Effect of BaO on Formation Mechanisms of Silico-ferrite of Calcium and Aluminum

Jian-tao JU,^{1,2)} Ke MA,¹⁾ Xiang-Dong XING^{1,2)*} and Gui-qing ZHAO³⁾

1) School of Metallurgical Engineering, Xi'an University of Architecture and Technology, Xi'an, 710055 PR China.

2) Research Center of Metallurgical Engineering and Technology of Shaan Xi, Xi'an University of Architecture and Technology, Xi'an, 710055 P.R. China.

3) JISCO Iron and steel Research Institute, Jiayuguan, Gansu, 735100 China.

(Received on June 3, 2021; accepted on August 25, 2021; J-STAGE Advance published date: October 25, 2021)

Silico-ferrites of calcium and aluminum (SFCA) are formed during the sintering process, and their changes are critical to the quality of the sinter. Aiming to further clarify the effect of BaO (0 mass%, 1 mass%, 2 mass%, 3 mass%, 5 mass%, 7 mass%, and 9 mass%) on the bonding process of SFCA. In this work, X-ray diffraction (XRD), scanning electron microscopy and energy dispersive spectroscopy (SEM-EDS), thermogravimetry-differential scanning calorimeter (TG-DSC) were used to analysis the formation mechanisms of SFCA. The results indicated that the main bonding phase was SFCA. In addition, SFCA-I, CF, C₂F, and silicate existed in the BaO-free sinter. Adding a small amount of BaO (up to 2 mass%) could increase the decomposing temperature of SFCA and increase the formation of the needle-like SFCA. With the increase of BaO adding from 2 to 9 mass%, the BaFe₁₂O₁₉ (FB) formed could reduce the decomposing temperature of SFCA, which deteriorated the quantity of sinter. And, BaO can promote the formation of C₂F in the CF and C₂F system, which decreased the eutectic melting temperature of CF and C₂F.

KEY WORDS: BaO; silico-ferrites of calcium and aluminum; bonding phase; sinter.

1. Introduction

The proportion of iron ore sinter in the iron raw material loaded into blast furnaces (BF) is greater than 60 mass% in the Asian region. Therefore, it is important to improve the quality of the sinter. The sinter usually contains four main parts: iron oxides (40–70 mass%), calcium silicates (≤ 10 mass%), glasses (≤ 10 mass%) and ferrites (20%–50 mass%).^{1,2)} According to previous studies,^{3–7)} the ferrite has a structure of solid solution of complex oxide with gangue contents such as SiO₂, Al₂O₃, and CaO. The ferrites are silico-ferrites of calcium and aluminum, also described as SFCA.⁸⁾ SFCA is one of the maximum produced minerals in iron ore sintering and has been considered as the main bonding phase during the production of industrial iron ore sinters.⁹⁾ So, it is necessary to know more about the formation mechanisms of SFCA, which have contributed to producing the high-quality sinter.

In recent years, Mumme *et al.*¹⁰⁾ explored that the SFCA had been classified as two main types according to composition, morphology, and crystal structure. The first type was a low-Fe form that was simply defined as SFCA with M₁₄O₂₀

stoichiometry which morphology had often been described as columnar, blocky, or lath shaped. And the second type was a high-Fe, low-Si form described as SFCA-I (it also defined as acicular) with M₂₀O₂₈ stoichiometry.¹¹⁾ The SFCA and SFCA-I only involved a substitution mechanism based on the exchange of $2(\text{Fe}^{3+}, \text{Al}^{3+}) \leftrightarrow (\text{Ca}^{2+}, \text{Fe}^{2+}) + \text{Si}^{4+}$,¹²⁾ but there were still some impurity elements that have the similar action in industrial sintering. It would further affect the microstructure and the content of different phases.

