Effect of binary basicity on chromium occurrence in stainless steel slag

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Abstract

Comprehensive utilization of stainless-steel slag (SSS) is restrained due to the risk of Cr\textsuperscript{6+} leaching. Based on the studying the microstructure of synthetic slag (SS) containing Cr\textsubscript{2}O\textsubscript{3} with XRD, SEM-EDS, and Image pro, the effect of binary basicity on the chromium occurrence in SSS was investigated. The results indicated that the binary basicity had a significant impact on the properties of spinel crystals. There was a positive correlation between the calcium content in spinel crystals and the SS basicity. The size of spinel crystals varied from large to small and the precipitation occurrence changed with the basicity increase. Furthermore, the chromium occurrences changed with basicity. The chromium was produced in spinel crystals at lower basicity, but as the basicity increased to 3.0, the chromium precipitated as calcium chromate. In view of the relationship between the chromium leaching behavior and its occurrence, increasing basicity raised the Cr\textsuperscript{6+} leaching.

Keywords: stainless steel slag (SSS); hexavalent chromium; spinel crystals; binary basicity

1. Introduction

The stainless steel production is 50.892 million metric tons in 2020, and the Chinese production was 30.139 million metric tons. SSS as by-product in the stainless steel production, its output is about 25 wt% of the total stainless steel amount, that means the Chinese SSS production was about 7.53 million tons[1,2]. At present, Chinese stainless-steel plants merely recover valuable metals such as iron, chromium and nickel through a grinding process, and parts of tailing slags can be applied as subgrade material, concrete aggregate, cement production, brick and block making, sintering for iron making and other materials. The rest tailing slags are stored as stacking or landfill. These materials and tailing slags contain chromium, which is able to leach Cr\textsuperscript{6+}. Cr\textsuperscript{6+} was reported to pollute the environment and cause human poisoning and carcinogenesis[3-8]. Therefore, to achieve the comprehensive utilization of SSS and enhance
economic benefits, it is necessary to solve the Cr⁶⁺ leaching issue and ensure the safety of SSS products for long-term applications.

The limitation of Cr⁶⁺ leaching from SSS is a significant challenge. Previous research implied three main measures to control the Cr⁶⁺ leaching: the addition of reductive compounds in the application of SSS, the adjustment of cooling regimes, and the modified components to transform the Cr occurrence. The reductive compounds, such as FeSO₄, can limit the Cr⁶⁺ leaching by chemical reduction of the oxidized Cr⁶⁺ to the nontoxic Cr³⁺ or Cr⁹ [9]. Nevertheless, this Cr⁶⁺ inhibition method is time-dependent and cannot ensure the long-term safety of SSS products. The rapid cooling approach includes two beneficial aspects: first, it promotes the formation of the glass phase and fixes heavy metal elements, such as Cr [10]; second, Cr⁶⁺ is stable only at temperatures lower than 1228 °C because of the different precipitated phases, so the rapid cooling rate restrains the amount of Cr⁶⁺[11,12]. The final measure is the transformation of the Cr occurrence, which is divided into an enriched state and dispersed state, to limit the Cr⁶⁺ leaching. The enriched state refers to Cr existing in spinel crystals, and the dispersed state includes an isomorphic solid solution and micro-inclusion. The structure of spinel crystals is Me⁶O(Me³⁺O₃), in which Me³ is a divalent metal ion, including Mg²⁺, Fe²⁺, Mn²⁺, and Me⁹ is a trivalent metal ion, including Cr³⁺, Al³⁺, Fe³⁺ [13]. Spinel crystals limit the leachability but also enhance the Cr oxidation resistance, and they are considered as a suitable mineral phase for Cr fixing. As such dispersed Cr is unstable, the Cr⁶⁺ leaching is negatively affected by the dissolution of matrix minerals [14-17].

