Experimental and mechanism research on carbothermal reduction of spodumene ore via vacuum

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Abstract
Considering the low resource utilisation rate and high environmental pollution afflicting the current technology for extracting Li from spodumene ore, this report proposes a clean process for the vacuum carbothermal reduction of spodumene ores for Li extraction, ferrosilicon alloy preparation, and alumina recovery. Thermodynamic analysis indicated that vacuum conditions can significantly promote the carbothermic reduction of spodumene ores and that the initial reaction temperature can be reduced by 480 K when an environmental pressure of 20 Pa is applied. According to the experimental results, two important factors in the above procedure are the reduction temperature and reduction time. When the reduction temperature was 1648 K and the reduction time 3 h, the reduction rate of Li in the spodumene ore exceeded 90%. Furthermore, the ferrosilicon alloy and alumina slag could be effectively separated from the reduction residue. The thermodynamic equilibrium simulation of the reduction process was combined with the experimental results to assess the vacuum carbothermal reduction mechanism of spodumene ores. Compared with the existing Li extraction approach, this method has the advantages of a straightforward process flow, almost zero waste water/waste residue production, environmental compatibility, and increased resource exploitation. Based on the above, this work provides new insights for advancing the conventional technology used for Li extraction from spodumene ores.

1. Introduction
Owing to its advantageous physical and chemical properties, lithium (Li) has been extensively used in numerous technological fields, spanning from industrial production to household applications [1, 2]. Due to its expanded use in batteries, aviation, and nuclear power generation, its demand has drastically increased in recent years, rendering it a primary focus of current technology and industry [3, 4]. Spodumene ore is a mineral with the benefits of high Li content, large reserves, and easy mining, so it is the predominant raw material for Li extraction [5]. The existing processes for extracting Li from spodumene ore are all based on the principle of high-temperature roasting to excite the minerals chemically. The processed spodumene ore is subsequently acid or alkali leached to extract Li from the spodumene crystal lattice [6, 7]. Using sulfuric acid for the above process is currently the most tested approach for extracting Li from spodumene ore. In industrial conditions, spodumene ore is roasted at a temperature of 1223–1373 K to obtain β-type spodumene, which is then finely ground and acid-leached at a temperature of 523–573 K to produce soluble lithium sulfate and insoluble gangue [8, 9].
products are leached and filtered to obtain a leaching solution containing Lithium sulfate and insoluble gangue residue. Finally, the leachate is purified and carbonated to procure lithium carbonate \cite{10, 11}. The sulfuric acid method has the advantages of strong adaptability to raw materials, the ability to process a variety of Li-containing ores, and high Li concentration in the procured leachate. However, significant amounts of concentrated sulfuric acid and sodium carbonate are required for this method, and these materials are expensive and difficult to process. Furthermore, concentrated sulfuric acid is a highly hazardous and toxic substance for both humans and the environment, demanding extensive safety measures and anti-corrosion equipment.

Spodumene, being a typical aluminosilicate ore, contains a small amount of lithium oxide (Li$_2$O) (approximately 3\%–6\%), and considerable amounts of alumina (Al$_2$O$_3$) and Silica (SiO$_2$) (16\%–25\% and 50\%–75\%, respectively) \cite{12}. The primary focus of the current technology utilised in the field is the extraction of Li from spodumene, which converts Al$_2$O$_3$ and SiO$_2$, the main components of the ore, into hazardous waste residue. This process, apart from wasting substantial amounts of resources, also causes considerable environmental pollution. In recent years, researchers have exploited Al in the form of Al$_2$O$_3$ during the processing silicate, adding Fe, to convert the Si in the mineral into a ferrosilicon alloy \cite{13}. This approach not only alleviates the high temperatures during the direct reduction of Al$_2$O$_3$ and SiO$_2$, but also facilitates the effective separation of Al and Si resources. Yang et al \cite{14} demonstrated in their study on the carbothermic reduction of fly ash that adding Fe can promote the decomposition of the mullite and quartz species in the ash (and particularly that adding iron trioxide (Fe$_2$O$_3$) has a better effect than adding plain Fe).

