Effect of EAF Slag Temperature and Composition on its Electrical Conductivity

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(Received on July 16, 2018; accepted on October 17, 2018)

Slag practice is one of the most important factors in molten steel production. Physical and chemical properties of slag determine the efficiency of the production process. Slag electrical conductivity is the second effective parameter in slag practice after viscosity. During current study, effect of temperature, FeO, CaO, SiO₂ content and basicity ratio B2 on slag's electrical conductivity was studied experimentally. It was found that, electrical conductivity increases with increasing temperature, %FeO, %CaO and basicity B2. On the other hand electrical conductivity was decreased with increasing SiO₂ content. Specific conductance and electric conductivity index for slag main constituents were also estimated.

KEY WORDS: slag; slag practice; basicity; electrical conductivity.

1. Introduction

Slag plays a very important role in hot metal production and refining. The properties of slag have great effect on energy, refractory and electrode consumption as well as steel quality and material yield. Around 25% of worldwide crude steel is produced by using electric arc furnace. In electric steelmaking, the second highest cost after raw material is the energy. Silicates is the basis of electric arc furnace slags and their physical properties are very dependent on the silicate structure developed in the molten slag. The dependence of property on structure is in the hierarchy,¹⁾ viscosity (η) > electrical conductivity (κ) and thermal conductivity (k) > thermal expansion coefficient (α) > density (ρ) > surface tension (γ) > Cp and enthalpy. One of the main factors affect the performance of slag in electric arc furnace is its electrical conductivity (κ).¹⁾ In addition, electrical conductivity of slag plays an important role in the electrochemical reaction between metal and slag.²⁾

Electrical conductivity of materials is the ability to transfer electrical charges by positive or negative carriers (cations, anions) under the influence of an external electric field.³⁾ Electrical conductivity is dependent upon the number of ions available, it follows that the electrical conductivity of $\kappa\text{Na}_2\text{O}$ > κCaO . The electrical conductivity is also dependent upon the mobility of the cations; thus it would be expected that the conductivity would be greater for smaller cations; this is valid for Li, Na, and K ions, but the reverse trend can be seen with Ba, Ca, and Mg. This is probably due

to the effects of increased polarization with decreasing ionic radius that could also affect the cationic mobility.¹⁾

1.1. Factors Influencing Electrical Conductivity

The electrical conductivity involves the movement of cations under the influence of an applied field. In this case, the polymeric silicate network hinders the movement of the cations. Thus the factors affecting the electrical conductivity (κ) are:

1. Chemical composition, charge and size of the cations.¹⁾

The highest electrical conductivity has a slag rich in FeO and MnO – except of ion conductivity they also have electron conductivity. Electron conductivity of the slag can be explained by the presence in them of the metal cations in both valency 2 and 3 ($\text{Fe}^{3+} + e = \text{Fe}^{2+}$)³⁻⁵⁾ with Standard Potential $E^\circ = 0.77$ volt. The electric conductivity of the slags containing large amount of FeO, MnO, TiO₂ are usually very high, but the current efficiency and the ionic migration rate are lower.²⁾

2. The polymeric network (as represented by Q)^{1,6)}

$$Q = 4 - \left(\frac{NBO}{T} \right) \dots\dots\dots (1)$$

$$\left(\frac{NBO}{T} \right) = \frac{2(X\text{CaO} + X\text{Na}_2\text{O} + X\text{Al}_2\text{O}_3)}{(X\text{SiO}_2 + 2X\text{Al}_2\text{O}_3)} \dots\dots\dots (2)$$

Where Q is the degree of polymerization, NBO is the non-bridging O, T is the tetragonal O and X is the mole fraction.

3. Temperature, conductivity increases with increasing

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DOI: <https://doi.org/10.2355/isijinternational.ISIJINT-2018-507>

temperature due to gradually loosens of the structure that hinders the movement of cations by the silicate network.^{1,6)} The value of electrical conductivity decreases rapidly to one hundredth when slag solidifies.³⁾

Table 1 shows the electrical conductivity of some pure oxides in the liquid phase at the temperature just above melting point of each one.⁷⁾ The low conductance of SiO₂ is characteristic of network-forming compounds. FeO exhibits the highest conductance. The specific electrical conductivity measurement can provide us with basic information about depolymerization of molten slag and thus the mobility of ions as well as other features such as viscosity and solidification process.⁸⁾ So, electrical conductivity presents very significant information about the molten slag.

