Progress on Quality Improvement Technology of Low-Quality Complex Bauxite

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Abstract

As the world's most important source of aluminium metal, bauxite is a strategic mineral resource that supports the development of modern industry. As the world's largest producer and consumer of primary aluminium, China has formed a complete aluminium industrial chain, but restricted by resource endowments, aluminium industry faces structural contradictions: on the one hand, the uneven distribution of domestic bauxite resources, high-quality resources have been nearly exhausted, resulting in a long-term dependence on imported ore above 60 %; on the other hand, low quality complex bauxite resources are relatively rich, but because of the ore "poor, fine, miscellaneous", comprehensive utilization is difficult, resulting in a serious backlog of resources. Aiming at two typical low quality bauxite types, high silicon type and high sulphur type, this study introduced the research status and existing problems of bauxite dressing technology and then proposed the efficient development and utilization methods of low-quality bauxite and clarified the future research direction of dressing technology. At the same time, to promote the sustainable development and utilization of domestic low-grade complex bauxite resources, it is necessary to give full play to the strategic role of the national "Belt and Road" initiative. It is recommended to build a multi-level bauxite resource security system, optimize the import strategy, realize the coordinated development of domestic resource development and international resource supply, and improve the bauxite resource security ability from the source. Provide solid resource support for the sustainable development of aluminium industry.

Keywords: Low quality complex bauxite, Mineral resources, Beneficiation technology, Desulphurization, Desilication.

1. Introduction

Aluminium is the most abundant metallic element in the Earth's crust and the second only to oxygen and silicon, and it is also the second most abundant metallic resource. As a core raw material in the aluminium industry, bauxite is widely used in fields such as alumina smelting, refractory material preparation, and the ceramic industry [1].

As the world's largest producer and consumer of aluminium, China's bauxite mining scale continues to expand. According to the latest statistics, China's bauxite reserves in 2024 are approximately 680 million tonnes, accounting for only 2 % of the global total reserves. Meanwhile, the output during the same period is as high as 93 million tonnes, making up 21 % of the global total output and ranking third in the world (only after Guinea and Australia). The supply and demand situation are becoming increasingly severe. Compared with the rest of the world, China's bauxite resource endowment is complex. Over 98 % of the proven deposits belong to the ancient weathering crust sedimentary type of boehmite ore, with typical characteristics of high aluminium, high silicon, low iron and accompanied by impurities such as sulphur and carbon.

Due to the fine particle size distribution, complex mineral composition and high impurity content of such ores, traditional beneficiation processes are confronted with problems such as lengthy procedures, high energy consumption and difficult tailings disposal, further increasing the cost of alumina smelting. To address this issue, China, on the one hand, selects imported high-quality bauxite, and on the other hand, intensifies the impurity removal and purification of the abundant reserves of low-grade and complex bauxite to meet the raw material requirements for bauxite products [2–5]. Therefore, conducting a comprehensive analysis of the current resource status of bauxite in China, the progress of beneficiation and quality improvement technologies for low-grade and complex bauxite, and the existing problems, and highlighting the future research directions, is of great significance for promoting the development and utilization of bauxite in China and enhancing the resource guarantee capacity.

2. Nature of Bauxite Resources in China

The bauxite resources in China are mainly sedimentary boehmite monohydrate, featuring significant regional distribution concentration and special ore quality. The aluminium-silicon ratio of this type of ore is generally low, and the contents of impurities such as sulphur, iron and silicon are relatively high, resulting in high processing difficulty and energy consumption. These complex mineral characteristics pose significant challenges for bauxite in China in terms of beneficiation quality improvement and alumina production.

(1) The basic reserves of bauxite in China are relatively low. The proportion of low-grade bauxite exceeds 90 %, and high-grade bauxite is scarce, and most of them are of the boehmite type with high energy consumption for dissolution. Compared with the laterite bauxite deposits abroad, the sedimentary deposits in China have thin bodies and deep burial, and the reserves suitable for open-pit mining only account for 34 %. The ratio of aluminium to silicon in the ore is generally lower than the international average level. Shanxi, Guangxi, Guizhou and Henan provinces and autonomous regions concentrate over 90 % of the country's resources [6].

