

A Review of Calcium Ferrite in Sintering of Iron Ore and The Effect of Gangue Composition on Its Formation

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Abstract: In this paper, published studies on the bonding phase of calcium ferrite are reviewed. As the main bonding phase of high-basicity sinter, calcium ferrite has the advantages of high strength, good reducibility and easy formation of liquid phase. In particular, we emphasize the formation process of calcium ferrite phases, especially Silico-Ferrite of Calcium and Aluminum ('SFCA'), and the influence of common gangue components (Al_2O_3 , SiO_2 , MgO) on its formation. Based on the critical analysis of the current data, some deficiencies in this field are put forward and the research directions we think will be key in this field in the future are attached, so as to improve the theories related to calcium ferrite in iron ore sintering. The relevant results provide theoretical basis for understanding the formation process of calcium ferrite and producing high quality sinter.

Keywords: Iron ore sintering, Gangue composition, Calcium ferrite, SFCA.

1. Introduction

As the main bonding phase of high-basicity sinter at present, calcium ferrite has the advantages of good reducibility, high strength and easy formation of liquid phase, which plays an important role in improving the quality of sinter [1-3]. Bonding phase is the premise for the consolidation of sintered raw materials into blocks. It binds the unmelted sinter together and determines the strength and yield of sinter [4, 6]. A large number of studies have shown that in the bonding phase of sinter, calcium ferrite, especially Silico-Ferrite of Calcium and Aluminum is the best, which is usually abbreviated as SFCA. The reducibility and strength of sinter are improved with the increase of calcium ferrite content [7, 8]. The schematic diagram of iron ore particle

mixture and the schematic diagram of sintered product with SFCA as the main bonding phase was shown in Figure 1 [9]. As the main raw material for sintering, iron ore contains not only Fe element, but also many gangue components, including Al, Si, Mg and other elements. Most of them exist in the form of oxides and react at high temperature to form silico-ferrite of calcium and aluminum, which has a high content in the sinter and obvious influence. Their influence on the quality of the sinter has attracted more and more attention. Therefore, it is very important to explore the influence of different gangue components on the formation of calcium ferrite and the reaction mechanism. On the one hand, the mixing scheme can be optimized to achieve energy saving and carbon reduction. On the other hand, it can improve the quality of sinter and the smelting performance of sinter.

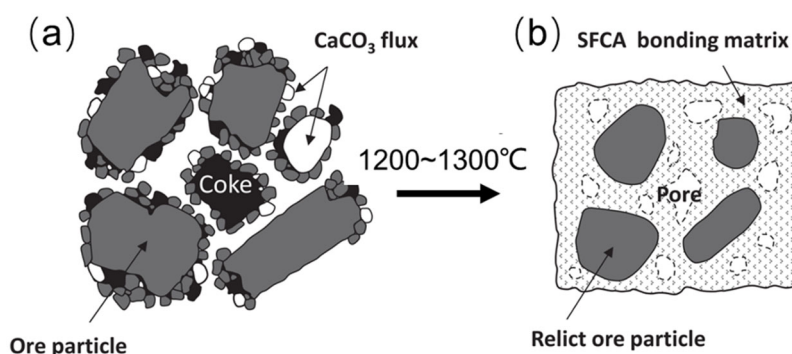


Figure 1. (a) Diagram of a typical mixture of iron ore particles surrounded by iron ore powder, solvent and coke and (b) Schematic illustration of a typical iron ore sintered product with porous 'SFCA' dominating matrix development [9]

In order to understand the formation process, crystal structure and stability of different gangue components on calcium ferrite and its influence on sinter properties, a large number of scholars have conducted extensive studies. Although there is a lot of seemingly comprehensive literature data available for reference, there is still a great deal of uncertainty in actual production due to the limitations of specific experimental conditions. In this paper, the formation process of calcium ferrite bonding phase in sintering is reviewed firstly, and then the influence of different gangue components on the formation of calcium ferrite phase and the

reaction mechanism are reviewed. The review focuses on well-constrained basic laboratory research, but also includes some pilot-scale results for areas of research with little or no laboratory coverage. This review aims to summarize previous studies on the formation mechanism of calcium ferrite, especially SFCA, as well as the effects of different gangue components on calcium ferrite formation and reaction mechanism. At the end of each section, we highlight some of the shortcomings and recommendations that we believe currently exist in this area. We hope that this review will enlighten readers and provide a platform for further research

in this field.

2. Formation Process of Calcium Ferrite in Sintering

As the main bonding phase of high-basicity sinter, calcium ferrite is defined as a calcium-containing ferrite [10]. It has been found that different sintering atmosphere can change the valence state of some iron ions in calcium ferrite, and Al^{3+} can replace Fe^{3+} when calcium ferrite is in contact with aluminum, silica-containing oxides or salts, and Si^{4+} can also form solid solution in calcium ferrite. This system is called Silico-Ferrite of Calcium and Aluminum. In the sintering of iron ore, the solid phase should start from 500~700°C, Fe_2O_3 and CaO react to produce calcium ferrite, the reaction rate is greatly accelerated with the increase of temperature, the formation of $CaO\cdot Fe_2O_3$ system at low temperature can generate enough liquid phase.