The vacuum method is a clean and efficient secondary resource utilisation approach \cite{15}. The vacuum condition not only effectively reduces the pressure in the reaction system and promotes the thermal reduction process, but also effectively prevents the oxidation of the active metal products during the reaction. Therefore, this study adopted a clean process for the vacuum carbothermal reduction of spodumene ore for Li extraction, ferrosilicon alloy preparation, and alumina recovery. The effects of the vacuum environment on the carbothermal reduction reaction process of spodumene ore were analysed by thermodynamic calculations. X-ray diffraction (XRD) and scanning electron microscopy (SEM) were performed to evaluate the reaction behaviour of spodumene and the formation mechanism of the ferrosilicon alloys. In addition, the reaction mechanism behind the carbothermal reduction of spodumene ore was further explored through thermodynamic simulations.

2. Experiment

2.1. Experiment materials

Spodumene ore, the main raw material, was obtained from a certain location. XRD analysis was performed to analyse its mineral composition, and the results are shown in figure 1. The raw material primarily contained quartz (SiO$_2$), spodumene (LiAlSi$_2$O$_6$), and a small amount of alumina (Al$_2$O$_3$). Inductively coupled plasma emission spectroscopy (ICP-OES) was used to analyse quantitatively the main chemical components of the raw materials, and the results are shown in table 1. Anthracite powder, with a particle size below 100 mesh, was used

![XRD pattern of the spodumene ore.](image)
as the reducing agent, and its chemical composition is shown in table 2. The directly purchased analytically pure Fe₂O₃ powder (impurity content < 0.1%) was used as an additive to promote the reaction.

2.2. Experimental procedure
Initially, the spodumene ore and anthracite powder were crushed to a particle size of less than 0.015 mm. Then, the spodumene powder, anthracite powder, and analytical pure ferric oxide powder were uniformly mixed (where the Si/Fe molar ratio was 1, and the mass ratio of anthracite to spodumene was 3:5). The mixed materials were pressed into 30 mm cylindrical blocks under a pressure of 15 kPa. Finally, the material blocks were placed in a vacuum furnace using the pre-set conditions for a vacuum carbothermal reduction experiment. A diagram of the vacuum furnace is shown in figure 2. The internal pressure applied was below 20 Pa, and the heating rate was 10 K min⁻¹. According to the experimental requirements, after the temperature reached a predetermined value, the samples were kept in the furnace for a period of time (1–5 h) and then cooled to room temperature (298K) under vacuum conditions.

2.3. Analysis method
2.3.1. X-ray diffraction (XRD) analysis
XRD (Japan Science D/max-R, target material: Cu, wavelength of Kα line: 1.5419, scanning speed: 0.06 s/step, step interval: 0.02°/step, angular increment: 4° min⁻¹, scan range 10°–90°) was performed to analyse the mineral composition of the spodumene ore and reduction products.

2.3.2. Scanning electron microscope (SEM) analysis
SEM (HITACHI TM-3030 Plus) was performed to analyse the microstructure of the reduced sample, whereas an attached module for energy dispersion spectroscopy (EDS, INCA Oxford) was used to determine the compositions of the magnetic and non-magnetic parts.

2.3.3. Inductively coupled plasma atomic emission spectrometry (ICP-OES) analysis
ICP-OES (Optima 8000 instrument, PerkinElmer, USA) was conducted to analyse quantitatively the Li species in the reduction product.
2.4. Evaluation index

The reduction rate of Li was calculated according to the following formula (I):

\[
\partial_{Li} = 1 - \frac{\omega_{Li}}{M_{Li}} \times 100\% \tag{I}
\]

where \(\partial_{Li}\) is the reduction rate of Li, \(\omega_{Li}\) is the mass of Li in the reduction residue, and \(M_{Li}\) is the mass of Li in the raw material.

3. Results and discussion

3.1. Effects of vacuum conditions on the carbothermic reduction of LiAlSi2O6

The composition analysis of the spodumene ore described in section 2.1 showed that the carbothermal reduction process with the participation of Fe2O3 mainly involved the two reactions of SiO2, Fe2O3, and C, along with LiAlSi2O6, Fe2O3, and C. Luo et al [16] performed analyses of pure Fe2O3 and SiO2 as raw materials to study the effects of vacuum conditions on the reaction processes of SiO2, Fe2O3, and C. Studies have shown that the initial reaction temperature to produce ferrosilicon alloys under 100 Pa conditions was reduced by 477–584 K, compared with that under normal pressure conditions. Nevertheless, LiAlSi2O6 possesses a highly stable structure and is often used to prepare refractory materials, so the reaction of LiAlSi2O6 is crucial for the carbothermal reduction of spodumene ores. The main reaction involved in the extraction of Li and preparation of ferrosilicon alloys, while recovering alumina with the participation of Fe2O3, as shown in reaction (I):

\[
2\text{LiAlSi}_2\text{O}_6 + 2\text{Fe}_2\text{O}_3 + 15\text{C} = 2\text{Li(g)} + 4\text{FeSi} + \text{Al}_2\text{O}_3 + 15\text{CO(g)}. \tag{1}
\]