Nathan A. S. *et al.*^{13,14)} reported that the presence of a small amount of MgO during the sintering process would increase the SFCA-I content. Further to increase the addition of MgO could inhibit the formation of complex ferrite (SFCA) and the loss of magnesium ferrite. At the same time, it had a stabilizing effect on the structure of SFCA-I which made it difficult to melt at high temperatures. Xin-yu LI *et al.* discussed that the calcium ferrite, hematite, and magnetite staggered distribution in the matrix when NiO adding was less than 3 mass%. Porosity and silicate glass phase content were both low, which contributed to improving the sinter quality.¹⁵⁾ The number of calcium ferrite reduced drastically with the further increased nickel adding. On the contrary, the content of Ca–Al-silicates increased which reduced the quality of the sinter. Pownceby Ian C *et al.*

* Corresponding author: E-mail: 3071395448@qq.com

studied that the formation of Fe-rich SFCA was suppressed with the TiO_2 concentration up to 6 mass%. SFCA is the only Ca-rich ferrite phase to crystallize from the melt during cooling which contained more Ti in its crystal structure compared with SFCA-I.¹⁶⁾ There was a special type of iron ore containing BaO in China and Egypt which could have a great influence on the formation of SFCA and SFCA-I. L. X. YAN *et al.* reported BaO-containing magnetite ore led to a high level of glass in the sinters even under oxidizing conditions.¹⁷⁾ But, the effect of BaO on the formation mechanisms of SFCA has not been studied yet.

Under the above background, the goal was to investigate the influence of the phase composition, microstructure of samples, and the melting temperature of phases. And then, the formation mechanism of SFCA with different BaO was clarified comprehensively in the study. These results provide technical and theoretical support for expanding the application of barium-containing iron ore in industry. This study is favorable for future research on the influence of BaO on the crystal structure of SFCA or SFCA-1 during cooling.

2. Experimental

2.1. Preparation of Sinter Simple

This study used analytical reagents to simulate the sintering process of iron ore fines and to avoid the influence of impurity elements on the experimental results, which were Fe_2O_3 (99.0%), SiO_2 (≥ 99.0 mass%), CaO (≥ 98.0 mass%), Al_2O_3 (≥ 99.0 mass%), BaO (≥ 98.0 mass%). There were nine samples, BaO-containing were 0, 1 mass%, 2 mass%, 3 mass%, 5 mass%, 7 mass%, and 9 mass%, respectively. The raw material compositions of sinter samples as shown in **Table 1**. The binary basicity ($R = \omega_{\text{CaO}}/\omega_{\text{SiO}_2}$) of industrial sinters was about 2.0, which depended on the requirements of the blast furnace. But, the binary basicity of all samples was 4.0, which to produce an appropriate amount of SFCA bonding phases during the sintering process for the investigation in this study. In addition, the alumina content of 5 mass% was determined for further research.^{18,19)} In the complex system environment of SFCA, other components were fixed and only BaO content was changed.

2.2. Method and Equipment

All the reagents by adding anhydrous ethanol to blend for 30 mins, and then the reagents were put into a drying oven for 60 mins at 70°C . After that, the reagents were mixed again for 30 minutes in the agate mortar to make the reagents well mixed. The mixed reagents were pressed into columnar tablets with 15 mm in diameter and 5 mm in thickness at a pressure of 5 MPa for 3 min by briquetting machine. The weight of each sample was 3 g and the samples were placed in seven labeled alumina crucibles. Then the samples were heated to $1\,200^\circ\text{C}$ at a heating rate of $10^\circ\text{C}/\text{min}$ in a muffle furnace that was presented in **Fig. 1** and sintered 8 h in air atmosphere. The samples were quenched to room temperature in N_2 . Finally, one part of the samples was crushed into powder for XRD and TGA, and the other part for SEM-EDS.

2.3. Characterization of Sinter Ores

A part of each annealed sample was ground into a fine

Table 1. Raw material compositions of sinter samples (wt.%).

