Methodological investigation of a four electrode electrical conductivity set-up in a binary SiO₂-PbO system

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Abstract

In order to meet current and future demands of precious metals, improvements are needed to further increase metal yields for the existing extractive and recycling metallurgical processes. One major challenge in the pyrometallurgical copper production is the amount of metal that is lost in the slag. Slag cleaning can be executed in electrical resistance furnaces where heat is produced using the Joule effect, making the slag's electrical conductivity an important parameter. In order to study this parameter, an experimental set-up was built using a four electrode configuration via Pt wires which are connected to a potentiostat, while the immersion depth of the electrodes is controlled via a linear unit. Several experiments with slags from a binary PbO-SiO₂ slag system were used to validate the setup. The current set-up produced results below the usually quoted experimental error of at most 10% while also showing agreement with conductivity values and activation energies of other authors investigating similar compositions. Moreover, the impedance spectra of our high temperature measurements also agree well with those found in literature.

1 Introduction

As a result of the globally increasing consumer use of electronic devices and transition towards a zero-carbon society, it is expected that pressure will keep on increasing on the supply chain of precious metals such as copper, silver, gold and platina group metals (PGM's) (Sarkis, 2019). These metals are currently produced either from primary resources (mined ores) or secondary resources (e-scrap). For both starting materials, one of the initial steps involves the separation of the precious metals from impurities at high temperatures. The products of this pyrometallurgical step are (impure) molten metal, a slag phase containing the impurities as oxides and gasses (Schlesinger et al., 2011).

However, this phase separation of metal and slag is typically incomplete and metals still end up in the slag either as oxides (chemical) or as entrained droplets (mechanical) (Bellemans et al., 2018). Hence, additional slag cleaning processes are needed to maximize metal recovery. The most commonly used furnace for such slag cleaning operations is the submerged arc furnace (SAF) (Friedrich et al., 2018). These furnaces can be used to reduce metals chemically trapped in the slag as well as allowing droplets to settle. For this furnace type, a set of electrodes is submerged into the slag through which a certain current I flows. This electric energy will be converted to heat as a result of the slag's resistance according to Joule's law as given in Equation (1). In this equation, Q represents the heat (J), I the current (A), R the resistance of the slag (Ω) and t the time (s). The slag's resistance R is in turn a function of the slag's electrical conductivity σ (S/cm) as well as the geometry, as described by Equation (2). This geometry depends amongst others on the furnace geometry and the electrode positioning within, which is described by the cell constant G (cm⁻¹).

$$Q = I^2 R t \tag{1}$$

$$R = \frac{G}{\sigma}$$
(2)

Therefore, considering the working principle of a SAF, the electrical conductivity of the slag is an important parameter. Unfortunately, conductivity data for secondary copper smelter slags are scarce and in addition significant deviations between studies investigating the same composition are reported (Thibodeau & Jung, 2016). As a first step for carrying out future conductivity experiments, a four electrode conductivity setup was constructed and validated with a binary SiO₂-PbO system. This system was chosen as it has been the subject of multiple studies (Ashizuka & Ohtani, 1969; Bockris & Mellors, 1956; Ejima et al., 1968; Ito & Yanagase, 1960; SAITO H et al., 1969; Schellinger & Olsen, 1949). These experiments were, however, carried out in two-electrode configurations which show some disadvantages over four electrode configurations as elaborated in Section 2.2. As such, specific attention is drawn to whether our setup and methodology results in comparable conductivity values with literature as well as to experimental reproducibility.