Cao and Zhao [18,19] analyzed the stability of 1.0, 1.5, 2.0 basicities slags with 5% Cr₂O₃ content, and found that the spinel phase was not obviously damaged in SEM pictures, and the periclase phase disappeared after leaching tests in the leaching solution of pH = 3.2. And the silicate phase was not able to limit the leaching of Cr⁶⁺. The leaching amount of Cr⁶⁺ was very low at 1600 °C, which was 2.82 mg/L, 2.26 mg/L, 3.68 mg/L, respectively, due to the existence of spinel phase. Spinel crystals further grew, and the leaching amount of Cr⁶⁺ decreased to 1.78 mg/L, 0.62 mg/L, 1.46 mg/L, respectively, as temperature decreased to 1300 °C. Cao[20]studied on growth behavior of spinel in SSS during cooling process further indicated that the leaching amount of chromium could reduce to less than 0.01 mg/L by controlling the cooling condition to promote the growth of spinel crystals. Esfahani[21] investigates the effect of composition on the crystallization behavior and found the crystalline phases were translucent and nucleation was limited to grow lager crystals at low basicity. Albertsson[22] found the range 1.0-1.4 of basicity of CaO-MgO-SiO₂-Cr₂O₃ synthetic slag was favoured to control the precipitation of Cr-spinel. The precipitation of spinel crystals are also affected by the oxygen partial pressure. Albertsson[23] did the low oxygen partial pressure on the chromium partition in CaO-MgO-SiO₂-Cr₂O₃-Al₂O₃ at elevated temperatures. It was found that low oxygen partial pressure had a strong impact on chromium partition.

In our previous study, the leaching experiments were performed on SSS with different basicity (the ratio of CaO% and SiO₂% is 1.25~1.89). It was confirmed that the Cr⁶⁺ leaching was higher for the sample with low Cr₂O₃ content and high basicity than for the sample with high Cr₂O₃ content and low basicity, which implied a good agreement between Cr stability and the occurrence state [24]. CaO–Al₂O₃–MgO–SiO₂–CrO₃ slag with varied CaO/ SiO₂ (1.1, 1.3, 1.5) was studied at 1673K by Shu[25], the results showed the biggest size of spinel crystal at 1.5 basicity and Cr is enriched in spinel phase and liquid phase. Liu found that the presence of
solid particles in slag has a critical influence on the viscosity at high basicity[26]. However, the
effect of basicity and Cr\textsubscript{2}O\textsubscript{3} content on viscosity was nonlinear at low or high basicity. Hence,
the viscosity change caused by the effect of compositions and basicity has no objective law. For
the actual complex SSS composed of multi-component oxides, specific problems need to be
analyzed in detail. The general idea is to promote the formation of spinel phase, the enrichment
of Cr in spinel phase, and then reduce the leaching amount of Cr. In this paper, the effect of
binary basicity (CaO%/SiO\textsubscript{2}%)
on the chromium occurrence in SSS by thermodynamic
calculations and theoretical analysis of synthetic slag (SS) was investigated. The element
distribution in spinel phase was further analyzed and its formation mechanism was explained.

2. Experimental

CaO, SiO\textsubscript{2}, MgO, Al\textsubscript{2}O\textsubscript{3}, Cr\textsubscript{2}O\textsubscript{3}, FeC\textsubscript{2}O\textsubscript{4}·2H\textsubscript{2}O, and H\textsubscript{3}BO\textsubscript{3} were used as raw materials for
SS. All reagents were of analytical grade (AR) produced by Sinopharm group. The specific
focuses were that FeO was replaced by FeC\textsubscript{2}O\textsubscript{4}·2H\textsubscript{2}O and 0.1 wt % H\textsubscript{3}BO\textsubscript{3} was added into the
SS to form a block sample.