The formation process of calcium ferrite has been deeply studied by many scholars, and the formation mechanism of calcium ferrite has been gradually improved, which plays an important role in sintering production. Hida et al. studied the formation process of acicular calcium ferrite by scanning electron microscopy as early as 1987, and found that $CaO\cdot Fe_2O_3$ was initially formed on the surface of iron oxide through solid phase reaction, and $CaO\cdot Fe_2O_3$ melted when the temperature rose to 1205°C. It reacts with iron oxide and absorbs small amounts of SiO_2 and Al_2O_3 from the melt, crystallizing to form SFCA [11]. With the progress of technology, Mumme et al. determined the composition of SFCA-I. In the sintering process, the addition of fuel leads to the uneven atmosphere in the sinter layer, resulting in a reducing atmosphere in a certain area, which promotes the formation of FeO and thus leads to the change of calcium ferrite composition [12]. Cirilli and Burdese et al. found the presence of $CaO\cdot FeO\cdot Fe_2O_3$ and $CaO\cdot 3FeO\cdot Fe_2O_3$ in the

sintering process through X-ray diffraction analysis. According to the analysis of thermodynamic phase diagram, Guo X M concluded that FeO appeared after the emergence of solution, and the formation process of ternary calcium ferrite in $CaO\text{-}FeO\text{-}Fe_2O_3$ system was the solid solution process of Fujiite into calcium ferrite [10]. Subsequently, Scarlett N V Y et al. studied the formation process of Silico-Ferrite of Calcium and Aluminum with solvent sinter composition accounting for about 50% through in-situ X-ray diffraction technology. The results show that Fe_2O_3 reacts with CaO at 750~800°C to form $2CaO\cdot Fe_2O_3$. With the increase of temperature, $2CaO\cdot Fe_2O_3$ reacts with Fe_2O_3 to produce $CaO\cdot Fe_2O_3$. The reaction temperature increases with the increase of Al_2O_3 content in the sintered material. At this time, SiO_2 remains inert and does not participate in the reaction. Until the temperature rose to 1050°C, SiO_2 participated in the reaction to form SFCA and SFCA-I [13, 14]. The in-situ XRD pattern of SFCA formation process and the quantitative analysis results of Rietveld finishing was shown in Figure 2. Webster et al. optimized the Scarlett N V Y experiment by keeping P_{O_2} at 5×10^{-3} atm and temperature rising to 1350°C for in situ X-ray diffraction analysis. The results show that SFCA-I is formed by the reaction of Fe_2O_3 , $2CaO\cdot Fe_2O_3$ and SiO_2 at 1054~1119°C, while SFCA is formed by the reaction of $CaO\cdot Fe_2O_3$ and SiO_2 at 1107~1164°C. During condensation and consolidation, Fe-rich phase (1179~1288°C) is the first phase crystallized out, which is similar to SFCA-I in chemical composition. With the decrease of temperature, SFCA-I crystallizes out (1145~1270°C) after combining with melt [15]. The reaction sequence determined by Webster et al. was shown in Figure 3. Compared with the earlier work of Scarlett N V Y, the study of Webster et al. is closer to the conditions of industrial sintering process, but in terms of heating and cooling rate, it can not be directly compared with industrial conditions.

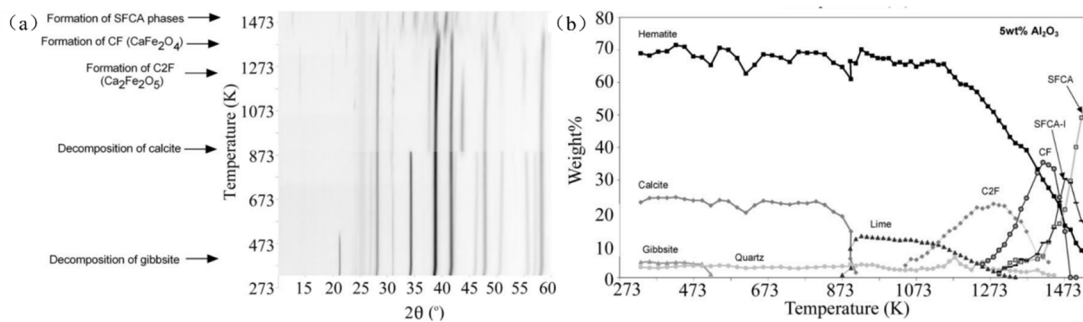


Figure 2. (a) In situ XRD pattern of SFCA formation process and (b) quantitative analysis result of Rietveld finishing [13]