Outotec HSC Chemistry Software HSC6.0 was used to calculate the thermodynamics of reaction 1 under standard conditions. Combined with the Gibbs free energy function method, if the activation energy of LiAlSi2O6, Fe2O3, C, FeSi, and Al2O3 is 1, \(\Delta G\) of reaction 1 can be calculated according to formula (II):

\[
\Delta G = \Delta G^0 + RT \ln \left( \frac{P_3}{P^0} \right), \tag{II}
\]

where \(\Delta G^0\) is the change in Gibbs free energy of the standard reaction, \(R\) is the gas constant, \(P^0\) is the standard atmospheric pressure, and \(P_3\) is the pressure in the reaction system (which can represent the vacuum degree under vacuum conditions). \(P_3 = P_{Li} + P_{CO}\), where \(P_{Li}\) is the Li vapor produced by the reduction reaction and \(P_{CO}\) is the CO gas produced by the reduction reaction. Therefore, the partial pressures of CO gas and Li vapor are important factors affecting the LiAlSi2O6 reaction.

Figure 3 shows the relationship between the initial reaction temperature of the LiAlSi2O6 carbothermal reduction reaction process and system pressure. As shown in figure 3(a), \(\Delta G\) decreases as the system pressure decreases, whereas the initial reaction temperature of LiAlSi2O6 significantly decreases as the system pressure decreases. When the system pressure decreases from 101,325 Pa to 20 Pa, the initial reaction temperature of LiAlSi2O6 decreases from 1542 K to 1062 K (figure 3(b)). Consequently, vacuum conditions can significantly reduce the temperature of the LiAlSi2O6 carbothermal reduction reaction and promote the carbothermal reduction process. The explanation for this behaviour is the following: under vacuum conditions, the mean free path of the vapor increases, enabling the CO gas generated by the reaction to be timely drained and inducing the
Li vapor to be condensed into a solid on the condenser, thus reducing the system pressure and promoting the forward reaction.

3.2. Effects of temperature on the carbothermal reduction of spodumene ore

Based on thermodynamic calculations, the initial experiment started at 1573 K, and the exploratory experiment was carried out with 50 K as a group. The experimental studies revealed that at a reaction temperature of 1623 K, the spodumene ore did not completely react. When the temperature was increased to 1673 K, the spodumene ore completely reacted, but due to the high temperature, the Al$_2$O$_3$ in the residual product continued to react as well. Due to these findings, a vacuum carbothermal reduction experiment was performed under temperature conditions of 1573, 1623, 1648, 1673, and 1723 K. Figure 4 shows the compositional changes of the residues, following the vacuum carbothermal reduction processes at different temperatures. As the temperature increases, the spodumene ore gradually begins to react, until it achieves a complete reaction. When the temperature reaches 1648 K, the main phases observed in the reduction residue are FeSi and Al$_2$O$_3$, whereas a Li-containing phase is absent, suggesting the successful separation of Li, Al, and Si in the ore and achieving the expected goal of the test. However, when the temperature increases beyond 1673 K, the diffraction peak of Al$_2$O$_3$ is abruptly weakened (or even disappeared), and a new phase of CaAl$_{12}$O$_{19}$ emerges. Thus, as the temperature increases, the Al$_2$O$_3$ in the reduction residue reacts with the calcium oxide (CaO) in the ash of the reducing agent, inducing the weakening (or disappearance) of the Al$_2$O$_3$ diffraction peak. In addition, the increase in temperature advances the growth of the ferrosilicon alloy; during the growth process, part of the Al$_2$O$_3$ is wrapped, causing its diffraction peak to weaken (or even disappear). In summary, the reaction temperature is an important factor affecting the carbothermal reduction reaction of spodumene: at low temperatures, the components in the spodumene mineral cannot completely react, whereas at higher temperatures, the residual Al$_2$O$_3$ will partly react with the CaO species in the reducing ash of the agent, while the remaining part will be wrapped in the ferrosilicon alloy, rendering the recovery of Al$_2$O$_3$ impossible. Therefore, reasonable control of the reduction temperature is crucial for the efficient carbothermal reduction of spodumene ore.