The objective of the current paper is to study the correlations of electrical conductivity of electric arc furnace slag to its chemical composition and temperature.

2. Experimental

In the current study, experimental work has been carried out at laboratories of EZZ steel factories located at Suez city, around 130 Km from Cairo. Electrical conductivity of CaO–SiO₂–FeO slag system has been studied in this paper. Al₂O₃ and MgO was kept within the technically preferred concentration throughout the study. Two-electrode alternative current impedance method was used. The experiments were carried out in the normal atmospheric air to simulate the actual industrial process.

2.1. Effect of Temperature on Slag Electrical Conductivity

Slag was heated up to 1 660°C in a zirconia boat by using laboratory resistance furnace. The sample was kept for 10 minutes inside the furnace for the slag to be melted completely. The sample size for each experiment was 15 g. By the end of 10 minutes time, the boat containing the completely melted slag sample was taken out and placed in another heated larger boat to reduce the cooling rate. The electrical conductivity of molten slag and temperature were measured from that temperature up to cooling. Also electrical conductivity of some trials was measured inside the furnace at lower temperatures. The circuit used to measure the conductivity is shown in **Fig. 1**.

2.2. Effect of Chemical Composition on Slag Electrical Conductivity

Number of slag samples was collected from EZZ Steel 185 tonne AC electric arc furnace with different FeO, CaO and SiO₂ concentration. From each one a series of samples

was modified. In each series all studied oxides was kept constant except one to be studied. Slag modification was done by using pure FeO, SiO₂ and CaO. First series was modified to have different concentration of FeO while other constituents kept constant. Second series was modified to have different concentration of CaO while other constituents kept constant. Third series was modified to have different concentration of SiO₂ while other constituents kept constant. The results of two CaO and SiO₂ series were used to study the effect of basicity B₂. Slag basicity B₂ is the ratio of %CaO/%SiO₂.

3. Results and Discussion

3.1. Effect of Temperature on Slag Electrical Conductivity

One industrial slag sample selected to be used for determination of electrical conductivity at different temperatures. Chemical composition of used sample is shown in **Table 2**. The logarithmic values of measured electrical conductivity against temperature are shown in **Fig. 2**. It was found that,

Fig. 1. Electric circuit used for measuring slag electrical conductivity.

Table 2. Chemical composition of slag sample used for temperature study.

%CaO	%SiO ₂	%FeO	%MgO	%Al ₂ O ₃	%MnO
35.3	18.1	25	8.8	5.38	1.58

Fig. 2. Relation between slag electrical conductivity and temperature.

Table 1. Electrical conductivity of pure oxides.

Oxide	T°C	κ , 1/ohm-cm
SiO ₂	1 710	10 ⁻⁵
Al ₂ O ₃	2 050	15
CaO	2 580	40
FeO	1 370	122
MgO	2 800	35

electrical conductivity increases exponentially as the temperature increases. The rate was very low at temperature less than 1 200°C as shown in Fig. 2. Then it increases at very high rate after 1 400°C which is nearly the melting point of FeO, the principle fluxing oxide. This can be explained by the looseness of the silicate structure and increase of ion mobility with temperature. The tested slag sample was completely nonconductive below 135°C. The obtained results are matched with the data reported by Jixiang *et al.*⁵⁾ The maximum applied temperature was 1 600°C which is less than the liquidus temperature of investigated slag as shown in Figs. 3 and 4. During investigating the system, sum of %CaO and %MgO taken as CaO since they have nearly the same behavior while Al₂O₃ was ignored since it is relatively low concentration. At that temperature the liquidus composition was liquid, 2CaO–SiO₂ and 3CaO–SiO₂.^{9,11)} As the temperature decreases the percentage of solid phase particles increased till reaching to all solid at around 1 480°C. Accordingly, during the current study all the measurements

were carried out for a molten slag which contains a liquid phase coexisted with another solid phase.