Based on the chemical composition of EAF smelting SSS, the CaO-SiO\textsubscript{2}-MgO-Al\textsubscript{2}O\textsubscript{3}-
Cr\textsubscript{2}O\textsubscript{3}-FeO slag system was designed, and the basicity (CaO%/SiO\textsubscript{2}%) was from 0.6 to 3.0.
According to the chemical composition shown in Table 1, the reagent powder was accurately
weighed by electronic balance, sieved (Φ 0.55mm) for 4 - 6 times, and then ground by grinder
(YP200) to mix fully. The mixture was put into molybdenum crucible (Φ 60 x 110) and melted
in a high-temperature carbon tube furnace (25 kW, 1650 ℃). The heating regime was heating
to1550 ℃ at the rate of 10 ℃/min in the nitrogen (3L/min) atmosphere, and held for 30 min.
The sample was quenched in water.

| No. | CaO | SiO\textsubscript{2} | MgO | Al\textsubscript{2}O\textsubscript{3} | Cr\textsubscript{2}O\textsubscript{3} | FeO | CaO%/SiO\textsubscript{2}% |
|-----|-----|-------------------|-----|----------------|----------------|-----|----------------|
| SS1 | 29.25 | 48.75 | 8.00 | 8.00 | 6.00 | 8.00 | 0.60 |
| SS2 | 45.50 | 32.50 | 8.00 | 8.00 | 6.00 | 8.00 | 1.40 |
| SS3 | 50.14 | 27.86 | 8.00 | 8.00 | 6.00 | 8.00 | 1.80 |
| SS4 | 53.63 | 24.38 | 8.00 | 8.00 | 6.00 | 8.00 | 2.20 |
| SS5 | 58.50 | 19.50 | 8.00 | 8.00 | 6.00 | 8.00 | 3.00 |

A scanning electron microscope (NanoSEM400) was used to investigate the
microstructure and morphology, and EDS analysis was used to determine the chemical
composition by line scanning and the mapping of the elements. XRD (X-Pert Pro MPD) was
used to analyze the mineral phase after grinding. The particle size of the spinel crystal in the
sample was calculated based on the SEM micrographs using Image-Pro Plus (IPP 6.0) image
analysis software, and 10 fields of the same magnification were randomly selected for each
sample to obtain a statistically relevant analysis. The Reaction module of FactSage 7.3 was
used to calculate the thermochemical properties.
Fig. 1 Microstructures of SS with different basicity; (a), (b), (c), and (d) represent the slag samples with the basicity 0.6, 1.8, 2.2, and 3.0, respectively.