Sample	Fe_2O_3	SiO_2	CaO	Al_2O_3	BaO
1	72.80	4.44	17.76	5.00	0.00
2	72.07	4.40	17.58	4.95	1.00
3	71.34	4.35	17.40	4.90	2.00
4	70.62	4.31	17.23	4.85	3.00
5	69.16	4.22	16.87	4.75	5.00
6	67.70	4.13	16.52	4.65	7.00
7	66.25	4.04	16.16	4.55	9.00

Fig. 1. Schematic diagram of the experiment equipment. (Online version in color.)

powder in an agate mortar and served with sieve (0.28 mm) used for XRD analysis. XRD analysis was conducted using a D8 Advance X-ray diffractometer (Bruker, Billerica, MA, USA), with Cu K α used as the radiation source (40 kV, 400 mA). To obtain data by using continuous scanning mode, of which the speed of scanning was $1^\circ/\text{min}$ and the range of 10 to 90° . The uncrushed samples were inserted in epoxy resin and then polished (400, 600, 800, 1 200, and 2 000 CW successively) for SEM-EDS (VEGA 3 XMU/XMH, Tescan, Czech Republic) analysis.

2.4. TG-DSC Analysis

The thermogravimetric (TG) and differential scanning calorimetry (DSC) methods were used to estimate the melt formation temperature of samples. A powder sample (50 mg) was placed into the corundum crucible and then moved into the TG-DSC furnace. The temperature was raised non-isothermally at $10^\circ\text{C}/\text{min}$ in the air atmosphere from room temperature to $1\,400^\circ\text{C}$. The melting temperature was estimated using the heat flow in terms of the DSC.

3. Results and Discussion

3.1. Mineral Phase Determination

Each group of sinter samples was triturated and taken for XRD analysis to research the phases formed after sintering with increasing BaO addition. **Figure 2** showed the powder XRD patterns of the samples. It could be seen BaO could influence the diffraction peaks intensity in the sinter samples. When the content of BaO ranges from 0 to 2 mass%,

Fig. 2. XRD analysis of the powdered samples with different BaO mass fraction. (Online version in color.)

Fig. 3. Crystal structure model of CaFe_2O_4 and $\text{BaFe}_{12}\text{O}_{19}$. (Online version in color.)

the peaks of BaO could not be identified. And, the diffraction peaks intensity of SFCA, SFCA-I, CaFe_2O_4 (CF), and Ca_2SiO_4 had not significantly changed, indicating that BaO exerted a marginal influence on the phase composition with its content less than 2 mass%. For the sample with 3 mass% BaO addition, the diffraction peaks of $\text{BaFe}_{12}\text{O}_{19}$ (FB) appeared and its intensity increased with BaO adding. However, the diffraction peaks intensity of SFCA, SFCA-I, CF, and C_2F gradually decreased which suggested the contents of these phases decreased and the generation process was inhibited. The diffraction peaks intensity of Ca_2SiO_4 increased. When the content of BaO reached 9 mass%, the diffraction peaks of $\text{BaFe}_{12}\text{O}_{19}$ was the dominant peaks, suggesting that the $\text{BaFe}_{12}\text{O}_{19}$ were the main phase, and SFCA and CF had a small change in peak positions with the BaO adding increased.

In addition, the BaO reacted with Fe_2O_3 to form FB needed more Fe_2O_3 compared with CaO, as shown in reac-

tions (1) and (2). The crystal structure of CF and FB were showed in Fig. 3. The more Fe^{3+} were contained in the crystal structure of FB.

This was the reason that the CF as the matrix reduced, which further decreased the contents of SFCA SFCA-I, CaFe_2O_4 (CF) phases. The Eqs. (1) and (2) showed that BaO was reacted easily with Fe_2O_3 , which led to a decrease in the reaction between Fe_2O_3 and CaO. So, the reaction between CaO with Fe_2O_3 was inhibited by BaO. So, the reaction between CaO with Fe_2O_3 was inhibited by BaO. It also was determined that the increase in BaO prompted the

reaction between CaO with SiO₂, which further increased the Ca₂SiO₄ formation, as shown in reaction (3).