(2) There are mainly two types of boehmite deposits: sedimentary and accumulative [7]. Sedimentary bauxite accounts for 82 % of the total reserves in the country and is mainly distributed in the sedimentary environment of ancient weathering crust. In the ore, hydrated bauxite closely coexists with siliceous minerals such as kaolinite and illite. The accumulation type deposits are represented by Pingguo, Guangxi, which are characterized by large ore body thickness and high aluminium-silicon ratio, but the reserves only account for 18 %.

(3) The aluminium-silicon ratio of bauxite is generally low, and the content of impurities such as sulphur, iron and silicon is high [8]. The boehmite in the ore is closely interwoven with silicate minerals, and the energy consumption for dissolution is high. Therefore, it is necessary to carry out mineral processing for quality improvement (such as silicon removal by flotation and iron removal by magnetic separation) to achieve resource utilization. The reserves of high-sulphur bauxite (with sulphur content exceeding 0.8 %) amount to hundreds of millions of tonnes. The presence of sulphur in the ore can easily corrode equipment and reduce the purity of alumina. It needs to be sulphurised to meet the production requirements of the Bayer process.

(4) It generally shows the symbiotic characteristics of multiple elements. In the occurrence system, in addition to the main ore body, there are often abundant associated resources. In typical bauxite deposits, refractory clay, carbonate rocks and iron ore can be seen coexisting with bauxite. The associated components mainly include useful elements such as gallium, vanadium, lithium, titanium and scandium [9].

With the continuous increase in China's alumina production capacity, the consumption of bauxite raw materials has been significantly pushed up. However, limited by the endowment of bauxite resources, the total amount of high-quality bauxite resources shows a decreasing trend, and the average grade of the ore gradually decreases. If this development trend continues, China's capacity to guarantee bauxite resources will face severe challenges, and there may be a risk of structural shortage in the future. How to achieve large-scale utilization of complex resources such as low-grade high-silicon bauxite and high-sulphur bauxite through process optimization and technological innovation has become the key to breaking through the bottleneck in the aluminium industry. This paper systematically sorts out and reviews the research progress of desilication and desulphurization technologies in the bauxite beneficiation process in recent years, and specifically proposes the future technical breakthrough directions, aiming to provide theoretical references for the efficient development of low-grade and complex bauxite.

3. Research Progress on Desilication Technology of Low-Grade Bauxite

Due to significant differences between China's bauxite and foreign bauxite, most of which are of the boehmite type with high silicon mineral composition, they are not suitable for direct application in the Bayer process. Therefore, to meet the requirements of raw materials for the production of alumina using the Bayer process commonly used in China, it is necessary to perform pre desilication treatment on bauxite to achieve an aluminium silicon ratio of 4 or above, in order to reduce the adverse effects of high silicon content. At present, physical, chemical, and biological beneficiation desilication technologies are the three mature pre desilication technologies for bauxite.

3.1 Physical Beneficiation Desilication Process

The physical beneficiation desilication process, as an important technical path for pre-desilication of bauxite, mainly achieves the separation of siliceous minerals by taking advantage of the differences in physical properties between aluminosilicate minerals and bauxite. At present, the widely used physical beneficiation desilication technologies include staged desilication, flotation desilication and gravity separation desilication, among which the flotation desilication method has the most extensive industrial application.