3. Results and Discussion

3.1 Effect of basicity on the microstructure and morphology of SS

Combined SEM micrographs (Fig.1) and XRD patterns (Fig.2) imply that the mineral phases of SS containing Cr$_2$O$_3$ transform obviously with the increase of basicity. The microstructure of SS1 is composed of spinel crystals, Ca(Mg,Fe)Si$_2$O$_4$, and silicate matrix, then, the microstructure of SS3 is similar to that of SS1, but Ca(Mg,Fe)Si$_2$O$_4$ is completely transformed to Ca$_2$MgSi$_2$O$_7$. The microstructure of SS4 is composed of Ca$_3$MgSi$_2$O$_8$ and (Mg$_x$Fe$_{1-x}$)O spinel crystals. Ca$_2$SiO$_4$, (Mg$_x$Fe$_{1-x}$)O, and CaCr$_2$O$_4$ are mineral phases present in the SS5 sample with the highest 3.0 basicity. Wu found that as the FeO content of the slag system was invariant, and in the basicity range of 1.0-1.5 (CaO% / SiO$_2$%), spinel solid solutions of (Mg, Fe) (Fe, Al, Cr)$_2$O$_4$ were formed in each sample[27]. In that study, the size of the spinel crystal with a regular shape is negatively related to basicity, spinel crystal could be produced only when the basicity is lower than 1.8. The average size of spinel crystals in SS1 was 12.30 µm, and it reduces to 4.47 µm in SS3. On the contrary, Cr does not precipitate anymore in the spinel crystals, but in the form of CaCrO$_4$ in SS5. Li studied the Cr distribution and enrichment in the CaO-Al$_2$O$_3$-MgO-SiO$_2$-CrO$_x$-Fe$_x$O slag system with 0.96 ~ 1.96 basicity[28], and their results showed that the Cr was enriched in CaCr$_2$O$_4$ at high basicity, and in spinel crystals at low basicity. Compared with Fig.1 and Fig.2, the main silicate phases in SS are Ca(Mg,Fe)Si$_2$O$_4$, Ca$_2$MgSi$_2$O$_7$, Ca$_3$MgSi$_2$O$_8$, and Ca$_2$SiO$_4$. 
The investigation of the effect of FeO on the stability of spinel crystal showed that the spinel crystal was an octahedral Mg\textsubscript{1-x}Fe\textsubscript{x}Fe\textsubscript{2}O\textsubscript{4} solid solution [29], with the shape of the spinel crystal similar to that shown in Fig.1. The spinel crystal embedded in the matrix or silicate phase is represented by a light-colored feature in the SEM micrograph. After the sample preparation, the interface between the spinel crystal and the matrix, or silicate phase, should be a regular straight line. As shown in Fig.1 (a), the hole-like feature that looks like the giant spinel crystal is Ca(Mg,Fe)Si\textsubscript{2}O\textsubscript{4}, and the matrix or silicate phase in the complete section at the lower right corner. That means the spinel crystals has been completely crystallized. Similar features occur for the spinel crystals in the central region of Fig.1 (c). The Cr\textsuperscript{6+} leaching mechanism proposed by Pillay assumes the reaction at the contact interface of CaO and Cr\textsubscript{2}O\textsubscript{3} to yield CaCrO\textsubscript{4} [9]. Although kinetics conditions of molten SSS at low basicity is better, the growth of a spinel crystal that belongs to a substitutional solid solution is restricted by the activity of substituting elements. However, the leaching risk might increase in the case of incompletely grown spinel crystals. As we have seen above, the number of mineral phases increases with the basicity. The spinel crystals exhibit the central defect, Fig.1(c), and at the basicity of 3.0, there is no spinel phase in SS5. In summary, the low basicity of 1.8 is suitable for the formation of spinel crystals.

3.2 Effect of basicity on the chromium occurrence

Concerning to the EDS results, the Cr occurrence has been assessed. The elemental mapping of Cr and Ca is shown in Fig.3, with basicity of 0.6, 1.4, and 3.0. The chemical compositions of different mineral phases are summarized in Table 2. The SS1 microstructure can be divided into three distinct phases. Among them, the white area with a regular shape is the spinel crystal, and the elemental mapping supports this observation. Cr mainly enriches the spinel crystal, while Ca exists only in the non-spinel mineral phase. The content of the elements differs significantly between the areas, having a well-defined boundary. This is also consistent.
with the line scanning observation in Fig. 4, which shows the step mutation curves of Cr and Ca contents in different precipitates.

Fig. 3 The elemental mapping of the spinel crystal with different basicity: (a), (b), and (c) represent the slag samples with the basicity 0.6, 1.4, and 3.0, respectively.

Table 2 Chemical composition of each precipitate in Fig. 3 /at%

| basicity | precipitation | O   | Cr | Ca  | Fe  | Mg  | Si   |
|----------|---------------|-----|----|-----|-----|-----|------|
| B=0.6    | White (P.1)   | 56.66 | 27.11 | 0.4 | 8.41 | 6.91 | 0.06 |
|          | Gray (P.2)    | 59.28 | 0.97  | 9.97 | 1.51 | 8.58 | 18.12 |
|          | Matrix (P.3)  | 59.66 | 0.21  | 10.43 | 1.12 | 1.00 | 22.33 |
| B=1.4    | White (P.1)   | 60.93 | 19.98 | 0.85 | 4.78 | 9.00 | 0.02 |
|          | Matrix (P.2)  | 57.86 | 0.08  | 19.28 | 2.20 | 3.89 | 12.94 |
| B=3.0    | White (P.1)   | 58.39 | 20.21 | 16.71 | 2.82 | 1.63 | 0.08 |
|          | Gray (P.2)    | 54.89 | 2.70  | 8.57  | 14.03 | 18.78 | 0.07 |
|          | Black (P.3)   | 57.28 | 0.05  | 30.36 | 0.18 | 0.09 | 11.72 |