Although the reaction time in this work was much longer than that in industrial sintering, ternary calcium ferrite bearing BaO was still not found. It could be inferred that BaO may not directly react with CF to form a substrate liquid phase unless there were any other chemical elements. The structures of Ba-bearing SFCA phases were complicated and the contents were low, which was below the detection level and could not be discovered in the X-ray patterns. The reaction sequence involved in the formation of SFCA can be summarized in Eq. (4).²⁰⁾

It was found that the SFCA and SFCA-I reduced due to the content of BaO exceeding 3 mass%. SFCA with high strength in sinter due to its microstructure,²¹⁾ therefore the presence of SFCA as the main bonding phase in the sinter effectively improved the sinter strength, which needed to further analysis was conducted by using SEM-EDS.

3.2. Microstructure Analysis

To better understand the influence of adding BaO on

microstructure, the scanning electron microscope (SEM) was used to capture the mineral phase images of the sample, and EDS was used to determine and analyze the mineral composition. The different amounts of adding BaO were presented in Figs. 4 and 5. Figure 4(a) showed that the SEM images of BaO-free sinter samples. It could be seen that the columnar-like SFCA (Dark gray area) was the main morphology, and there were also CF, C₂F, SFCA-I (light grey area), and silicate in the overall morphology. And, compact and dense microstructures were obtained owing to these phases had tightly distributed and intertwined with each other with no clearly observable cracks. Figures 4(b) and 4(c) shown that when BaO addition was increased from 1 mass% to 2 mass%, the microstructure of sample compared with BaO-free samples. The needle-like SFCA increased, and CF, C₂F, and SFCA-I were roughly unchanged with addition of BaO. Few needle-like SFCAB was observed at the boundary of silicate and SFCA. Moreover, silicate gradually increased and irregular holes appeared in the matrix. The elements composition of SFCA and SFCA-I were shown in Table 2. It was observed that the content of Ca²⁺ and Si⁴⁺ in SFCA were reduced and Al³⁺ increased, which because that a small amount of BaO was dissolved in the SFCA. resulting the needle-like SFCA increased during the sintering process.

When the BaO addition from 3 mass% to 9 mass%, the

Fig. 4. The SEM images of the samples: (a) sample 1 (0 wt.% BaO), (b) sample 2 (1 wt.% BaO), and sample 3 (2 wt.% BaO). from the content of BaO range from 0 to 2 wt.%. (Online version in color.)

Fig. 5. The SEM images and EDS results of the samples: (a) sample 4 (3 wt.% BaO), sample 5 (5 wt.% BaO), sample 6 (7 wt.% BaO), sample 7 (9 wt.% BaO). (Online version in color.)

Table 2. EDS results of the samples from the content of BaO range from 0 to 2 wt.%.

Elements	Fe	Ca	Al	Si	Ba	O
SFCA	51.64	11.75	2.63	2.43	–	31.55
SFCA-I	51.79	16.21	1.00	–	–	31.00
SFCA	51.10	11.94	2.45	1.52	–	32.98
SFCA-I	52.50	15.89	0.59	–	–	31.02
SFCAB	49.96	9.04	3.30	5.25	4.41	28.03
SFCA	48.68	11.36	2.55	3.33	–	34.08
SFCA-I	53.76	17.03	0.52	–	–	28.69
SFCAB	38.29	6.14	5.38	4.38	15.87	29.94