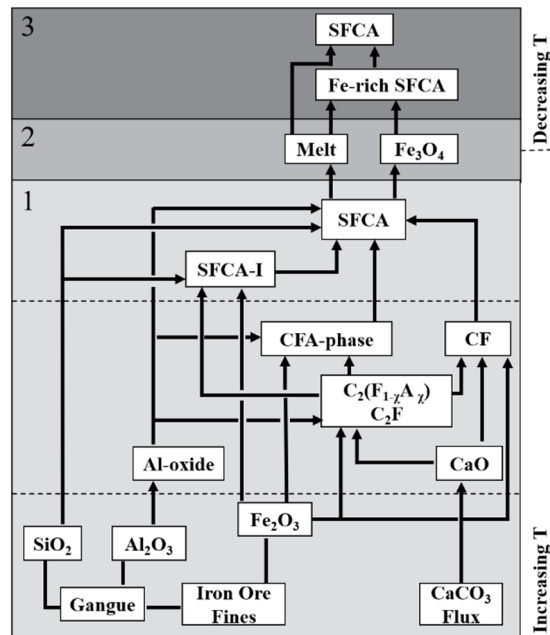


Figure 3. The sequence of reactions in which SFCA phases are formed during heating (zone 1) and cooling (Zone 3). Zone 2 is the zone where Fe_3O_4 and melt coexist (T from 25°C to 1350°C , $P_{\text{O}_2}=5 \times 10^{-3}\text{atm}$) [15]

The formation of calcium ferrite in conditions is closely to or associated with industrial sintering has been studied by a large number of researchers using a variety of techniques. However, under different conditions and composition, there are still significant differences between the reaction sequence proposed by different researchers and the phase formed. These technologies cannot completely replicate the environment of industrial sintering, and the sensitivity of process conditions is rarely evaluated systematically. Further research is needed to fully understand the mechanism of formation and reaction between calcium ferrite bonding phases in industrial sintering. In addition, during the heating and cooling process, the exploration of the formation mechanism, thermodynamic and kinetic conditions of Silico-Ferrite of Calcium and Aluminum should be carried out under the same or similar conditions as industrial processes as far as possible, and the transformation process and reaction conditions between phases should be comprehensively understood by combining with the basic research in the laboratory, so as to provide better guidance for industrial production.

3. Effect of Gangue Components on Formation of Calcium Ferrite

3.1. Effect of Al_2O_3 on formation of calcium ferrite

In recent years, due to the extensive use of high alumina iron ore in sintering production, the influence of Al_2O_3 on the formation temperature and liquid phase volume in the initial phase of sintering process has been widely concerned. Heish L H studied the influence of sintered raw material composition on mineral phase composition as early as 1993. The results show that the content of calcium ferrite increases with the increase of Al_2O_3 content, while the content of glass phase decreases. In addition, at low temperature, the lower content of Al_2O_3 promotes the formation and densification of the bonding phase. The role of Al_2O_3 in sintering is mainly reflected in the low temperature section of solid phase reaction, and promotes the formation of calcium ferrite with

the increase of sintering basicity [16]. And then, Maeda T et al. showed through experiments that adding Al_2O_3 could improve the formation rate of calcium ferrite bonding phase and the dissolution rate of hematite into liquid phase [17]. Nakashima K et al. studied the wetting behavior of calcium ferrite solution on hematite, and the results showed that adding 5mass% Al_2O_3 to $\text{CaO} \cdot \text{Fe}_2\text{O}_3$ at 1200°C can produce a large amount of bonding phase, and increasing Al_2O_3 can improve the wettability of calcium ferrite bonding phase [18]. Kalenga M K investigated the influence of Al_2O_3 in iron ore on the mineral characteristics of sinter. It is found that the SFCA content increases with the increase of Al_2O_3 , but the mineral properties of sinter deteriorate [19]. Peng J et al calculated the liquid phase content in the $\text{CaO}-\text{Fe}_2\text{O}_3-\text{Al}_2\text{O}_3$ ternary system, and the results showed that the liquid phase content in the system could be increased by increasing the Al_2O_3 content from 0 to 3mass% at 1280°C [20]. Guo H studied the influence of Al_2O_3 on the formation of initial liquid phase and calcium ferrite and showed that adding Al_2O_3 could promote the formation of CFA in the solid phase reaction stage and play an important role in improving the formation of bond phase at low temperature. The initial temperature and volume of the liquid phase under different calcium ferrite compositions were tested by differential thermal experiments. It was found that $\text{CF}_{3.9}$ was eutectic with CF, and the liquid phase formation temperature was 1206°C . When Al_2O_3 is added to the sintered sample, CFA generated by solid phase reaction can be eutectic with CF, and the liquid phase formation temperature drops to 1201°C , and when the mass ratio of the two is 2:8, more liquid phase can be generated [21].