At basicity of 0.6, the spinel crystal is enriched in Cr, while Ca is contained in the non-spinel mineral phase in SS2. Compared with SS1, the characteristics of the element occurrence in SS2 are reflected at the boundary of spinel crystals. Fig. 4 shows that there is a tiny compositional decreasing gradient of Ca distribution towards the interior of spinel crystals near the spinel crystal surface, within which the element weights of Ca and Cr are negative correlation. As shown in Table 2, the Ca content of spinel crystals in SS1 and SS2 are 0.40 at% and 0.85 at%, respectively, while the Cr content is 27.11 at% and 19.98 at%.
In comparison with other samples, the distribution of Cr and Ca changes considerably in SS5 at basicity of 3.0. Fig.5 shows that Ca exists along the entire scanning line, while Cr is mainly concentrated in the bright white and gray-white areas. The Cr content in the gray area is 2.70 at%, and the black area has the lowest Cr content of only 0.05 at%. The SS5 differs from the lower basicity samples by the coexistence of Ca and Cr, with CaCr$_2$O$_4$ and Ca$_2$SiO$_4$, which reduces the Cr stability in SS and increases the risk of Cr leaching.

3.3 Effect of microstructure on the Cr$^{6+}$ leaching

The natural Cr$^{6+}$ leaching is determined by the microstructure of the mineral phase of SSS. The standard Gibbs free energy ($\Delta G$) of Cr$^{6+}$ in standard conditions (25°C and 100kPa) is calculated by FactSage 7.3 as follows:

$$ \begin{align*} 
2\text{Cr}_2\text{O}_3 + 3\text{O}_2 & = 4\text{CrO}_3 \quad \Delta G_1 = 77.08\text{kJ/mol} \\
2\text{Cr}_2\text{O}_3 + 3\text{O}_2 + 4\text{CaO} & = 4\text{CaCrO}_4 \quad \Delta G_2 = -775.65\text{kJ/mol} 
\end{align*} $$

As we can see in Eq.1, the reaction of Cr$_2$O$_3$ and O$_2$ is not spontaneous, but it becomes spontaneous when CaO is present, as Eq.2. Compared with the elemental scanning lines in Fig. 4 and Fig. 5, Cr in the matrix or CaCrO$_4$ phase is in direct contact with CaO or calcium silicate around it, which increases the feasibility of the reaction. The solubility of CaCrO$_4$ in water at 20 °C is 2.25g. The natural SSS leaching model is an irreversible unreacted core model, and Eq.
2 determines the leaching rate. There is almost no Ca element in the spinel crystal, and Cr in the spinel phase is trivalent. The oxidation of trivalent Cr\(^{3+}\) to hexavalent Cr\(^{6+}\) requires an increased oxygen partial pressure, the activity of Cr\(_2\)O\(_3\), and lattice damage of spinel. Therefore, Cr in spinel does not oxidize readily. Cr\(^{6+}\) in acidic solutions is related to its concentration and the pH value [30]. Under acidic conditions, Cr\(^{6+}\) can be reduced to Cr\(^{3+}\) in the presence of Fe\(^{2+}\), as Eq. 3 [31], which indicates that the spinel crystal has good resistance to natural leaching of Cr\(^{6+}\), although the crystal structure is damaged.