3.2. Effect of FeO Content on Slag Electrical Conductivity

One industrial slag sample containing lower FeO content was selected to determine the effect of FeO content on its electrical conductivity. Chemistry of selected sample is depicted in Table 3. The electrical conductivity of the selected sample and the modified samples prepared from it to get higher FeO content is shown in Fig. 5. It was found that, the electrical conductivity increases at high rate as the FeO increases. The electrical conductivity increased five times when the concentration of FeO was duplicated. FeO has the lowest melting point among slag constituents; accordingly its effect on electrical conductivity is very deep. Also FeO exhibit both ionic and electronic conductivity. This can be proved by the XRD pattern, Fig. 6, for one of the tested samples which shows presence of both Fe³⁺ and Fe²⁺. The obtained results are matched with the results obtained by Lijun Wang for the same FeO content and basicity.¹⁰⁾ At the working temperature of 1 600 °C and 20% FeO, the liquidus composition was liquid, 2CaO–SiO₂ and 3CaO–SiO₂.^{9,11)} As the %FeO increases the solid particles decreased till 38%FeO which is the maximum investigated concentration.

3.3. Effect of SiO₂ Content on Slag Electrical Conductivity

One industrial slag sample containing lower SiO₂ was selected to determine the effect of silica content on its electrical conductivity. Chemistry of selected sample is depicted in Table 4. Electrical conductivity of the selected sample and the modified samples prepared from it to get higher SiO₂ content is shown in Fig. 7. The highest conduction was registered at lowest SiO₂ content then the conductivity decreased as the SiO₂ increased. Increasing SiO₂ enhances the silicate network that hinders the movement of ions and reduces the electrical conductivity. Also increasing SiO₂ content increases the viscosity and accordingly reduces the conductivity. At the working temperature of 1 600 °C and 13.7% SiO₂, the liquidus composition was liquid, 2CaO–SiO₂ and 3CaO–SiO₂.^{9,11)} As the % SiO₂ increases the solid

Fig. 3. Phase relation in the system CaO–SiO₂–FeO in contact with metallic iron.

Fig. 4. The 1 600°C isothermal section through the system CaO–SiO₂–FeO.

Table 3. Chemical composition of slag sample used for FeO study.

%CaO	%SiO ₂	%FeO	%MgO	%Al ₂ O ₃	%MnO
40	19.7	20	5.7	6.7	1.8

Fig. 5. Relation between slag electrical conductivity and FeO content at 1 600°C.

Fig. 6. EAF slag X-ray diffraction pattern. (Online version in color.)

 Table 4. Chemical composition of slag sample used for SiO₂ study.

%CaO	%SiO ₂	%FeO	%MgO	%Al ₂ O ₃	%MnO
33.1	13.7	38.1	6.91	5.5	0.9

Table 5. Chemical composition of slag sample used for CaO study.

%CaO	%SiO ₂	%FeO	%MgO	%Al ₂ O ₃	%MnO
30	15	30.4	7.7	6.1	1.2

 Fig. 7. Relation between slag electrical conductivity and SiO₂ content at 1 600°C.

Fig. 8. Relation between slag electrical conductivity and CaO content at 1 600°C.

particles increased.

3.4. Effect of CaO Content on Slag Electrical Conductivity

One industrial slag sample containing lower CaO was selected to determine the effect of CaO content on its electrical conductivity. Chemistry of selected sample is depicted in Table 5. The electrical conductivity of the selected sample and the modified samples prepared from it to get higher CaO content is shown in Fig. 8. Electrical conductivity was low at lower CaO and increased as the concentration of CaO increased. CaO break the silicate network, reduce the slag viscosity, increase the ion mobility and accordingly increase the electrical conductivity. At the working temperature of 1 600 °C and 30% CaO, the liquidus composition was liquid, 2CaO–SiO₂ and 3CaO–SiO₂.⁹⁾ As the % CaO increases the solid particles increased.

3.5. Effect of Basicity B₂ on Slag Electrical Conductivity

The electrical conductivity results of selected and modified samples for CaO and SiO₂ were used to study the effect

of basicity B₂. It was found that electrical conductivity increases with increasing basicity. This can be explained by breaking of the silicate network that hinders the movement of cations and also reducing the slag viscosity as per Eq. (3). The obtained results are depicted in Fig. 9.

It was reported that, slag electrical conductivity is a function of optical basicity.¹¹⁾ Wanli *et al.*¹²⁾ studied the electrical conductivity of CaO–SiO₂–Al₂O₃–MgO system as well as the viscosity and found the relation:

$$\ln \eta = -0.041 - 1.14 \ln \kappa \dots \dots \dots (4)$$

So, there is a direct relation between slag electrical conductivity with its viscosity and degree of polymerization. Although Eq. (4) is applied for a slag system that is different from investigated one but both contain CaO and SiO₂ which is the main constituents affecting viscosity and degree of polymerization.