3.1.1 Graded Desilication Process

Due to the significant difference in grindability between boehmite and aluminosilicate gangue minerals, conventional bauxite beneficiation and desilication processes often result in excessive crushing of aluminosilicate gangue minerals, and severe polarization of particle size distribution in the milled products, which affects desilication efficiency. Based on the differences in particle size distribution characteristics and dissociation laws of aluminium silicon minerals in bauxite, the graded desilication method achieves the cascade separation of silicon minerals through the synergistic effect of aluminium silicon mineral properties and multi-level particle size regulation. Lingshi Sheng [10], based on the characteristics of low Mohs hardness, easy pulverization, and modification of clay minerals containing silicon in monohydrate alumina type bauxite, crushes the ore and uses efficient grading equipment to remove fine-grained gangue minerals to achieve desilication and improve the aluminium silicon ratio of bauxite. Ma Junwei [11] has developed the "pre-screening washing crushing grading and tailings disposal" to address the gradual decrease in the aluminium silicon ratio of bauxite with high mud content as the particle size becomes finer.

After processing the raw ore with this process, high-quality aluminium concentrates with an Al_2O_3 content of 64.33 % and A/S 15 can be obtained. Yu Xinyang [12] has developed a "selective grinding classification" process for overseas bauxite with difficult to process mud content. The raw ore with an aluminium silicon ratio of 3.14 is processed by this process to obtain a coarse-grained concentrate with Al_2O_3 content of 65.90 % and A/S of 14.38, while the fine-grained product enters the flotation desilication process. The successful development of the "selective grinding grading treatment" process can obtain high-quality bauxite concentrate, achieve excellent sorting indicators, and effectively avoid the loss of useful minerals in coarse particles, as well as the adverse effects of fine particles generated by over grinding, further improving the efficiency of bauxite separation and desilication.

At present, the graded ore washing process has been industrialized and applied in enterprises such as Aluminium Corporation of China Limited Guangxi Branch, with stable production and operation, providing a practical and feasible process route for the development and utilization of low-grade bauxite.

3.1.2 Flotation Desilication Process

The flotation desilication process is currently one of the most widely used methods for desilication of bauxite. Based on the differences in physical and chemical properties of mineral surfaces, selective inhibition and collection are used as the basis. By adjusting the slurry and adding collectors, the surface wettability of aluminium minerals and silicate minerals is different, and then separation is achieved with the help of bubble carriers. Li Mingxiao [13] used sodium silicate as a silicon containing gangue mineral inhibitor and YZ-3 as a collector to obtain aluminium concentrate with Al_2O_3 content of 57.51 % and a recovery rate of 70.22 % through a positive flotation desilication process for a low-grade monohydrate bauxite mine in Yunnan. A/S of the ore increased from 4.82 to 11.02. Liu Anrong conducted a positive flotation closed-circuit experiment on a bauxite mine in Guizhou and finally obtained an Al_2O_3 content of 67.49 % and a recovery rate of 78.04 %. The aluminium to silicon ratio of aluminium concentrate has increased from 4.46 to 8.81. Zhou Jieqiang [14] conducted flotation desilication and upgrading experiments on a high sulphur and high silicon bauxite mine in Chongqing. By using a mixed dosing method, the indicators of concentrate alumina content of 62.18 %, sulphur content of 0.11 %, and alumina recovery rate of 79.67 % were obtained, achieving the goal of synchronous desulphurization and desilication.

Since the 11th Five-Year Plan, Zhengzhou Non-ferrous Metals Research Institute Co., Ltd. of Chalco has conducted extensive research on the low recovery rate of silica alumina from low-grade bauxite by positive flotation and the many problems that exist in the grinding and filtration processes. The integrated innovation of non-transmission flotation tank, coarse particle rapid sorting process technology, and coarse tailings regrinding and mixing process technology has formed the "low-grade bauxite non transmission flotation technology". In 2014, it was industrialized and applied in a certain aluminium company in China. After flotation, the raw ore with A/S of 3.12 can obtain the indicators of concentrate yield of 62.72 %, A/S of 6.88, and Al_2O_3 recovery rate of 71.44 %.