\[
\text{CrO}_4^{2-} + 3\text{Fe}^{2+} + 8\text{H}^+ \rightarrow \text{Cr}^{3+} + 3\text{Fe}^{3+} + 4\text{H}_2\text{O}
\]

The transform between bivalent and trivalent of Cr is as equation(4),(5).

\[
\frac{\text{Cr}^{3+} + \frac{1}{4} \text{O}_2}{\text{Cr}^{2+}} = k_1 \text{P}^{\frac{3}{2}} \text{O}_2
\]

The transform between trivalent and hexavalent of Cr is as equation(6),(7).

\[
\frac{\text{Cr}^{3+} + \frac{3}{4} \text{O}_2}{\text{Cr}^{6+} + \frac{3}{2} \text{O}_2} = k_2 \text{P}^{\frac{3}{2}} \text{O}_2
\]

Nell and De Villiers studied the distribution of chromium in CaO-CrO-Cr\(_2\)O\(_3\)-SiO\(_2\) under low oxygen partial pressure, found that the Cr were main in the CaCr\(^{2+}\)SiO\(_4\) and (Ca\(_{0.4}\)Cr\(_{0.6}\)\(^{2+}\))Cr\(_2\)^{3+}O\(_4\). These phases can react to produce more oxidation phases, and improve the temperature of liquid line at lower oxygen partial pressure[32]. Mirzayousef studied the CaO-SiO\(_2\)-CrO\(_x\) and found that the value of Cr\(^{3+}\)/Cr\(^{2+}\) in the system increased with the increase of oxygen partial pressure at 1600°C and low oxygen partial pressure, and the increase of basicity also led to the decrease of Cr content. Cr\(^{6+}\) content will increase with the increase of oxygen partial pressure, and the increase of basicity will increase the content of Cr\(^{6+}\) under the condition of high oxygen partial pressure [33].

Cr occurrence is the decisive factor for the Cr\(^{6+}\) leaching. The typical mineral phases in the EAF SSS include merwinite (Ca\(_3\)MgSi\(_2\)O\(_8\)), anorthite (Ca\(_2\)MgSi\(_2\)O\(_7\)), gehlenite (Ca\(_2\)Al\(_2\)SiO\(_7\)), dicalcium silicate (Ca\(_2\)SiO\(_4\)), spinel crystals, and simple oxide solid solution (MeO) [18,34]. Spinel crystals and MeO phases are considered to be available mineral phases for Cr solidification, which cannot only inhibit the oxidation of Cr\(_2\)O\(_3\), but they are also poorly soluble in water. Minerals such as dicalcium silicate, merwinite, and melilitite easily dissolve in water, so Cr leaches with the dissolution of these minerals. Garcia-Ramos stabilized Cr\(_2\)O\(_3\) by adding Al\(_2\)O\(_3\) or MgO to the CaO-SiO\(_2\)-Cr\(_2\)O\(_3\) slag system [16]. The results showed that calcium chromite (CaCr\(_2\)O\(_4\)) was produced with no Al\(_2\)O\(_3\) or MgO added. After the Al\(_2\)O\(_3\) or MgO addition, the CaCr\(_2\)O\(_4\) phase disappeared, and the Cr leaching was significantly decreased. It must also be mentioned that the Cr solubility in industrial slag is mainly affected by basicity and MgO content. Given that Cr in calcium dichromate (CaCr\(_2\)O\(_4\)) easily dissolves in acid rain, as the basicity is about 2.2, and CaCr\(_2\)O\(_4\) oxidizes to calcium chromate (CaCrO\(_4\)) in the slag yard. The Cr solubility is further enhanced because CaCrO\(_4\) is more soluble in the aqueous solution. Hence, the rise of basicity is increasing the Cr leaching risk in SSS.
4. Conclusions

The effect of binary basicity on Cr occurrence in SSS was investigated using. The main conclusions can be represented as follows:

(1) The size of spinel crystals varied from large to small, and the precipitated phases changed with the increase of SS basicity. The main silicate species evolved from Ca(Mg,Fe)Si₂O₄, Ca₂MgSi₂O₇, Ca₃MgSi₂O₈, and Ca₂SiO₄.

