CHARACTERISTICS AND CORROSION BEHAVIOR ON REFRACTORIES OF MOLTEN SLAG UNDER ELECTROMAGNETIC FIELD

Lian peng fei, Huang ao, Gu huazhi, Zou yongshun, Wang yajie, Fu lvping
The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology,
Wuhan 430081, China

ABSTRACT

Electromagnetic technology has been widely used in metallurgical process of high quality steel and alloy material. It can improve the cleanliness of molten steel, ensure the quality of steel and increase productivity. However, electromagnetic smelting seriously affects the high temperature corrosion behavior of molten slag, which not only reduces the service life of refractory materials, but also has a negative effect on the quality of molten steel. In the paper, a resistance furnace with controllable electromagnetic field was design and made, the high temperature thermal simulation experiment was performed, the slag properties such as viscosity and wettability were investigated under the conditions of high temperature and electromagnetic field, the influence of slag composition and ferromagnetic oxide were discussed. And the slag corrosion presumption on refractories was analyzed by means of the X-ray diffraction and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDX). The results show that, the spreadability, wettability and associated viscosity of the molten slag can be improved by introducing Fe_2O_3 in the static magnetic field; meanwhile, the magnetic field can promote the formation of the high melting point phase in the molten slag during the cooling process or temperature drop gradient of refractories and reduce the slag infiltration and corrosion of refractory materials.

Key words: Electromagnetic field; slag; viscosity; refractory; corrosion

INTRODUCTION

Electromagnetic fields are widely used in metallurgical processes, being an important tool for improving the quality of steel and for producing specialized steel[1]. In addition, the electrorheological and magnetorheological effects, which form the basis of an induced intelligent material field, are attracting increased attention worldwide[2]. These effects can influence high-temperature melt performance and its refractory interface.

Previously, Okazawa[3] and Wang[4] measured the viscosities of oxides and mold powders under the influence of an electric power supply, examining the viscosity changes under the resultant electric field. Their results showed that the viscosity decreases under the influence of a direct-current (DC) power supply. However, when the viscosity decreases to a certain value, it remains unchanged despite further changes to the DC supply. Further, when an alternating current (AC) power supply is used, the viscosity increases. In addition, Wang[5] has indicated that the viscosities of mold fluxes increase and the crystal sizes decrease significantly under a high-frequency electromagnetic field. Similarly, Zhang[6] has shown that increases in the electromagnetic field intensity cause the viscosity of slag to increase to a certain value. As regards the wettability, Christos[7] has performed wettability experiments under an electric field, reporting that the electric field can change the wettability between slag and magnesium oxide; promote electron transfer and exchange to promote the interface reaction; affect the generation and distribution of the high-temperature phase or low-melting phase; and accelerate magnesium oxide dissolution in the slag. Khoroshavin[8] theoretically discussed the impact of electronic technology on the performance of a refractory material, and predicted that the electromagnetic field would affect the movement of electrons in the redox reaction. Further, Potschke[9] has noted that an electric field affects the permeation behavior of slag, suggesting that an electric double layer forms between refractory materials and slag under high temperature, which affects the slag wettability on the refractory material. Finally, Aneziris[10] has experimentally examined the interface reaction of molten slag and magnesium-oxide refractory material under an electric field, confirming the influence of the electric field on the reaction between the refractory material and the steel slag interface. The results indicate that the wetting angle of the slag and refractory material increases with increased electric field intensity, with the penetration of refractory-material being reduced. In addition, the electric field alters the phase composition of the slag/refractory interface.

To summarize the above reports, it has been shown that an electromagnetic field has a significant influence on the properties of slag and on the slag/refractory interaction under high temperature. However, as research has focused on the influence of the electric field, the independent action of the magnetic field remains unknown. Therefore, in this study, wettability experiments are performed under a magnetic field and the interaction of molten slag and an alumina refractory under the influence of a constant magnetic field is explored. The resultant specimens are characterized using a scanning electron microscope (SEM; JEOL JMS - 6610) and EDS (EDS; Bruker QUANTAX200-30) combination, to explore the effect of the magnetic field independently.

EXPRIMENTAL

The industrial tools used to produce a static magnetic field can be roughly divided into three types: permanent magnets, electromagnets, and coils. The coil is the device most commonly used to create a magnetic field, as it has several advantages: 1) the coil is easy to process; 2) the magnetic field generated by the coil has a high degree of stability and good linearity; 3) a magnetic field with a specific distribution in space can by generated via a given coil configuration. Thus, a hollow solenoid coil was adopted in this experiment in order to create a static magnetic field using a DC power supply.

As shown in Fig. 1, 0.12-mm-thick enamel wire was used to wrap a hollow solenoid coil. The coil length was 160 mm; the internal diameter was 180 mm; the number of turns N was 725; and the entire coil resistance was 12.4 Ω.