With the continuous decrease of bauxite grade, bauxite flotation desilication has become an important technical means to ensure the production of alumina. Currently, bauxite flotation desilication technology has been industrialized and applied in Henan, Shanxi, Shandong and other places, with a total production capacity of about 11.75 million tonnes per year. At present, great progress has been made in the flotation desilication technology of bauxite, but the decreasing aluminium silicon ratio of bauxite in China has put forward increasingly high requirements for the desilication work of bauxite. In response to the current situation of "poor fineness and impurities" in ore properties, existing technologies are facing many bottlenecks that urgently need to be overcome. On the one hand, the characteristics of poor ore lead to a significant increase in the unit energy consumption and chemical dosage of bauxite. On the other hand, fine mineral particles are tightly embedded, and traditional grinding is prone to over grinding or insufficient dissociation. In addition, the complex mineral composition makes it difficult for some associated minerals to achieve precise sorting, resulting in aluminium mineral loss and high tailings grade.

Therefore, future research should focus on precise sorting, such as selective dissociation technology, environmentally friendly agents for processing fine-grained minerals, and the development of intelligent equipment, which will be the focus of future research.

3.1.3 Re-selection Desilication Process

The re-selection desilication method is a mineral processing technology based on the density difference between aluminium minerals and gangue silicon minerals to achieve separation. After crushing and grinding the mineral monomers, aluminium silicon separation is achieved in a gravity field using equipment such as spiral chutes and shaking tables.

Mohammad Zarbayani et al. [15] used heavy liquids to separate bauxite of the gibbsite type. They conducted separation experiments on different particle size fractions of bauxite using heavy liquids with densities of 2.8 g/cm³, 3.0 g/cm³, 3.2 g/cm³ and 3.4 g/cm³. The A/S ratios of the concentrates of -3350+710 µm, -710+212 µm and -212+125 µm were 5.03, 5.16 and 5.15 respectively, and the recovery rates were 89.09 %, 91.24 % and 84.68 %. Xie Haiyun [16] found in their study on desilication of high silica bauxite in a certain area of Yunnan that spiral chute gravity separation had a good desilication effect on bauxite with good monomer dissociation after rough grinding of the original ore. They successfully developed the "heavy floating" combined desilication technology. After one coarse and one fine gravity separation desilication treatment, qualified coarse-grained gravity separation aluminium concentrate with yield of 44.65 %, A/S of 7.25, and alumina recovery rate of 43.83 % could be obtained.

The reselection desilication method has attracted much attention in recent years due to its simple process, environmental friendliness, and high efficiency, and has shown great potential for desilication of low-grade bauxite.

3.2 Chemical Desilication Process

The chemical desilication process is based on the differences in chemical properties, dissolution characteristics, or reaction activity between aluminium containing minerals and silicon containing gangue minerals in bauxite. By adding chemical agents or adjusting reaction conditions (such as temperature, concentration, pH, etc.), silicon containing minerals can be selectively dissolved or transformed to achieve aluminium silicon separation. Based on different process flows, the widely used chemical beneficiation desilication technologies currently include pre roasting sodium hydroxide leaching desilication method and sodium hydroxide direct leaching sorting desilication [17]. Luo Lin's research on high silica boehmite type bauxite shows that after roasting the ore at 600-800 °C, kaolinite is converted into active amorphous SiO_2 and γ-Al_2O_3, and then selectively leached with NaOH solution to increase the aluminium silicon ratio of the concentrate from 4–5 to over 10. The key to this process lies in the control of roasting temperature. If the temperature is too low, kaolinite will not decompose completely, while if it is too high, inert mullite will be generated, significantly reducing the silicon leaching rate. In industrial experiments, the desilication rate can reach 70 %, but the energy consumption is relatively high [18]. The direct dissolution separation method of sodium hydroxide is based on the different dissolution characteristics of boehmite and kaolinite in NaOH solution, as well as the differences in particle size, density, and composite field behaviour between hydrated sodium aluminosilicate and boehmite particles to achieve aluminium silicon separation.

Chemical desilication is beneficial for solving the problem of extremely fine-grained ores that are difficult to process by physical methods and can also recover alumina from some gangue mineral minerals. However, due to the high concentration of alkaline solution or high-temperature roasting required by chemical desilication process, it has the disadvantages of high cost, complex process, and low efficiency, and is not suitable for industrial promotion and application at present.