microstructures of samples were depicted in Fig. 5. As depicted in Fig. 5(a), SFCA was still the main mineral phase component of the substrate, and a small amount of irregular silicate and pores were found. However, a large amount of needle-like SFCA disappeared, and grained and plate-like SFCA appeared. FB precipitated on the edge of the substrate, and it was off-white in the shape of a block. Figure 5(b) shown that SFCA in the form of grained and plate-like was still the main mineral phase component of the substrate, and irregular silicates increased and pores become larger. A large amount of FB (off-white small-grained) precipitated from the SFCA and SFCA-I phases, which enlarged the diameter of the pores and reduced the strength of the entire bonding phase. As shown in Fig. 5(c), the needle-like SFCA in the matrix disappeared completely and existed in a plate-like form. With the increase of BaO content, the newly-emerged FB particles gradually increased and transformed into a columnar evenly distributed on the substrate. However, the increased of FB affected the strength of the sintered sample. Figure 5(d) showed that a lot of bulk-grained FB was existed in the sinter, and the plate-like SFCA was distributed in the crevices. **Tables 3** and **4** showed that the EDS analysis results of the four sinter samples, exhibiting the chemical composition of the SFCA, SFCA-I, FB, and SFCAB. The Si^{4+} was no found in FB, and a large amount of Si^{4+} was present in the SFCA mineral phase.

The SEM and EDS analysis results showed that when the BaO adding exceeded 2 mass%, the new phase FB was precipitated from the SFCA phase. It was observed that there was not Si^{4+} existed in the FB and most of Si^{4+} was present in the SFCA, suggesting that the presence of barium prevented the diffuse of Si^{4+} from SFCA to FB since the Si^{4+} was not detected in the SFCA, which was similar to the results of Li *et al.*²²⁾ It was also found that the Ba^{2+} was concentrated in the FB phase, but there was still a small amount of Ca^{2+} and Al^{3+} as the content of barium oxide increases. Because the content of Ca^{2+} and Al^{3+} in the melt was much higher than Ba^{2+} , a little of Ca^{2+} and Al^{3+} probably diffused into $(\text{Ba}_{1-x}\text{Fe}_x)\cdot\text{Fe}_2\text{O}_3$.

3.3. Thermal Analysis

The data of 700–1400°C was used to draw thermogravimetric and differential scanning calorimetry curves (TG-DSC curves) to facilitate the analysis of the experimental results. As depicted in **Fig. 6**, the TG-DSC curves of the samples with BaO contents (0, 1 mass%, 2 mass%,

Table 3. Barium -containing region composition of four sinter samples.

Elements	Fe	Ca	Al	Si	Ba	O
FB (a)	57.79	1.12	1.6	–	11.08	28.41
FB (b)	58.58	4.99	1.6	–	7.28	27.55
FB (c)	56.92	1.04	1.77	–	11.51	28.75
FB (d)	57.57	0.62	2.08	–	12.18	27.54

Table 4. EDS results of the samples from the content of BaO range from 3 wt.% to 9 wt.%.

Elements	Fe	Ca	Al	Si	Ba	O
SFCA	51.53	9.62	4.21	1.99	–	32.66
SFCA-I	51.89	15.39	1.11	–	–	31.61
SFCAB	48.17	5.21	3.83	1.7	8.76	32.33
SFCA	52.63	14.42	2.52	0.88	–	29.55
SFCA-I	52.43	16.86	0.66	–	–	30.05
SFCAB	30.26	5.48	6.62	2.22	29.13	26.29
FB	55.65	2.27	2.06	–	11.21	28.81
SFCA	49.15	14.44	2.21	0.84	–	33.36
SFCAB	34.37	8.76	4.49	2.25	16.9	33.21
FB	58.01	1.43	1.91	–	9.75	28.89
SFCA	43.95	17.33	3.22	1.94	–	33.56
SFCAB	48.83	7.92	2.85	1.18	8.7	30.52
FB	57.88	0.99	2.08	–	11.82	27.23

3 mass%, 5 mass%, 7 mass%, and 9 mass%) were showed. As the temperature of sample increased from 700°C to 1400°C, there were mainly two endothermic peaks in these seven samples, which were referred to as A and B respectively during the heating process. According to the binary phase diagram of $\text{CaO-Fe}_2\text{O}_3$, the endothermic peak A ($T=1208^\circ\text{C}$) was corresponding to the eutectic melting temperature of CF and C_2F .^{23,24)} The endothermic peak B ($T=1280^\circ\text{C}$) was close to the decomposing temperature of SFCA, which was similar to the result of Zhe Wang *et al.*²⁵⁾ For these seven experiments, two obvious weightless stages, which respectively were 1200–1300°C, and 1300–1400°C.