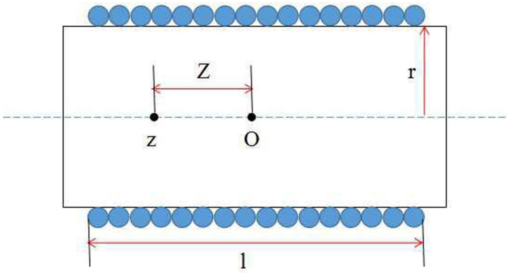

Figure 1. Schematic diagram of solenoid coil

The magnetic induction intensity of the hollow solenoid coil is expressed as Eq(1):

$$B_{z0}=\frac{1}{2}\mu_0 NI[\frac{\frac{1}{2}l+Z}{\sqrt{r^2+(\frac{1}{2}l+Z)^2}}+\frac{\frac{1}{2}l-Z}{\sqrt{r^2+(\frac{1}{2}l-Z)^2}}] \quad (1)$$

where μ_0 is the vacuum permeability ($\mu_0 = 4\pi \times 10^{-7}$ T·m/A); I is the current [A]; r is the solenoid radius [m]; Z is the distance from point z to point O on the solenoid center axis [m]; and l is the coil length [m].

For $Z = 0$, Eq(2) was obtained:

$$B_0=\frac{1}{2}\mu_0 NI\frac{l}{\sqrt{r^2+\frac{1}{4}l^2}} \quad (2)$$

The actual magnetic field intensity in the hollow solenoid coil (Z = 0) was measured via a Gauss meter. Only a small discrepancy was found between the measured and calculated values, as shown in Fig. 2The actual magnetic field intensity in the hollow solenoid coil (Z = 0) was measured via a Gauss meter. Only a small discrepancy was found between the measured and calculated values, as shown in Fig. 2.

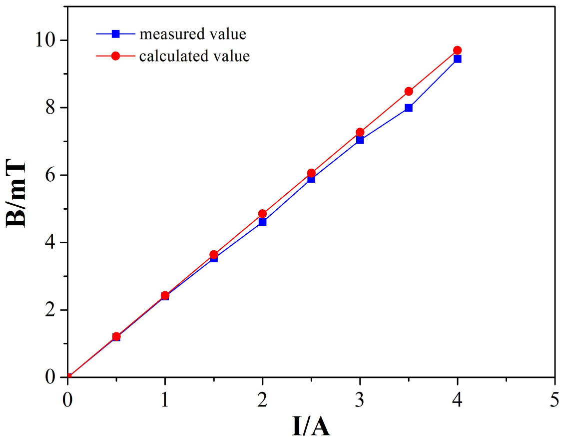

Figure 2. Measured magnetic induction intensity compared to calculated value

The slag was prepared via the following steps. The analytical reagents listed in Table 1 were mixed in a graphite crucible and then pre-melted in a resistance furnace at 1373 K for 3 h. Thereafter, the slag was removed from the furnace at 1373 K and quenched. After breaking and grinding, two kinds of slag powder (1 for S1 and 2 for S2) were obtained. Subsequently, the slag powder was pressed to yield $\Phi 3 \times 3$ mm^2 cylindrical specimens.

The experiment was conducted according to Fig. 3. A cylindrical slag specimen was placed on an alumina plate. To position the sample in the center of the coil (Z = 0), an alumina block was placed under the alumina plate. A relatively large current (4 A) was selected to yield a clear galvanomagnetic effect. To conduct wettability spreading experiments for the slag under the influence of a magnetic field, DC power was supplied when the furnace was in operation. The wettability spreading experiments were performed in a homemade electromagnetic furnace or an ordinary furnace at a temperature of 1373 K for 30 min. After natural cooling to room temperature, the slag spreading behaviors on the alumina in contact with S1 and S2 were compared. Then, the sample microstructures and compositions were characterized using SEM to allow independent investigation of the effect of the magnetic field.

Table 1. Slag composition and content

	SiO_2	CaO	Al_2O_3	Na_2O	Fe_2O_3	MgO	MnO_2	CaF_2
1	35	21	5	12	-	4	5	18
2	35	21	5	10	2	4	5	18

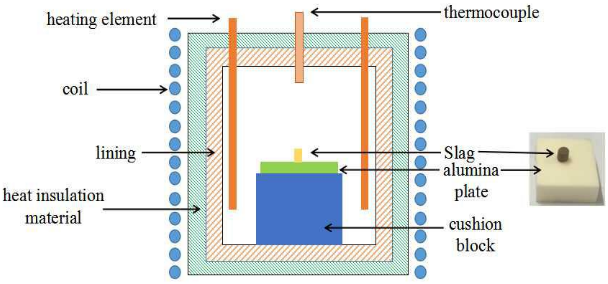

Figure 3. Schematic of experimental setup

RESULTS AND DISCUSSION

The samples were observed after the wettability spreading experiment. Figure 4 shows that the S1 specimens all spread on the alumina plate, for experimental conditions with and without the static magnetic field. In contrast, the S2 specimens spread on the alumina plate in the absence of the magnetic field, but did not disperse when the static magnetic field was applied.