The stability of Al_2O_3 on calcium ferrite has also attracted the attention of many researchers. Patrick T R C et al. confirmed that SFCA is a ferrite solid solution composed of $\text{CF}_3-\text{CA}_3-\text{C}_4\text{S}_3$ pseudo-ternary system through the study of SFCA stability was shown in Figure 4. The solubility of Al_2O_3 and C_4S_3 in SFCA was investigated by means of pure reagent synthesis. It was found that the solubility of Al_2O_3 in SFCA was 0~31.5mass%, and the solubility of C_4S_3 in SFCA was 3~11mass%. It was also found that the increase of Al_2O_3

content inhibited the decomposition of SFCA [22]. Scarlett N V Y et al. found that the presence of Al_2O_3 expanded the stable existence interval of SFCA and SFCA-I, reduced the temperature of initial formation, and the crystallization rate of solution also accelerated with the increase of Al_2O_3 content [13, 14]. Hessien M M et al. studied the reaction of aluminum-bearing iron ore during sintering temperature rise. It is concluded that the stability of SFCA in sinter depends on the content of Al_2O_3 . When the content of Al_2O_3 is lower than 1.5mass%, SFCA will decompose into magnetite and silicate solution at high temperature; when the content of Al_2O_3 is higher than 2.5mass%, SFCA can exist stably and increase

with the increase of the content of Al_2O_3 [23]. Cores A et al. investigated the influences of different iron ore compositions on the quality of sinter. The experimental results show that the quality of sinter is optimal when the Al_2O_3 is lower than 1.40mass%, and the lower the Al_2O_3 content, the lower the low temperature reduction degradation rate (RDI). At the same time, the high basicity is conducive to the formation of acicular calcium ferrite, and the sinter has good strength and reducibility [24]. With the progress of technology, Webster N A S improved the experiment of Scarlett N V Y et al. which also showed that the presence of Al_2O_3 improved the stability of SFCA and SFCA-I at high temperature [15].

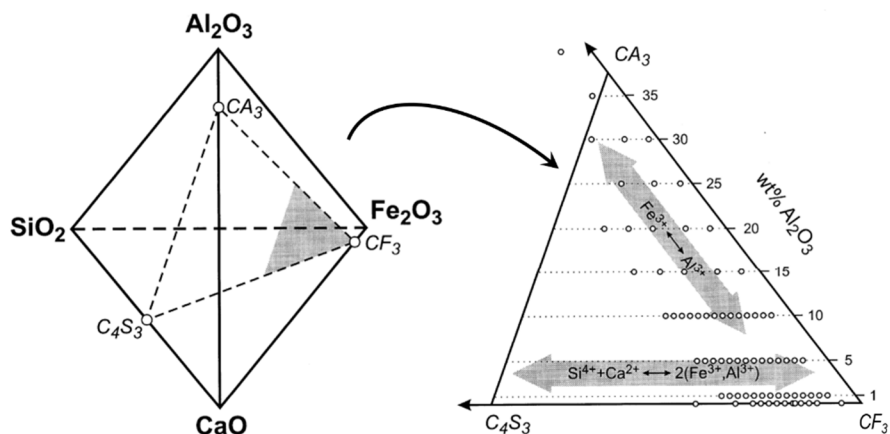


Figure 4. Chemical composition of SFCA and its ion substitution relationship [22]

In summary, it is not difficult to see from previous research results that the influence of Al_2O_3 on calcium ferrite in sinter is mainly reflected in the effect of solid phase reaction on its formation capacity and stability. However, the mechanism of Al_2O_3 's participation in the formation of SFCA and the reasons for the exacerbation of low temperature reduction degradation still need to be further studied. On the other hand, because the reaction involving liquid phase is more difficult than solid phase reaction in experiment, so there are relatively more researches on solid phase reaction, and more research focus should be shifted to liquid phase reaction in the future.

3.2. Effect of SiO_2 on formation of calcium ferrite

The main bonding phase of high-basicity fluxes sinter is $\text{CaO-Fe}_2\text{O}_3$ system formed at low temperature, and the sintering fuel ratio is relatively reduced, which promotes the development of low silicon ($\text{SiO}_2 < 5.0\%$) sintering technology. However, due to the existence of SiO_2 , with the change of carbon allocation, sintering atmosphere, the composition of the liquid phase will also change greatly, which affects the formation of calcium ferrite. SiO_2 has an effect on the amount and type of liquid phase. When basicity is the same, the absolute amount of CaO added by low silicon decreases and calcium ferrite is formed. Olivine liquid phase decreased, relative magnetite or hematite increased. Matsuno F showed that when there is a liquid phase, SiO_2 is easy to dissolve into the liquid phase of calcium ferrite and form a silicate melt. In the process of cooling, iron oxide is precipitated, and the type of iron oxide precipitated (hematite or magnetite) depends on the oxygen partial pressure of the melt [25, 26]. Debrincat D et al. found in the study of sinter structure that the increase of SiO_2 content in raw materials would refine pores in sinter, and the lower SiO_2 content was conducive to the merger and