Between 1200–1300°C, the weight of the samples (TG value) went down from about 1200°C, which corresponded to the endothermic peak appearing on the DSC curve. The key reason for mass loss was the decomposition of numerous Fe_2O_3 in the system. The equation of the decomposition was:

The formula (5) is the decomposition reaction of Fe_2O_3 . After 1300°C, the TG curve dropped slowly. It indicated that fewer Fe_2O_3 decomposed in the SFCA phase.

The development of the sinter bonding phases may include the appearance of a low-melting phase, and the second liquid phase generated. The sinter strength was improved by the bonding phase agglomeration during cooling.²⁶⁾ The peak area of the DSC curves corresponded to

Fig. 6. Curves of the mixed powders with different BaO contents. (a) 0, (b) 1 wt.%, (c) 2 wt.%, (d) 3 wt.%, (e) 5 wt.%, (f) 7 wt.%, (g) 9 wt.%. (Online version in color.)

the amount of liquid phase produced and the amount of liquid phase depended on the CF and SFCA phases content. When the content of BaO range from 0 to 2 mass%, the area of the endothermic peak A changed less as shown in Fig. 7(a), which suggested that the formation of CF liquid phase

was relatively small. The area of the endothermic peak B increased was showed in Fig. 7(b) and the decomposing temperature of SFCA went up as shown in Fig. 8(b), it could determine that the formation of the SFCA liquid phase had gone up significantly. This indicated that a small amount of

Fig. 7. (a) The DSC method is used to estimate the eutectic melting temperature of CF by the heat flow in air atmosphere. (b) The DSC method is used to estimate the decomposing temperature of SFCA by the heat flow in air atmosphere. (Online version in color.)

Fig. 8. (a) The eutectic melting temperature curve of CF with increase in BaO addition determined by the DSC method in inert atmosphere. (b) The decomposing temperature curve of SFCA with increase in BaO addition determined by the DSC method in inert atmosphere. (Online version in color.)

BaO was dissolved in the $\text{CaO-Fe}_2\text{O}_3\text{-Al}_2\text{O}_3\text{-SiO}_2$ system to form complex barium-containing SFCA. The eutectic melting temperature of the CF and C_2F declined in the samples as shown in Fig. 8(a). The eutectic melting temperature of the CF and C_2F was showed in Fig. 8(a). It could be observed that the eutectic melting temperature of the CF and C_2F reduced with the addition of BaO. According to the regular pattern of phases transition, it could obtain that the content of CF reduced in the sintering process. And, the CF transformed into C_2F and L under high temperature that the reaction was Eq. (6).

where L is liquid phase. The ratio of C_2F increased in the CF and C_2F system, which would decline the eutectic temperature of CF and C_2F . The DSC curves of SFCA was showed in Fig. 7(b), it could be seen that the area of endothermic

peak of SFCA decreased with the content of BaO exceeded 2 mass%, suggesting that the formation of the SFCA liquid phase declined. The temperature trend of SFCA was showed in Fig. 8(b), it could be seen that the decomposing temperature of SFCA went up with the content of BaO exceeded 2 mass%, which indicated that the stability of SFCA reduced at high temperature. Thus, the content of SFCA decreased with the addition of BaO. The FB solid solution was precipitated from the $\text{CaO-Fe}_2\text{O}_3\text{-Al}_2\text{O}_3\text{-SiO}_2$ system and a small amount of Al^{3+} migrated from SFCA to FB, which was consistent with the results described in SEM-EDS. The results explained the fact why the SFCA peak area reduced first and decreased then on the DSC curves with increased the content of BaO. SFCA was one of the most maximum produced minerals in iron ore sintering and had been considered as the main bonding phase during the production of industrial iron ore sinters.^{5,9)} Therefore, less liquid phase

Fig. 9. mechanism of action of BaO in sinter. (Online version in color.)

reduced the bonding strength of the sinter.