[19]. In the future, it is necessary to reduce production costs and environmental footprint through technological innovation. Under the "dual carbon" goal, developing low-energy chemical physical combined processes will be one of the inevitable paths for the utilization of high silica bauxite.

3.3 Biological Desilication Process

Biological beneficiation desilication utilizes organic acids and polysaccharides produced by the metabolism of silicate bacteria to selectively dissolve silicate minerals in bauxite, while retaining aluminium containing minerals such as boehmite. This method is particularly suitable for treating gelatinous ultrafine grained bauxite [20]. Groudeva et al. extracted 12.5 % to 73.6 % of silicon from five different high silica bauxite ores within 120 hours using wild strains and mutant strains propagated in the laboratory. The former Soviet Union conducted a bioleaching experiment on kaolinite and trihydrate alumina in Kazakhstan. Bacteroid bacteria were used to leach fine mud and magnetic products at a leaching temperature of 28 ℃-30 ℃ for 9 days, resulting in a desilication rate of approximately 62 % and alumina recovery rate of 99 %. Zhong Chanjuan used Bacillus subtilis P04 and P17 screened from Poyang Lake soil for bauxite in Jiaozuo, Henan. After 12 days of leaching under laboratory conditions, the aluminium silicon ratio of bauxite increased from 5.17 to 10.99 (P04) and 7.61 (P17), with a desilication rate of over 60 % [20].

The biological desilication process is conducive to solving the desilication problem of low-grade complex embedded ores and is a desilication method with good prospects. The amount of bacteria attached to the aluminium concentrate after biological beneficiation is extremely low, mainly because the washing process after beneficiation can effectively remove most of the free bacteria. However, a small amount of microbial spores or biofilms may remain on the mineral surface, especially in the mineral fissures or pores. Currently, there is no direct research data indicating that these residual microorganisms will have an adverse effect on the Bayer process. The Bayer dissolution process is usually carried out under high temperature and high alkali concentration. This extreme environment can theoretically inactivate the vast majority of microbial cells and their enzyme systems. However, due to reasons such as long cycle, slow reaction rate and poor adaptability of strains in biological desilication, it is still in the laboratory research stage and difficult to be industrialized. Biological desilication is a key technology for green mines, but it needs to break through the barriers of efficiency and cost. In the short term, it is more suitable to be used as a supplementary process to physical mineral processing for tailings or extremely low-grade ores. In the medium and long term, it is necessary to screen and cultivate silicate bacteria with efficient desilication performance and combine them with physical sorting chains to achieve industrial application.

4. Research Progress on Desulphurization Technology of High-sulphur Bauxite

According to the grade standard for bauxite ore (YB/T 5057-93), bauxite with a sulphur content greater than 0.8 % is called high sulphur bauxite. China has abundant reserves of high sulphur bauxite, which can serve as a supplement to bauxite resources. However, in the Bayer process for producing alumina, sulphur can lead to increased alkali consumption, equipment corrosion, deterioration of red mud settling performance, and increased iron content in the product [21]. Therefore, the industry requires that the sulphur content of alumina raw materials should be less than 0.4 %. In recent decades, scholars at home and abroad have conducted a lot of research on desulphurization of high sulphur bauxite. At present, the beneficiation processes for high sulphur bauxite mainly include roasting desulphurization process, flotation desulphurization process, chemical oxidation desulphurization process, microbial desulphurization process [22], among which flotation desulphurization process is the most widely used and has been applied in industrial production.

4.1 Roasting Desulphurization Process

Roasting desulphurization achieves the purpose of desulphurization by decomposing sulphur-containing minerals in high sulphur bauxite into sulphur dioxide gas through high-temperature roasting. The roasting desulphurization process mainly includes two types: conventional roasting desulphurization and microwave roasting desulphurization. Conventional roasting uses roasting equipment such as muffle furnace, suspension furnace, boiling furnace, and fluidized bed for heating and roasting, while microwave roasting directly heats high sulphur bauxite using microwave energy.