deformation of pores in melt [27]. Pang J M et al. prepared sintered samples with different SiO_2 contents with chemical reagents and sintered them at 1300°C . They found that with the decrease of SiO_2 content, alkalinity increased, calcium ferrite content increased, and magnetite content decreased. After sintering, the porosity of the sample decreases and the porosity tends to be unevenly distributed. When SiO_2 content is very high, silicate phases appear [28]. Wang R C et al. studied the sintering technology of high iron and low silicon, and showed that the mineral composition of the sinter formed by high iron and low silicon is mainly calcium ferrite, magnetite and hematite, which contains trace amounts of calcium iron olivine and glass phase. In order to ensure that high quality sinter with good strength and reducibility can be obtained by sintering with high iron and low silicon, it is necessary to control a series of technical measures such as SiO_2 content at 4.5%, basicity between 2.0 and 2.4, high moderate material layer, low carbon, lime dosage at 3.0% and Al_2O_3 at about 2.0% [29]. Li G S investigated the melting characteristics of the bonding phase as a function of its chemical composition. The results showed that when the molar ratio of CaO to Fe_2O_3 was 1:1, the liquid phase formation capacity of the calcium ferrite bonding phase was the best, and the formation capacity of the bonding phase was improved by the addition of an appropriate amount of SiO_2 [30]. Umadevi T et al. studied the change of reducibility of iron ore with different silicon content after sintering, and the research showed that SiO_2 can promote the formation of SFCA in sinter, but it is more conducive to the formation of SFCA-I under the condition of low silicon. Therefore, the reducibility of low silicon sinter is better than that of high silicon sinter [31]. Ding X et al. studied the effect of SiO_2 on the formation of calcium ferrite melt, and found that the addition of SiO_2 can reduce the formation temperature of the

bond phase in the sintering process, and the melting temperature is the lowest when the content of SiO₂ is 3mass%, which is caused by the formation of ternary system composite calcium ferrite CaO·Fe₂O₃ and SFC eutectic [32, 33].

In conclusion, the addition of SiO₂ can improve the formation capacity of calcium ferrite and the reduction performance of sinter. In addition, SiO₂ plays an important role in reducing the melting point of the bonding phase, which is conducive to increasing the liquid phase amount. It is beneficial to the formation of bonding phase. At present, low silicon sintering technology has been gradually developed in sintering production. However, due to the existence of SiO₂, with the change of carbon allocation, sintering atmosphere, the composition of the liquid phase will also change greatly, which affects the formation of calcium ferrite. SiO₂ has an effect on the amount and type of liquid phase. Research on SiO₂ is mostly confined to laboratory and experimental phenomena, and the specific reaction mechanism needs to be further revealed.

3.3. Effect of MgO on formation of calcium ferrite

At present, the research on MgO mainly focuses on the stability of magnetite structure and its influence on the formation of bonding phase. Ren Y F et al. found that Mg²⁺ would enter the magnetite lattice to replace Fe²⁺ and fill in the octahedral vacancy, thus reducing the lattice defects of hematite, forming stable magnetite and reducing the content of secondary hematite [34]. Sugiyama et al. determined two kinds of complex calcium ferrite SFCAM containing magnesium, whose crystal structure was similar to that of Ca₂(Ca, Fe, Al, Mg)₆(Fe, Al, Si)₆O₂₀. The chemical composition is respectively Ca₂(Ca_{0.1} Mg_{1.2} Fe_{5.55} Si_{1.5} Al_{3.65})O₂₀ and Ca₂(Mg₂ Fe_{4.45} Si_{2.15} Al_{3.4})O₂₀, Mg²⁺ replace tetrahedron place Si⁴⁺ in SFCA form SFCAM solid solution, SFCAM is a triclinic system composed of one hedral layer and one octahedral layer. Plot of Si (a. p. f. u.) versus Ca+Mg (a. p. f. u.) in the octahedral sites for the SFCAM phase were shown in Figure 5 [35]. Zhou M et al. studied the influence of MgO on the sintering of vanadium titanomagnetite and found that MgO reacts with Fe₂O₃ to form a magnesite-bearing magnetite in the sintering process. Therefore, MgO has a stabilizing effect on magnetite, which reduces the stress generation in the low-temperature reduction process of sinter and improves the low-temperature reduction degradation performance of sinter [36]. Pownceby M I et al. conducted an in-depth study on the mechanism of mutual substitution between ions, and the results showed that The mechanism of ion substitution in complex calcium ferrite is as follows: Fe₂O₃-CaO-SiO₂ ternary system, Fe₂O₃-CaO-SiO₂-Al₂O₃ quaternary system, and more complex Fe₂O₃-CaO-SiO₂-Al₂O₃-MgO quaternary system[37].

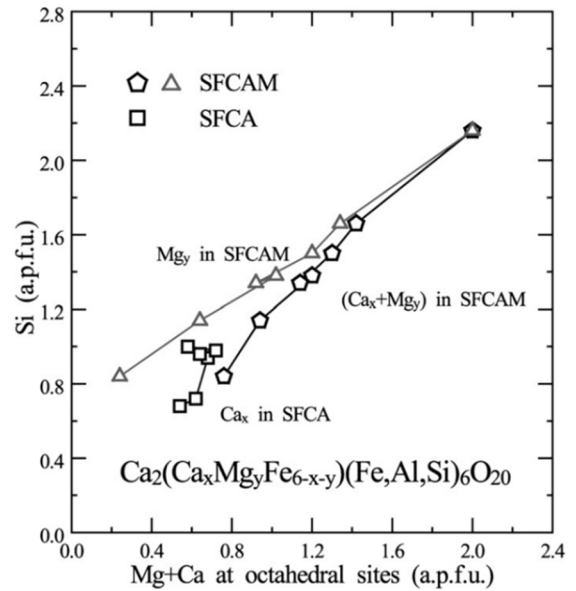
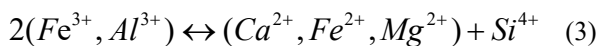
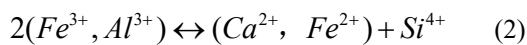
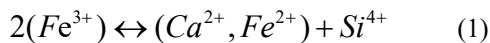