Sensitivity of slag electrical conductivity per percent of

Fig. 9. Relation between slag electrical conductivity and basicity at 1600°C.

constituent was calculated from the obtained results. It was found that, when FeO increased from 20 to 25%, a range of 5%, the conductivity increased 80 units. Also, when CaO increased from 30 to 35%, a range of 5%, the conductivity increased 300 units. On the other hand, when SiO₂ increased from 15 to 20%, a range of 5%, the conductivity decreased 150 units. Although FeO has lowest melting point and the highest conductivity, Table 1, and also it undergoes both ionic and electronic conductivity, the sensitivity of CaO and SiO₂ is larger. Most likely this because the effect of CaO and SiO₂ on existence of silicate network and its great effect on viscosity. Average conductivity index per percent of each slag main constituent was calculated. It was calculated by dividing the total change in conductivity by the total change in concentration for each constituent. Conductivity index for CaO at 1600°C was estimated and found +60 S/m per each 1% increase in CaO. Also, Conductivity index for FeO at 1600°C was estimated and found +16 S/m per each 1% increase in FeO. On the other hand, Conductivity index for SiO₂ at 1600°C was found -30 S/m per each 1% increase in SiO₂.

4. Conclusion and Recommendations

The effect of Temperature, FeO, SiO₂, CaO and basicity of slag on its electrical conductivity was investigated. The following conclusions can be drawn:

- As the temperature increases, the slag electrical con-

ductivity increases.

- As the FeO and/or CaO content increase, the slag electrical conductivity increases.
- As the SiO₂ content increases, the slag electrical conductivity decreases.
- As the basicity B₂ increases, the slag electrical conductivity increases.

Accordingly and to bring slag to the optimum electrical conductivity, it is recommended to keep the basicity higher than 2, it is level that guarantee the breaking of the entire silicate network. Also it is recommended to keep the FeO content at a level high enough but not to the limit of reaching the watery slag.

Acknowledgment

The authors are deeply grateful to EZZ FLAT STEEL Company for supporting this study and also to Eng. Ahmed Ali and his team for their help in facilities setting up.

REFERENCES

- 1) K. C. Mills, L. Yuan and R. T. Jones: *J. South. Afr. Inst. Min. Metall.*, **111** (2011), 649.
- 2) J. Jia, X. Liao, D. Li, C. Ni, G. Zhao and D. Cao: Proc. 9th Int. Conf. on Molten Slags, Fluxes and Salts, Tsinghu Knowledge Network Technology, Beijing, (2012), 64.
- 3) A. Sorek, P. P. Ostrowska and M. Niesler: *Arch. Mater. Sci. Eng.*, **57** (2012), Issue 2, 53.
- 4) L. Mongalo, A. S. Lopis and G. A. Venter: *J. Non-Cryst. Solids*, **452** (2016), 194.
- 5) R. J. Hundermark, S. Jahanshahi and S. Sun: 22nd Int. Mineral Processing Cong., South African Institute of Mining & Metallurgy, Marshallton, (2003), 1370.
- 6) K. C. Mills, L. Yuan, Z. Li, K. Chou and G. Zhang: Proc. 9th Int. Conf. on Molten Slags, Fluxes and Salts, Tsinghu Knowledge Network Technology, Beijing, (2012), 301.
- 7) Q. Jiao and N. J. Themelis: *Metall. Trans. B*, **19** (1988), 133.
- 8) Y. U. Han and D. J. Min: Advances in Molten Slags, Fluxes, and Salts: Proc. 10th Int. Conf. on Molten Slags, Fluxes and Salts (MOLTEN16), Wiley-TMS, Hoboken, NJ/Warrendale, PA, (2016), 501.
- 9) H. C. Chuang, W. S. Hwang and S. H. Liu: *Mater. Trans.*, **50** (2009), No. 6, 1448.
- 10) L. Wang: *Steel Res. Int.*, **80** (2009), 680.
- 11) Slag Atlas, 2nd ed., ed. by VDEh, Verlag Staheisen, Düsseldorf, (1995), 17.
- 12) W. Li, X. Cao, T. Jiang, H. Yang and X. Xue: *ISIJ Int.*, **56** (2016), 205.