In terms of conventional roasting and desulphurization of high sulphur bauxite, Liu Xijun used a suspended roasting device to reduce the sulphur content in bauxite from 1.86 % before roasting to 0.45 % after roasting, with a sulphur removal rate of 80.56 %. By increasing the early roasting temperature, the roasting time can be further shortened, and the roasted bauxite can meet the production requirements of alumina for enterprises [23]. Ma Xingfei conducted desulphurization experiments on high sulphur, high silicon, and low-grade bauxite using low-temperature roasting technology. Under the conditions of roasting temperature of 650 °C, roasting time of 3 minutes, and ore particle size of 48 μm, the sulphur removal rate of bauxite reached 75.83 %, and the sulphur decreased to 0.29 % after roasting [24]. Zhang Nianbing et al. used microwave heating to treat high sulphur bauxite with a sulphur content of 1.39 %, and roasted it at 400 °C for 2 minutes, reducing the sulphur content to below 0.8 %. When roasted at 550 °C for 10 minutes, the sulphur content reached 0.23 %. It was found that microwave separated S^{2-} from pyrite and promoted S^{2-} to diffuse towards the surface and react with oxygen to generate SO_2 gas, accelerating the escape of sulphur and improving desulphurization efficiency. Yang Qian was found that a microwave box type high-temperature reactor roasting desulphurization experiment was conducted on a certain high sulphur bauxite mine. After 20 minutes of microwave roasting at 600 °C, the sulphur content decreased from 3.88 % to 0.23 %, and the desulphurization rate reached 95.11 % [25]. Compared with conventional roasting, it has the advantages of low roasting temperature, short roasting time, and high sulphur removal rate.

At present, the roasting desulphurization technology has been industrialized and applied in Guizhou region, with a production capacity of 2 million tonnes per year. The conventional roasting method usually operates at higher temperatures. Although the desulphurization speed is fast and the desulphurization effect is good in high-temperature environments, there are problems such as high energy consumption and increased production costs. The microwave roasting process has the advantages of significant desulphurization effect, fast speed, and low required temperature, and has good application prospects. However, this process faces challenges such as limited single processing capacity, high operational difficulty, and high equipment investment costs, and has not yet achieved industrial promotion and application. From the perspective of energy supply, the bauxite roasting desulphurization process has not yet widely adopted renewable energy as the main energy source in large-scale production. Its energy structure still mainly relies on traditional fossil fuels (such as coal and natural gas) or grid power supply. Although microwave roasting theoretically can save 30–40 % of energy, its power consumption still mainly depends on grid power supply. These energy structures result in a significant carbon footprint in the roasting process, which has become a key obstacle to the green transformation of industry. In the future, the integrated application of renewable energy sources such as solar heating, biomass combustion and green electric-driven microwave technology will also be one of the important development directions of calcination desulphurization technology.

4.2 Flotation Desulphurization Process

The flotation desulphurization process is based on the difference in surface hydrophobicity between sulphur minerals and aluminium containing minerals and achieves selective separation through chemical control. The flotation desulphurization process, based on the principle of "less flotation and more suppression", has the advantages of simple process, high sulphur removal efficiency, high alumina recovery rate, and can also achieve zero tailings discharge. At present, it has become the mainstream method for processing high sulphur bauxite.