(2) Basicity changed the Ca content in the spinel crystal and at the interface between spinel crystal and silicate phase. Thus, the phase interface between the spinel crystal and the silicate phase is gradually blurred.

(3) Basicity changed the Cr occurrence as well. Cr was mainly in the spinel crystals at lower basicity. Still, the Cr content in the precipitated phases increased with the basicity. Once the basicity was 3.0, Cr precipitated in the form of CaCrO₄. The higher basicity such as 3.0 enhances the risk of leaching without spinel crystals in slag. Due to the incomplete spinel crystals at lower basicity, it is a feasible range of basicity from 1.8 to 2.2 to product spinel crystals to control the leaching of Cr⁶⁺.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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Table Contents
Table 1 Chemical composition of SS/wt %.
Table 2 Chemical composition of each precipitate in Fig.3 /at%

Table 1 Chemical composition of SS/wt %.

| No. | CaO   | SiO₂  | MgO  | Al₂O₃ | Cr₂O₃ | FeO  | CaO%/SiO₂% |
|-----|-------|-------|------|-------|-------|------|------------|
| SS1 | 29.25 | 48.75 | 8.00 | 8.00  | 6.00  | 8.00 | 0.60       |
| SS2 | 45.50 | 32.50 | 8.00 | 8.00  | 6.00  | 8.00 | 1.40       |
| SS3 | 50.14 | 27.86 | 8.00 | 8.00  | 6.00  | 8.00 | 1.80       |
| SS4 | 53.63 | 24.38 | 8.00 | 8.00  | 6.00  | 8.00 | 2.20       |
| SS5 | 58.50 | 19.50 | 8.00 | 8.00  | 6.00  | 8.00 | 3.00       |

Table 2 Chemical composition of each precipitate in Fig.3 /at%

| basicity | precipitation | O   | Cr  | Ca  | Fe  | Mg | Si   |
|----------|---------------|-----|-----|-----|-----|----|------|
| B=0.6    | White (P.1)   | 56.66 | 27.11 | 0.4  | 8.41 | 6.91 | 0.06 |
|          | Gray (P.2)    | 59.28 | 0.97  | 9.97 | 1.51 | 8.58 | 18.12 |
|          | Matrix (P.3)  | 59.66 | 0.21  | 10.43 | 1.12 | 1.00 | 22.33 |
| B=1.4    | White (P.1)   | 60.93 | 19.98 | 0.85  | 4.78 | 9.00 | 0.02 |
|          | Matrix (P.2)  | 57.86 | 0.08  | 19.28 | 2.20 | 3.89 | 12.94 |
| B=3.0    | White (P.1)   | 58.39 | 20.21 | 16.71 | 2.82 | 1.63 | 0.08 |
|          | Gray (P.2)    | 54.89 | 2.70  | 8.57 | 14.03 | 18.78 | 0.07 |
|          | Black (P.3)   | 57.28 | 0.05  | 30.36 | 0.18 | 0.09 | 11.72 |

Figure Contents
Fig. 1 Microstructures of SS with different basicity: (a), (b), (c), and (d) represent the slag samples with the basicity 0.6, 1.8, 2.2, and 3.0, respectively.
Fig. 2 XRD patterns of SS.
Fig. 3 The elemental mapping of the spinel crystal with different basicity: (a), (b), and (c) represent the slag samples with the basicity 0.6, 1.4, and 3.0, respectively.
Fig. 4 Chemical composition change behavior in local area of SS1
Fig. 5 Chemical composition change behavior of spinel crystal interface in SS4
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Fig. 4. Chemical composition change behavior in local area of SS1

Fig. 5. Chemical composition change behavior of spinel crystal interface in SS4