Figure 5. Plot of Si (a. p. f. u.) versus Ca+Mg (a. p. f. u.) in the octahedral sites for the SFCAM phase[35]

Heish L H et al. found that the effect of MgO was related to the form of flux addition. When MgO was added in the form of dolomite, the production of calcium ferrite was reduced, while the content of calcium ferrite was increased when MgO was added in the form of serpentine, and MgO could effectively reduce the content of secondary hematite in the cooling and cooling stage [16]. Loo et al. found a small amount of Mg²⁺ in SFCA. He believed that this was due to the fact that Mg²⁺ was not precipitated in time during the formation of calcium ferrite from CaO and magnesium-bearing magnetite [38]. Yadav U S studied the effect of MgO on the sintering characteristics of iron ore and found that MgO would increase the liquidus temperature of melt, reduce the liquid phase production and increase the porosity, resulting in the need for more heat in the sintering process, thus reducing the productivity. The results also show that MgO can promote the decomposition of hematite and inhibit the formation of calcium ferrite [39]. The increase of MgO content is believed to increase the liquid phase formation temperature of sinter, which leads to higher sintering temperature, more fuel is needed, and the sintering rate decreases [40]. Fan X H studied the influence mechanism of MgO on the strength of high-basidity sinter and found that when the content of MgO in the sinter with basicity of 2.0 increased from 1.15mass% to 3.5mass%, the drum strength decreased from 71.33% to 61.13%. With the increase of MgO content, the formation temperature of liquid phase increases and the amount of liquid phase decreases. The stability of magnetite is improved when Mg²⁺ is mainly dissolved into the magnetite lattice, which prevents it from being oxidized in the cooling process. However, the bonding phase in the form of acicular calcium ferrite is reduced, and the formation of liquid phase is difficult [41]. Ö. Saltuk BÖLÜKBAŞI pointed out that when flux was added in the form of dolomite, the formation of calcium ferrite in sinter was inhibited, but MgO was added in the form of olivine, which promoted the formation of calcium ferrite. Meanwhile, the finer the particle size of calcium ferrite generated, the higher the strength of sinter [42]. Yang N et al. studied the effect of MgO on the formation of liquid phase at the initial stage of sintering, and showed that MgO reacted with Fe₂O₃ to form magnesium-containing magnetite at the stage of solid phase reaction, which reduced the

thermodynamic stability of $\text{CaO}\cdot\text{Fe}_2\text{O}_3$ and inhibited the formation of $\text{CaO}\cdot\text{Fe}_2\text{O}_3$, resulting in the reduction of liquid phase at the initial stage of sintering. When the content of MgO exceeds 3mass%, the liquid phase volume at the initial stage of sintering decreases significantly, and it is found that the addition of MgO increases the crystallization temperature and promotes crystallization, which is believed to lead to the deterioration of sinter after the addition of MgO [43]. Therefore, MgO content is generally controlled at about 2mass% at present.

In conclusion, MgO can form a solid solution with Fe_3O_4 , stabilize the crystalline structure of Fe_3O_4 , inhibit its reoxidation to Fe_2O_3 , and significantly reduce the low temperature reduction degradation of sinter. However, the amount of liquid phase in sintering decreases, and the content of acicular calcium ferrite with good strength decreases, which leads to the decline of the strength of sinter. Excessive MgO will also lead to more complex mineral composition of sinter. In the process of rapid temperature change, it is easy to cause internal stress caused by different crystallization capacity of various minerals, which will reduce the strength of sinter. The formation of calcium ferrite occurs in two phases of solid phase reaction and liquid phase crystallization, and the chemical composition and crystal form of calcium ferrite in the final sinter are determined by the liquid phase crystallization stage, but the action mechanism of MgO in the liquid phase crystallization stage still needs to be further explored.

4. Summary

Based on the research results of a large number of researchers, the formation process of calcium ferrite, the main bonding phase of high-basicity sinter, and the influence of different gangue components on its formation are reviewed, and a more comprehensive understanding of the theoretical basis of calcium ferrite system is established. However, due to the complexity of chemical systems and operating conditions involved in the sintering process, there are significant differences in the data reported in literatures. Future research suggests a comprehensive understanding of the basic theory of calcium ferrite system formation. In addition, the influence of different gangue components on the formation of calcium ferrite has been preliminarily understood, but there is far more than one component in the actual sinter. The reaction mechanism between them and the influence of their joint action on the formation and crystallization of calcium ferrite still need to be further explored. It is suggested that future research should focus on establishing a good correlation between laboratory results and actual sintering production, which will bring better reference for actual sintering production.