Figure 5 shows the effects of the reduction temperature on the Li reduction rate and Li content-in-condensate, during the carbothermal reduction of spodumene ore. It can be inferred that as the temperature increases, both factors gradually increase. When the temperature exceeds 1648 K, the upward trend in the Li reduction rate is significantly mitigated, whereas the Li content-in-condensate begins to stabilise (due to the almost complete reaction of LiAlSi$_2$O$_6$ by that point). In accordance with the above observations concerning the phase composition of the reduction residue, the removal rate of Li, and the content of Li in the condensate, it can be determined that the optimal reduction temperature for the spodumene ore carbothermal reduction process under vacuum conditions is 1648 K (which is within the temperature range in our experiments).

3.3. Effects of reduction time on the carbothermal reduction of spodumene

Figure 6 shows the compositional change of the reduction residue during the vacuum carbothermal reduction process of spodumene ore, with a reduction temperature of 1648 K and a reduction time of 1–5 h. As can be deduced from the results, as the reduction time increases, the diffraction peaks of FeSi and Al$_2$O$_3$ gradually become stronger, and the spodumene ore progressively achieves complete reaction. When the reduction time is
3 h, FeSi and Al$_2$O$_3$ become the predominant phases in the reduction residue. As the reaction time continues to increase, the diffraction peaks of Al$_2$O$_3$ abruptly start to decline (or even disappear), and a new phase of CaAl$_{12}$O$_{19}$ emerges. Thus, as the temperature increases, the Al$_2$O$_3$ in the reduction residue reacts with the CaO species in the ash of the reducing agent, causing the Al$_2$O$_3$ diffraction peak to weaken or even disappear. Similarly, the increase in temperature further advances the growth of the ferrosilicon alloy. During the growth of the alloy process, a portion of Al$_2$O$_3$ is wrapped, causing the Al$_2$O$_3$ diffraction peak to weaken or even disappear.

Figure 7 shows the effects of the reduction time on the Li reduction rate and Li content-in-condensate during the carbothermal reduction of spodumene ore. It can be seen that as the reduction time increases, the reduction rate of Li and content of Li in the condensate gradually increase as well. When the reduction time exceeds 3 h, the increase in the reduction rate of Li is notably reduced and the Li-content-in-condensate gradually starts to stabilise (owing to the almost complete reaction of LiAlSi$_2$O$_6$ by that point). Considering the effects of the reduction time on the phase composition of the reduction residue, removal rate of Li, and content of Li in the condensate, it was determined that the optimal reduction time was 3 h at a temperature of 1648 K.

SEM and EDS were performed to analyse the reaction behaviour of the carbothermic reduction process and the formation mechanism of the ferrosilicon alloy. Figure 8 shows the SEM image and EDS analysis of the reduction product at the optimal reduction temperature and time. As can be seen from figure 8(a), multiple particles with different sizes are present on the reduction product, which were confirmed to be a carbon-containing ferrosilicon alloy phase (figure 8(b), area 1). The Fe:Si:C mass ratio was 60.954:29.131:9.915, respectively (figure 8(g)), indicating that C species were partly present in the alloy during the vacuum thermal
reduction process. The C in the alloy significantly reduced the melting point of Fe, improving the fluidity of the alloy and promoting the aggregation and growth of the alloy particles [17]. In addition, several grey-black phases (points 2 and 3 in figure 8(b)) are observed on and around the surface of the alloy particles and were identified as Al2O3 (figure 8(h) and (i)). The appearance of the Al2O3 phase in these areas originated from the reaction of the spodumene ore during the carbothermal reduction process, causing the formation of the ferrosilicon alloy and subsequent release of free Al2O3 particles, which in turn caused the alumina to attach on the periphery of the alloy. As can be observed from the surface scan of the reduction products (figures 8(c)–(f)), the ferrosilicon alloy and Al2O3 particles in the reduction residue were effectively separated, achieving our experimental goal.