The sulphur in high sulphur bauxite mainly exists in the form of pyrite. Some scholars have found that yellow medicine agents only have excellent capture effects on sulphides and basically do not interact with aluminium minerals. Therefore, reverse flotation desulphurization technology is often used for flotation desulphurization. Wang Zhenjie [26], and Li Shaoying [27] conducted flotation desulphurization experiments on a high sulphur bauxite mine in Guizhou. After the reverse flotation desulphurization process, the sulphur content in the aluminium concentrate can be reduced to 0.26 %–0.53 %, and the desulphurization rate can reach over 85 % for the raw ore with a sulphur content of 1 %–6 %. Chen Hongde [28] and others conducted flotation desulphurization experiments on a high sulphur bauxite mine in Shanxi Province. They used the "one coarse, one fine, one sweep" flotation process to obtain aluminium concentrate with a concentrate yield of 89.32 % and a sulphur content of 0.29 %, which meets the production requirements of alumina. Wu Guoliang [29] conducted laboratory and industrial flotation desulphurization experiments on a high sulphur bauxite mine in Henan Province. They used a closed-loop flotation desulphurization process of "one coarse, one fine, and one sweep" to obtain aluminium concentrate with a concentrate yield of 93 % and a sulphur content of 0.23 %. The sulphur removal rate reached 83.16 %. In response to the acidification of high sulphur bauxite in a certain area of southwestern China, Zhengzhou Non-ferrous Metals Research Institute Co. Ltd of CHALCO has successfully developed the "comprehensive utilization technology of non-transmission alkaline flotation desulphurization" using a new flotation device and a non-transmission flotation cell, achieving good experimental indicators. When the original ore contains 2.15 % sulphur, an aluminium concentrate with a yield of 91.65 % and a sulphur content of 0.23 % was obtained, and the sulphur removal rate was 90.25 %. At the same time, the flotation energy consumption was saved by 30 % compared to ordinary flotation machines.

At present, the flotation desulphurization technology of bauxite has been industrialized and promoted in Henan, Chongqing, Guizhou and other places, with a total production capacity of about 5 million tonnes per year.

4.3 Chemical Oxidation Desulphurization Process

Chemical oxidation desulphurization belongs to the desulphurization process in the production process. During the dissolution process, a chemical reaction occurs to convert the low valence sulphur in the solution into sulphate ions, which are removed in the form of sulphates in subsequent processes.

Hu Xiaolian used an autoclave to simulate the dissolution process. Under optimal temperature and pressure conditions, most of S^{2-} was oxidized to high valence SO_4^{2-}, and the removal rate of S^{2-} in the solution reached 99.0 %, indicating significant desulphurization effect [30]. Qin Zhihui studied the removal behaviour of S^{2-} in sodium aluminate solution by adding chemical reagents. The experimental results showed that copper chloride can remove S^{2-} from the solution through chemical reactions, and potassium permanganate can completely remove S^{2-} from the solution under certain experimental conditions [31]. Liu Long studied the effect of adding zinc oxide on desulphurization of high sulphur bauxite and found that the S^{2-} content decreased with the increase of zinc oxide addition, but other valence states of sulphur did not change, making it suitable for processing high sulphur bauxite with sulphur content not exceeding 1.373 % [32]. Liu Zhanwei studied the leaching of pyrite and sulphate in the Bayer process of high sulphur bauxite production and found that pyrite and sulphate entered the solution in the form of S^{2-} and SO_4^{2-}, respectively. They proposed that adding ZnO during the leaching process can remove S^{2-} from the leaching solution, and adding $BaO \cdot Al_2O_3$ can remove SO_4^{2-} [33].

The chemical oxidation desulphurization process has high desulphurization efficiency and can oxidize and remove most of the S^{2-} in the solution. The process operation is relatively simple, but it still cannot eliminate the corrosion problem of sulphur elements on equipment. At the same time, when the sulphur content in the ore is too high, the amount of desulphurizer used will also increase. The use of expensive zinc salts and barium salts will lead to increased costs and make it difficult to apply in industrial production.

4.4 Microbial Desulphurization Process

Microbial desulphurization utilizes certain microorganisms in nature to convert sulphur minerals in high sulphur bauxite into harmless substances such as sulphates, thereby achieving the removal of sulphur from high sulphur bauxite.