References

- [1] Long H M. Sintering principle and technology of iron ore powder[M]. Beijing: Metallurgical Industry Press, 2010: 5-9.
- [2] Fan X H. Principle and technology of optimized ore blending by sintering of iron ore[M]. Beijing: Metallurgical Industry Press, 2013: 66-72.
- [3] Lv, X W, Bai, C G, et al. Behavior of Liquid Phase Formation during Iron Ores Sintering [J]. ISIJ International, 2022, 51(5): 722-727.
- [4] Xin R F, Du Y, Guo X M. Effect of alumina on crystallization behavior of calcium ferrite in Fe_2O_3 -CaO-SiO₂-Al₂O₃ system[J]. Materials, 2022, 15(15): 5257.
- [5] Ding, X, Guo X M. The formation process of silico ferrite of calcium (SFC) from binary calcium ferrite[J]. Metallurgical and Materials Transactions B, 2014, 45(4): 1221-1231.
- [6] Liu Z J, Wang J B, Zhang J L, et al. Status Quo of Blast Furnace Energy Consumption and Prospect of Consumption Reduction Technology[J]. Journal of Iron and Steel Research, 2022, 14(1): 1-14.
- [7] Dong J J, Wang G, et al. Effect of high alumina iron ore of gibbsite type on sintering performance[J]. Ironmaking & Steelmaking, 2014, 42(1): 34-40.
- [8] Peng J, Zhang L, et al. Relationship between liquid fluidity of iron ore and generated liquid content during sintering[J]. Metallurgical and Materials Transactions B, 2017, 48(1): 538-544.
- [9] Stuart N, Jiang C, et al. A review of the chemistry, structure and formation conditions of silico-ferrite of calcium and aluminum ('SFCA') Phases[J]. ISIJ International, 2018, 58(12): 2157-2172.
- [10] Guo X M. Formation of calcium ferrite during sintering and its mineralogy[M]. Beijing: Metallurgical Industry Press, 1999: 59-64.
- [11] Hida Y, Okazaki J, Itoh K, et al. Formation mechanism of acicular calcium ferrite of iron ore sinter[J]. Tetsu-to-Hagane, 1987, 73(15): 1893-1900.
- [12] Mumme W G, Clout J M F, Gable R W. The crystal structure of SFCA-I, $\text{Ca}_{3.18}\text{Fe}_{14.66}\text{Al}_{1.34}\text{Fe}_{0.82}\text{O}_{28}$, a homologue of the aenigmatite structure type and new crystal structure refinements of β -CFF, $\text{Ca}_{2.99}\text{Fe}_{14.30}\text{Fe}_{0.55}\text{O}_{25}$ and Mg-free SFCA, $\text{Ca}_{2.45}\text{Fe}_{9.04}\text{Al}_{1.74}\text{Fe}_{0.16}\text{Si}_{10.6}\text{O}_{20}$ [J]. Neues Jahrbuch für Mineralogie-Abhandlungen, 1998, 173(1): 93-117.
- [13] Scarlett N V Y, Madsen I C, Pownceby M I, et al. In situ X-ray diffraction analysis of iron ore sinter phases[J]. Journal of Applied Crystallography, 2004, 37(3): 362-368.
- [14] Scarlett N V Y, Pownceby M I, et al. Reaction sequences in the formation of silico-ferrites of calcium and aluminum in iron ore sinter[J]. Metallurgical and Materials Transactions B, 2004, 35B(5): 929-936.
- [15] Webster N A S, Pownceby M I, Madsen I C, et al. Silico-Ferrite of Calcium and Aluminum (SFCA) Iron Ore Sinter Bonding Phases: New Insights into Their Formation During Heating and Cooling[J]. Metallurgical and Materials Transactions B, 2012, 43(6): 1344-1357.
- [16] Heish L H, Whiteman J A. Effect of Raw Material Composition Lime-fluxed Iron Ore Sinter[J]. ISIJ International, 1993, 33(4): 462-473.
- [17] Maeda T, Nishioka K, et al. Formation rate of calcium ferrite melt focusing on SiO₂ and Al₂O₃ component[J]. ISIJ International, 2004, 44(12): 2046-2051.
- [18] [Nakashima K, Saito N. Wetting and penetration behavior of calcium ferrite melts to sintered hematite[J]. ISIJ International, 2004, 44(12): 2052-2056.
- [19] Kalenga M K, Craig A M G. Investigation into how the magnesia silica and alumina contents of iron ore sinter influence its mineralogy and properties[J]. The journal of the southern African Institute of Mining and Metallurgy, 2010, 110(8): 447-456.
- [20] Peng J, Zhang L, et al. Relationship between liquid fluidity of iron ore and generated liquid content during sintering[J]. Metallurgical and Materials Transactions B, 2017, 48B(1): 538-544.