Magnetic separation was conducted to separate the ferrosilicon alloy and alumina slag in the reduction residue under optimal conditions. Quantitative chemical analysis of Si, Fe, and Al was performed on the separated magnetic and nonmagnetic materials. During the carbothermal reduction process of the spodumene ore, the Si–Fe content of the magnetic part was 81.70% and the content of Al2O3 in the non-magnetic part was 54.72% under the best conditions. The main reason for these low indicators is that in the process of carbothermal reduction of spodumene ore, the production of alumina is accompanied by the polymerization of
ferrosilicon alloy, causing the growth of ferrosilicon alloy, which will adhere to part of alumina, and part of the ferrosilicon alloy with small particles will be wrapped by alumina slag. Figure 9 shows SEM images of the magnetic and non-magnetic materials obtained after the reduction residue was separated under the optimal conditions. It can be seen that a lot of alumina slag is still attached to the surface of the alloy particles in the magnetic material. The content of Al2O3 is 12.36%, and non-magnetic materials are also wrapped in many small-particle ferrosilicon alloys. In addition, the formation of SiC during the reduction process will cause a decrease in the content of Al2O3 in non-magnetic materials. Therefore, the separation mechanism of ferrosilicon alloy and alumina slag requires further study.

3.4. Reaction mechanism of the vacuum carbothermal reduction of spodumene ore
To explore the mechanism behind the vacuum carbothermal reduction of spodumene through the addition of ferric oxide, we used the corresponding module in HSC6.0 to calculate the thermodynamic equilibrium component of the reduction process. Figure 10 shows the change in equilibrium composition at different temperatures. The system pressure was 20 Pa, and the initial ingredients were LiAlSi2O6 (0.256 kmol), SiO2 (0.696 kmol), Fe2O3 (0.604 kmol), Al2O3 (0.054 kmol), C (4.74 kmol), and CaO (0.03 kmol).
As can be seen from figure 10, when the reduction temperature is low (800 K), Fe$_2$O$_3$ sustains a gradual reduction reaction and eventually produces Fe, whereas LiAlSi$_5$O$_8$ undergoes a different reaction to produce LiAlSiO$_4$. As the temperature increases, SiO$_2$ begins to react, combined with a decrease in the molar amount of the Fe phase and the appearance of Fe$_3$Si and FeSi phases. As the temperature increases further, SiO$_2$ starts to react and the molar amount of the Fe phase begins to decrease gradually, whereas the molar amounts of the Fe$_3$Si and FeSi phases begin to increase gradually. These findings indicate that at this point the reduction reaction of SiO$_2$ with the participation of Fe starts to occur, generating Fe$_3$Si and FeSi in the process. As the temperature continues to rise, LiAlSiO$_4$ gradually begins to react, accompanied by the appearance of the Li phase and an increase in the molar amount of Al$_2$O$_3$. When the temperature reaches 1500 K, the phases of the components tend to stabilise. At this time, the LiAlSiO$_4$ phase disappears and the molar weight of the Li (g) phase remains unchanged, implying that LiAlSi$_5$O$_8$ has completely reacted. When the reaction temperature exceeds 1700 K, the molar amount of the SiC phase starts to decrease gradually, due to the remaining Fe in the reduction product, which compromises the stability of SiC. Furthermore, when CaO was present under the experimental conditions, it reacted with Al$_2$O$_3$ to form a CaO-6Al$_2$O$_3$ phase. During the reduction process, some of the unstable Fe$_3$Si and Fe$_2$Si phases gradually evolved into FeSi, indicating that a high temperature is beneficial for the formation of ferrosilicon alloys with higher Si content. That is because at low temperatures (1250 K), some of the Si was not reduced and reacted with excess Fe species, leading to the formation of a metastable ferrosilicon phase with higher Fe content. On the contrary, as the temperature increased, additional Si elements were reduced, gradually increasing the Si content in the ferrosilicon alloy, and eventually producing a stable FeSi phase.