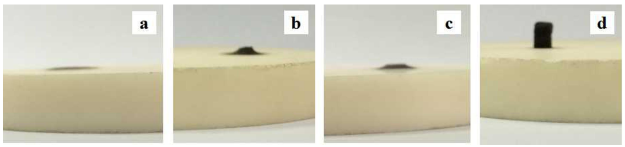

Fig.4 The samples after wetting spreading experiment (a)S1 without magnetic field(b)S1 in magnetic field

(c)S2 without magnetic field(d)S2 in magnetic field

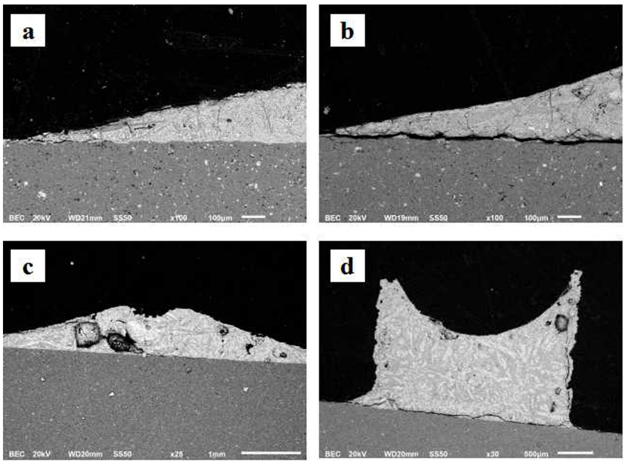

Fig.5 Microstructure of Slag after wetting spreading experiment
(a)S1 without magnetic field(b)S1 in magnetic field
(c)S2 without magnetic field(d)S2 in magnetic field

The slag sample microstructures were observed after the wettability spreading experiment using SEM. As shown in Fig. 5, the S1 specimens exhibited good wetting and spreading on the alumina plate both with and without the magnetic field. Further, there is no obvious difference in the contact angles between the slag and alumina plate for both cases. In addition, the S2 specimens exhibited good spreadability without the magnetic field; however, they were unable to disperse under the static magnetic field. Finally, the contact angle between the slag and alumina plate in the case with the magnetic field was slightly larger than that without the magnetic field.

The static magnetic field had no obvious effect on the spreading of the S1 specimen. For the S2 case, when ferromagnetic oxide (Fe_2O_3; i.e., paramagnetism) was added, the static magnetic field had a relatively large effect. On the one hand, the S2 may have exhibited a magnetorheological effect, which induced an increase in the slag viscosity under the constant magnetic field. The slag samples tended to exhibit a kind of semi-solid state and could not disperse on the alumina plate completely. On the other hand, the contact angle was increased between the S2 and alumina under the action of the static magnetic field. Both the slag viscosity and the contact angle have a significant effect on reducing the corrosion and penetration of the refractory material by the slag.

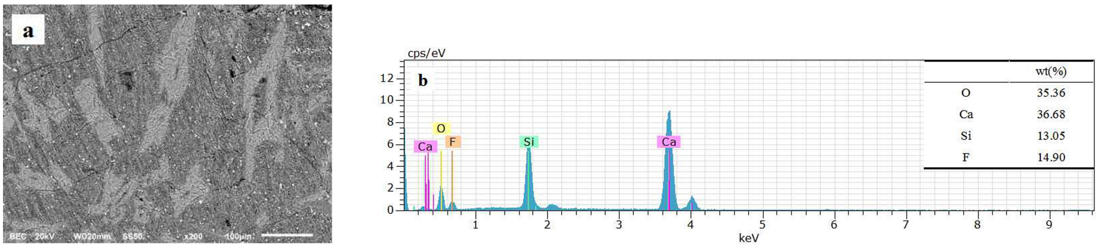

Figure 6. SEM and EDS results for S2 in magnetic fiel (a)SEM of S2 (b)EDS of the gray phase

As shown in Fig. 6, after heat treatment and natural cooling to room temperature, a large gray phase fraction was formed in the S2 specimens under the magnetic field. This phase was conformed to be cuspidine via EDS analysis. Note that almost no cuspidine formed in the S2 specimens in the absence of the magnetic field. This result shows that the static magnetic field promoted the precipitation of the cuspidine phase in the S2 specimens. The cuspidine melting point was 1644K. As the static magnetic field is beneficial to the precipitation of certain phases, the formation of a high-melting-point phase is expected under the influence of the static magnetic field and by favorably adjusting the slag composition. The formation of such a phase would protect the refractory material and reduce the penetration and corrosion of the refractory material by the slag.

CONCLUSION

(1) A static magnetic field has little effect on slag that does not contain ferromagnetic oxide (Fe_2O_3). However, addition of Fe_2O_3 to optimize the slag composition facilitates an increase in the slag viscosity. Further, the contact angle with the alumina refractory may be increased, and the degree of spread may decrease rapidly.

(2) In the cooling process or under a decreasing material-temperature gradient, a static magnetic field is advantageous for promoting the formation of a certain phase with a relatively high melting point within the slag; this phase can reduce the corrosion and penetration of the refractory material by the slag.

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