Zhou Jikui conducted desulphurization experiments using ferrous sulphide bacteria, and the desulphurization rate was 83.57 % under the conditions of slurry concentration of 10 %, initial pH 2.0, temperature of 30 °C, and leaching time of 20 days [34]. Hao Yuepeng obtained a ferrous acidophilic sulphur oxidizing bacterium with strong sulphur removal efficiency by screening bacterial strains. Under laboratory conditions, the sulphur content in a high sulphur bauxite mine in Chongqing with a sulphur content of 3.83 % was reduced to 0.69 % after microbial leaching, and the Al_2O_3 recovery rate was 97.72 % [35]. Li Shoupeng selected moderately thermophilic bacterial strains with stronger enzyme activity and growth activity, which have stronger growth and metabolic capacity and a simpler desulphurization process. Under the optimal microbial composition conditions, the sulphur content decreased from 1.31 % to 0.29 %, and the sulphur removal rate was 77.86 % [36]. The desulphurization efficiency was better than that of a single microbial community, attributed to the synergistic effect of iron and sulphur metabolism.

The acidic environment in the biological desulphurization process is fundamentally in conflict with the highly alkaline process of the Bayer process. Acidic pulp needs to consume a large amount of alkaline solution to neutralize it to neutral or weakly alkaline before it can enter the Bayer process system, significantly increasing production costs. However, microbial desulphurization remains a desulphurization method with development potential, featuring good environmental friendliness and sustainability. But it has problems such as a long desulphurization cycle, high difficulty in microbial cultivation, and high requirements for production conditions. Currently, there are no industrial application examples.

5. Conclusions

(1) The physical beneficiation and desilication technology of mineral processing and desilication process is relatively mature and has industrial application cases in terms of process technology, optimization of reagent system, and separation theory research. However, with the "lean, fine, and miscellaneous" transformation of ores, the difficulty of comprehensive utilization is high. The main research direction in the future should strengthen the development of selective dissociation technology, environmentally friendly reagents for processing fine-grained minerals, and intelligent equipment; The main direction of chemical desilication process is to reduce its energy consumption and alkali consumption; The promising biological desilication technology still needs to break through efficiency and cost barriers. It is necessary to screen and cultivate silicate bacteria

with efficient desilication performance and cooperate with physical sorting chains in order to achieve industrial implementation under the "dual carbon" goal.

(2) In terms of desulphurization of high sulphur bauxite, although roasting desulphurization can effectively remove sulphur, there is a problem of high energy consumption, and the stability of desulphurization effect is insufficient during large-scale industrial production. It is necessary to develop efficient roasting equipment and optimize process parameters to reduce energy consumption and costs; As the most widely used desulphurization method currently, flotation desulphurization has become increasingly complex as the grade of bauxite decreases and the sulphur content increases. Therefore, it is necessary to develop flotation reagents with stronger selectivity and optimize the flotation process; chemical oxidation desulphurization technology has a certain effect on the transformation of sulphur forms, but further research is still needed on the oxidation reaction mechanism of sulphur forms other than S^{2-} in sodium aluminate solution; microbial desulphurization, as an environmentally friendly technology, can improve desulphurization efficiency by screening more adaptable and efficient bacterial strains, optimizing bacterial culture conditions.

(3) The selection of bauxite desilication and desulphurization technologies and their cost impacts should be dynamically evaluated based on ore characteristics, process compatibility, and logistics conditions. At the ore property level, the form and content of silicon and sulphur directly determine the technical route; process selection needs to balance initial investment, operating costs, and by-product benefits; fluctuations in ocean freight rates have strengthened the strategic value of local processing. Compared with imported ores, the economic efficiency of domestic high-sulphur ore processing depends on the efficiency of technology conversion and regional resource endowment. Under the combined effect of ore purchase prices, transportation costs and environmental protection costs, technological innovation is gradually narrowing the cost gap. To promote the sustainable development and utilization of low-grade and complex bauxite resources in China, it is necessary to give full play to the strategic role of the national "the Belt and Road" initiative. It is suggested to build a multi-level bauxite resource guarantee system, optimize the import strategy, realize the coordinated development of domestic resource development and international resource supply, improve the bauxite resource guarantee ability from the source, and provide solid resource support for the sustainable development of the aluminium industry.

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