3.4. Mechanism Analysis

Figure 9 indicated that BaO plays an important role in microstructures of SFCA. To determine the change mechanism, the morphology of SFCA with different BaO contents was elucidated. As depicted in Fig. 9, the mechanisms for the formation of by added BaO were explained. A little of BaO participated in the solid solution reaction of SFCA with the content of BaO was 1 mass%, 2 mass%, respectively. The existence of Ba^{2+} absorbed part of Al^{3+} into SFCA, which increased the formation of needle-like SFCA. When the BaO content from 3 mass% to 9 mass%, the most BaO reacted directly with Fe_2O_3 to form FB. The Si^{4+} -free FB was precipitated from the SFCA phase and a larger amount of silica was present in the SFCA bonding phase, which indicated that the barium prevented the solid solution behavior of Si^{4+} .

4. Conclusions

To investigate the effect of BaO on formation mechanisms of silico-ferrite of calcium and aluminum, the phase composition of the samples was determined by XRD, SEM-EDS, and TG-DSC. The results were summarized as follows:

(1) BaO promoted the formation of needle-like SFCA and increased the decomposing temperature of SFCA with the amount of BaO increased to 2 mass%.

(2) New bonding phase FB was generated with the amount of BaO exceeded 2 mass%. The decomposing temperature of SFCA significantly decreased, but still higher than the original temperature. However, BaO pushed the formation of C_2F in the CF and C_2F system, which decreased the eutectic melting temperature of CF and C_2F .

(3) The quality of sinter ore was improved when BaO content less than 2 mass%. With the further increase of BaO content, which could decrease the strength of sinter and was harmful for the quality of sinter.

Acknowledgments

The present work was financially supported by National Nature Science Foundation of China (Grant No. 2019M663932XB) and Natural Science Basic Research Program of Shaanxi (Program No. 2019JLP-05).