- [21] Guo H. Mechanisms of calcium ferrite formation in sintering process and low temperature reduction degradation for Al-bearing hematite[D]. Beijing University of Science and Technology Beijing, China, 2019: 65-69.
- [22] Patrick T R C, Pownceby M I. Stability of Silico-ferrite of Calcium and Aluminum(SFCA) in air-solid solution limits between 1240°C and 1390°C and phase relationships within the Fe₂O₃-CaO-Al₂O₃-SiO₂(FCAS) system[J]. Metallurgical and Materials Transactions B, 2002, 33B(1): 79-89.
- [23] Hessien M M, Kashiwaya Y, Ishii K, et al. Sintering and heating reduction processes of alumina containing iron ore samples[J]. Ironmaking & steelmaking, 2008, 35(3): 191-204.
- [24] Cores A, Babich A, et al. The influence of different iron ores mixtures composition on the quality of sinter[J]. ISIJ International, 2010, 50(8): 1089-1098.
- [25] Matsuno F. Changes of mineral phases during the sintering of Fe₂O₃-CaO-SiO₂ system[J]. Transactions ISIJ, 1979, 19(2): 595-604.
- [26] Matsuno F, Harada T. Changes of mineral phases during the sintering of iron ore-lime stone system[J]. Transactions ISIJ, 1981, 5(21): 318-325.
- [27] Debrincat D, Loo C E, et al. Effect of iron ore particle assimilation on sinter structure[J]. ISIJ International, 2004, 44(8): 1308-1317.
- [28] Pang J M, Wang Z Q. Effect of SiO₂ on the composition of sinter facies[J]. Journal of Anhui University of Technology, 2005, 22(4): 338-340.
- [29] Wang R C, Fu J Y. Research on sintering technology of high iron and low Silicon[J]. Iron & Steel, 2007(06): 17-20.
- [30] Li G S. Discussion on the influence mechanism of bonding relative strength of sinter and its reasonable components[D]. Shenyang Northeastern University, China, 2008: 26-29.
- [31] Umadevi T, Brahmacharyulu A, et al. Optimization of MgO addition in low and high silica iron ore sinter to improve sinter to improve sinter reducibility at JSW Steel Limited[J]. Ironmaking & Steelmaking, 2014, 41(4): 270-278.
- [32] Ding X. Study on formation mechanism of calcium ferrite (SFC) in Fe₂O₃-CaO-SiO₂ system [D]. Beijing University of Science and Technology Beijing, China, 2019: 90-92.
- [33] Ding X, Guo X M. The characteristics of mixing SiO₂ with calcium ferrite at 1473K(1200°C)[J]. Metallurgical and Materials Transactions B, 2015, 46B(4): 1742-1750.
- [34] Ren Y F, Jiang L Y, Wang S T. Occurrence state and function of MgO in artificial rich ore[J]. Journal of University of Science and Technology Beijing, 1983(4): 1-12.
- [35] Sugiyama K, Monkawa A, Sugiyama T. Crystal structure of the SFCAM phase Ca₂(Ca, Fe, Mg, Al)₆(Fe, Al, Si)O₂₀[J]. ISIJ International, 2005, 45(4): 560-568.
- [36] Zhou M, Yang S T, et al. Influence of MgO in form of magnesite on properties and mineralogy of high chromium, vanadium, titanium magnetite sinters[J]. Ironmaking & steelmaking, 2015, 42(3): 217-224.
- [37] Pownceby M I, Clout J M F. Phase relations in the Fe-rich part of the system Fe₂O₃(Fe₃O₄)-CaO-SiO₂ at 1240-1300°C and oxygen partial pressures of 5×10⁻³atm: implications for iron ore sinter[J]. Trans. Instn. Min. Metall., 2000, 109(1): 36-48.
- [38] Loo C E, Mackey L C, England B M, et al. Behavior of magnesia-bearing fluxes during iron ore sintering[J]. Transactions of the Institution of Mining and Metallurgy Section C, 1996, 105: C175-C189.
- [39] Yadav U S, Pandey B D, Das B K, et al. Influence of magnesia on sintering characteristics of iron ore[J]. Ironmaking & steelmaking. 2002, 29(2): 91-95.
- [40] Wu S L, Han H L, Jiang W Z, et al. Action mechanism of MgO in sinter[J]. Journal of University of Science and Technology Beijing, 2009, 31(4): 428-432.
- [41] Fan X H, Li W Q, Gan M, et al. Effect of MgO on strength of high alkalinity sinter and its mechanism [J]. Journal of Central South University (Science and Technology), 2012, 43(09): 3325-3330.
- [42] Bölükbaş Ö S, Tufan B, Batar T, et al. The Influence of Raw Material Composition on the Quality of Sinter[J]. Life Science Journal, 2013, 10(4): 584-594.
- [43] Yang N, Guo X M, et al. Effect of MgO on formation and crystallization behaviors of calcium ferrite during heating and cooling processes[J]. ISIJ International, 2018, 58(8): 1406-1412.