Based on the above analysis, it can be concluded that during the carbothermal reduction of spodumene ore by ferric oxide addition, under vacuum conditions and an ambient pressure of 20 Pa, the reactions that occurred were as follows:

**Below 800 K:**

\[
3\text{Fe}_2\text{O}_3 + \text{C} \rightarrow 2\text{Fe}_3\text{O}_4 + \text{CO} (g)/(434 \text{ K})
\]

\[
\text{Fe}_3\text{O}_4 + \text{C} \rightarrow 3\text{FeO} + \text{CO} (g)/(716 \text{ K})
\]

\[
\text{FeO} + \text{C} \rightarrow \text{Fe} + \text{CO} (g)/(680 \text{ K})
\]

**Above 800 K:**

\[
\text{LiAlSi}_5\text{O}_8 \rightarrow \text{LiAlSiO}_4 + \text{SiO}_2/(1038 \text{ K})
\]

\[
\text{SiO}_2 + 3\text{Fe} + 2\text{C} \rightarrow \text{Fe}_3\text{Si}_3 + 2\text{CO} (g)/(1184 \text{ K})
\]

\[
\text{SiO}_2 + \text{Fe} + 2\text{C} \rightarrow \text{FeSi} + 2\text{CO} (g)/(1236 \text{ K})
\]

\[
5\text{Fe}_2\text{Si} + 4\text{Si} \rightarrow 3\text{Fe}_3\text{Si}_3/(\text{all temperatures})
\]

\[
2\text{SiO}_2 + \text{Fe} + 5\text{C} \rightarrow \text{FeSi} + \text{SiC} + 4\text{CO} (g)/(1250 \text{ K})
\]

\[
2\text{LiAlSi}_5\text{O}_8 + 4\text{Fe} + 9\text{C} \rightarrow 2\text{Li} (g) + \text{Al}_2\text{O}_3 + 4\text{FeSi} + 9\text{CO} (g)/(1397 \text{ K})
\]

\[
2\text{LiAlSi}_5\text{O}_8 + 3\text{Fe} + 10\text{C} \rightarrow 2\text{Li} (g) + \text{Al}_2\text{O}_3 + 3\text{FeSi} + \text{SiC} + 9\text{CO} (g)/(1402 \text{ K})
\]

\[
\text{CaO} + 6\text{Al}_2\text{O}_3 \rightarrow \text{CaAl}_{12}\text{O}_{19}/(\text{all temperatures})
\]

In summary, the carbothermal reduction of spodumene ore under vacuum conditions and the addition of Fe oxide can effectively separate the Li, Al, and Si elements in spodumene ore to obtain Li-rich ash, ferrosilicon alloy, and alumina slag. Based on these findings, we proposed a comprehensive, efficient, and clean process for the vacuum carbothermal reduction of spodumene ore with the purpose of Li extraction, ferrosilicon alloy preparation, and alumina recovery. Compared with the existing Li extraction from spodumene methods, our proposed reduction process produced minimal waste water and waste residue, thus retaining environmental compatibility. Furthermore, during the Li extraction process, high-value-added ferrosilicon alloys and alumina slag were obtained. Our method realised the comprehensive and efficient utilisation of resources in spodumene ore while providing new insights for the advancement and innovation of current Li extraction from spodumene ore technologies.

### 4. Conclusion

A comprehensive, efficient, and clean process for the vacuum carbothermal reduction of spodumene ore for Li extraction, ferrosilicon alloy preparation, and alumina recovery was proposed, and its feasibility was verified. The main conclusions of this study can be summarised as follows:

1. Vacuum conditions can significantly reduce the reaction temperature of spodumene ore and promote the carbothermal reduction reaction stemming from the significant increase in the mean free path of the vapor under vacuum conditions. The CO gas generated by the reaction will be efficiently drained from the system, whereas the Li vapor condenses into a solid on the condenser, reducing the system pressure and promoting the forward reaction.
2. The reduction temperature and reduction time are important factors affecting the carbothermal reduction reaction of spodumene ore. Under a low reduction temperature and/or short reduction time, the spodumene ore cannot react completely. With a suitably higher reduction temperature and longer reduction time, part of the Al₂O₃ will be wrapped by the alloy, whereas the remaining Al₂O₃ will react further, rendering the recovery of Al₂O₃ impossible. In particular, under the conditions of 1638 K and 3 h for the vacuum carbothermal reduction of spodumene ore process, the effective separation of Li, Al, and Si in the mineral can be achieved. The reduction residue comprises mainly ferrosilicon alloy and alumina slag, whereas the reduction rate of Li reaches 92.69%.

3. The reaction mechanism of the vacuum carbothermal reduction of spodumene ore by adding Fe oxide, is as follows: at low temperatures, ferric oxide is gradually reduced to Fe, and as the temperature increases, SiO₂ and LiAlSiO₄ are sequentially reduced with the participation of Fe to form a Si-Fe alloy, Al₂O₃, and Li.

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