REFERENCES

- N. A. S. Webster, M. I. Pownceby, I. C. Madsen and J. A. Kimpton: *ISIJ Int.*, **53** (2013), 774. <http://doi.org/10.2355/isijinternational.53.774>
- T. R. C. Patrick and R. R. Lovel: *ISIJ Int.*, **41** (2001), 128. <http://doi.org/10.2355/isijinternational.41.128>
- L. X. Yang and C. E. Loo: *ISIJ Int.*, **37** (1997), 449. <https://doi.org/10.2355/isijinternational.37.449>
- H. S. Kim, J. H. Park and Y. C. Cho: *Ironmaking Steelmaking*, **29** (2002), 266. <https://doi.org/10.1179/030192302225004511>
- T. R. C. Patrick and M. I. Pownceby: *Metall. Mater. Trans. B*, **33** (2002), 79. <https://doi.org/10.1007/s11663-002-0088-0>
- K. Sugiyama, A. Monkawa and T. Sugiyama: *ISIJ Int.*, **45** (2005), 560. <https://doi.org/10.2355/isijinternational.45.560>
- X. D. Xing, Y. L. Du, J. L. Zheng, S. Wang, S. Ren and J. T. Ju: *JOM*, **73** (2021), 1328. <https://doi.org/10.1007/s11837-021-04628-8>
- R. Mežbrický and M. Fröhlichová: *ISIJ Int.*, **56** (2016), 1111. <https://doi.org/10.2355/isijinternational.ISIJINT-2016-044>
- I. Tonžetić and A. Dippenaar: *Miner. Eng.*, **24** (2011), 1258. <https://doi.org/10.1016/j.mineng.2011.04.012>
- W. G. Mumme, J. M. F. Clout and R. W. Gable: *Neues Jahrb. für Mineral. Abhandlungen*, **173** (1998), 93. <https://doi.org/10.1127/njma/173/1998/93>
- K. Yajima and S. M. Jung: *ISIJ Int.*, **52** (2012), 535. <https://doi.org/10.2355/isijinternational.52.535>
- K. Zöll, T. Manninger, V. Kahlenberg, H. Krüger and P. Tropper: *Metall. Mater. Trans. B*, **48** (2017), 2207. <https://doi.org/10.1007/s11663-017-0988-7>
- M. I. Pownceby, N. A. S. Webster and J. R. Manuel: *Miner. Process. Extr. Metall.*, **125** (2016), 140. <https://doi.org/10.1080/03719553.2016.1153276>
- N. A. S. Webster, M. I. Pownceby, R. Pattel, J. R. Manuel and J. A. Kimpton: *ISIJ Int.*, **59** (2019), 263. <https://doi.org/10.2355/isijinternational.ISIJINT-2018-573>
- X.-y. Li, B.-x. Su, L.-g. Xia, J.-l. Zhang and H.-w. Guo: *J. Iron Steel Res. Int.*, **22** (2015), 478. [https://doi.org/10.1016/S1006-706X\(15\)30030-3](https://doi.org/10.1016/S1006-706X(15)30030-3)
- N. A. S. Webster, J. G. Churchill, F. Tufail, M. I. Pownceby, J. R. Manuel and J. A. Kimpton: *ISIJ Int.*, **56** (2016), 1715. <https://doi.org/10.2355/isijinternational.ISIJINT-2016-162>
- L. X. Yang and E. Matthews: *ISIJ Int.*, **37** (1997), 854. <https://doi.org/10.2355/isijinternational.37.854>
- T. Maeda, K. Nishioka, K. Nakashima and M. Shimizu: *ISIJ Int.*, **44** (2004), 2046. <https://doi.org/10.2355/isijinternational.44.2046>
- Y. F. Chai, W. T. Yu, J. L. Zhang, S. L. An, J. Peng and Y. Z. Wang: *Ironmaking Steelmaking*, **46** (2019), 424. <https://doi.org/10.1080/03019233.2018.1503629>
- E. A. Mousa, A. Babich and D. Senk: *Iron Steel Res. Int.*, **86** (2015), 1350. <https://doi.org/10.1002/srin.201400368>
- N. A. S. Webster, M. I. Pownceby, I. C. Madsen and J. A. Kimpton: *Metall. Mater. Trans. B*, **43** (2012), 1344. <https://doi.org/10.1007/s11663-012-9740-5>
- N. Yang, X. M. Guo, N. Saito, K. Nakashima and J. T. Zhao: *ISIJ Int.*, **58** (2018), 1406. <https://doi.org/10.2355/isijinternational.ISIJINT-2018-028>
- N. V. Y. Scarlett, M. I. Pownceby, I. C. Madsen and A. N. Christensen: *Metall. Mater. Trans. B*, **35** (2004), 929. <https://doi.org/10.1007/s11663-004-0087-4>
- C. Ding, X. Lv, Y. Chen, G. Li, W. He and X. Lv: *J. Alloys Compd.*, **789** (2019), 537. <https://doi.org/10.1016/j.jallcom.2019.02.325>
- Z. Wang, D. Pinson, S. Chew, B. J. Monaghan, M. I. Pownceby, N. A. S. Webster, H. Rogers and G. Q. Zhang: *ISIJ Int.*, **56** (2016), 1138. <https://doi.org/10.2355/isijinternational.ISIJINT-2015-598>
- Z. G. Pang, X. D. Xing, J. L. Zheng, Y. L. Du, S. Ren and M. Lv: *J. Non-Cryst. Solids*, **571** (2021), 121071. <https://doi.org/10.1016/j.jnoncrystsol.2021.121071>