were the same as the vanadic titanomagnetite parameters. Through many experiments, the optimal parameters of the process were as follows: carbon mass fraction of 10%, reduction temperature of 1250°C and reduction duration of 25 minutes. The smelting duration in the electric arc furnace was 30 min. The nickel-laterite ore presented in the paper

originated from Malaysia and the main composition is presented in table 4. The composition of reductant coal is presented in table 2.

The experimental result is presented in table 5. From the table 5, it could be observed that the Ni content in ferronickel was 8.73 wt% and the Fe content was 83.78 wt%, so this ferronickel is high-quality raw material to produce stainless steel. The main chemical composition of the slag was SiO_2 , MgO and Al_2O_3 . The slag could be utilized in the production of rock wool, hollow bricks and other building materials. The experimental study results demonstrated that the direct reduction-melting and separation process was suitable to produce ferronickel, with nickel-laterite ore as the raw material.

Table 5. Compositions of laterite nickel ore wt. %

Item	Ni	TFe	FeO	SiO_2	CaO	MgO	Al_2O_3	S	P
Mass fraction wt. %	1.68	18.72	0.63	37.61	1.21	14.60	2.79	0.051	0.012

Table 6. Compositions of Ferronickel wt. %

Item	Fe	Ni	P	S
Mass fraction wt. %	83.78	8.73	0.036	0.085

4. Experimental study of copper tailings

Copper tailings mainly consist of magnetite, chalcopyrite, pyrite, hematite, associated Au, Ag, Cu, Zn and other elements. With the exploitation of mineral resources, high amounts of tailings not only occupy significant amounts of land, but also cause environment pollution and resource waste [8-9]. In this paper, the direct reduction - melting and separation process was attempted to be adapted to copper tailings recycling. This process is suitable to recycle most of the iron of copper tailings with the high iron content and to enrich precious metals in the slag, such as Au and Ag. The experimental study of the copper tailings was executed through the direct reduction-melting and separation process. The copper tailings studied in the paper were from the Yunnan province of China and the main compositions of the copper tailings are presented in table 6. The reductant coal composition is presented in table 2. The copper tailings, the coal powder and the adhesive were mixed following the designed ratio. The mixtures were placed into the briquetting machine to be pressed into carbon-containing pellets. Consequently, the dried pellets were sent to the high temperature furnace for reduction. The carbon-containing pellets were turned into metallized pellets following direct reduction in the high temperature furnace.

Table.7 Compositions of Copper Tailings wt%

ite m	TFe	FeO	Fe_2O_3	SiO_2	Cu	S	Au	Ag	As	Sb	Pb	Zn
Mas s frac tion wt. %	41.00~ 43.00	16.0~ 18.0	40~ 43%	26.00~ 29.00	0.26~ 0.32	0.30~ 0.40	0.05~ 0.10	<10 .00	0.20~ 0.30	0.10~ 0.16	0.50~ 0.60	2.00~ 2.50

Remark: Au and Ag units are in g/t.

The briquetting parameters of the copper tailings were the same as the vanadic titanomagnetite parameters. Through many experiments, the best economical parameters of the process were as follows: carbon mass fraction of 14%, reduction temperature of 1473K and reduction duration of 40 minutes.

Carbon-containing pellets turned into metallized pellets after direct reduction in the high temperature furnace. The total iron and metallic iron content were detected by chemical analysis. Chemical analysis shows that the metallization rate of Fe was 85.62%, and gold and silver metal content of copper tailings can be increased by 1.8~1.9 times.

5. Conclusion

Through the direct reduction-melting and separation process, the vanadium titanomagnetite consisting of Fe of 22.4~24.5 wt% and of TiO_2 of 55.3%~57.0 wt. % as the raw material, the high-titanium slag of 82.5% in TiO_2 and the Fe $\geq 97\%$ of the pig iron containing vanadium were obtained; the nickel-laterite ores consisting of 18.72 wt. % in TFe and of 1.68 wt.% in Ni, as well as the ferronickel of 8.73 wt% in Ni and of 83.78 wt% in Fe were obtained. The experimental results demonstrated that the direct reduction-melting and separation process could demonstrate the comprehensive utilization of the low grade complex iron ore, which is available in industrialization.

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