2 Measuring electrical conductivity of slags

2.1 General principles

Before explaining the designed experimental set-up, it is necessary to look at the basic principles of how the electrical conductivity of slags is measured and which set-ups are available. First of all, the electrical conductivity is a measure for the ability of a material to conduct an electrical charge. Unfortunately, this material parameter cannot be measured directly and needs to be derived from the resistance. Rewriting equation (2), one obtains the following expression for the electrical conductivity (Fried et al., 2001).

$$\sigma = \frac{G}{R} = \frac{l}{A} \frac{1}{R}$$
(3)

In Equation (3), I is the length of the current path (cm) and A is the cross-sectional area of the current path (cm²). The cell constant G is then defined as I/A. For solid materials, the dimensions of the current path typically coincide with the material's geometry and hence the cell constant is well-defined. However, for liquids, electrodes need to be submerged in the liquid and thus the current can travel throughout the whole volume of the liquid. This makes the current path between these electrodes ill-defined and hence, a calibration procedure is typically required. During a calibration, the resistance of a solution with a well-known conductivity is measured from which the cell constant of the set-up can be calculated. This calibration is typically done at room temperature with aqueous KCl solutions (Barati & Coley, 2006). During calibration, the temperature needs to be measured as well to take into account the Arrhenian temperature dependency of the conductivity which is defined according to Equation (4) in which A is the pre-exponential factor (S/cm), E_a the activation energy (kJ/mol), R the universal gas constant (J/mol.K) and T the temperature (K).

$$\sigma(T) = A. \exp\left(\frac{-E_a}{RT}\right) \tag{4}$$

Note that the cell constant is also dependent on the immersion depth of the electrodes within the liquid as this will increase the area A via which the current can flow. Therefore, both the calibration and the high temperature experiment needs to be carried out at the same immersion depth. In addition, the calibration procedure is only accurate when the current path is invariant with respect to the investigated liquid, the electrode configuration and the electrodes (Schiefelbein et al., 1998). A short overview of the different types of set-ups will be provided in subsection 2.2.

Furthermore, a slag is an ionic liquid. Therefore, the conduction mechanism involves the movement of ions within the slag as charge carriers. Hence direct current (DC) measurements are impossible since the moving ions will become stationary after a certain amount of time due to polarization at the electrodes (Fried et al., 2001). Thus an alternating current needs to be applied. As a result, an impedance Z (Ω) will be measured which will contain a real part Z_{real} and an imaginary part Z_{imag}, as illustrated in Equation (5) with j being the imaginary unit. Moreover, this impedance will be a function of the applied frequency f (Hz).

$$Z(f) = Z_{real}(f) + jZ_{imag}(f)$$
(5)

In order to obtain the resistance, which is a measure for the resistance against ionic movement, it is necessary to isolate the real part from other contributing factors such as electrode polarization. This electrode polarization is typically represented by a capacitance and hence contributes to the imaginary part of the impedance (Simonnet et al., 2003). Pragmatically, a frequency sweep can be carried out revealing the frequency f⁰ for which

the imaginary impedance equals 0. In addition, a certain range of frequencies f* may exist for which $Z_{real}(f^*) = Z_{real}(f^0)$ (Barati & Coley, 2006; Bockris & Mellors, 1956; Hundermark, 2003). As such, a single frequency impedance measurement can be carried out at any frequency within this range. The electrical conductivity σ is subsequently derived from the measured real impedance Z_{real} according to equation (3) using the cell constant G from the calibration.

2.2 Measurement set-ups

In order to carry out electrical conductivity measurements on a liquid, a set-up needs at least two electrodes immersed in the liquid to apply a current I and measure the voltage V to calculate the impedance Z. The most commonly used set-ups are depicted in Figure 1 (Schiefelbein et al., 1998). The most basic set-up is a two electrode set-up (Figure 1 a) in which two electrodes are immersed into the liquid. Within this set-up, the current path spreads out from the electrodes radially into all directions. Due to this complex current pattern, the calibration procedure introduces some errors. For the central electrode technique (Figure 1 b), the crucible is made from a conductive material and thus functions as the second electrode. For this set-up, the current path is also complex and, in addition, the large electrode area results in a small cell constant and thus low impedances which may introduce a larger error for highly conductive samples (Hundermark, 2003). The ring electrode technique (Figure 1 c) does have a clearly defined current path between the central rod and the cylindrical electrode. Unfortunately, fringe currents underneath and above the cylinder are still present which cannot be determined and thus this technique also suffers from a lower accuracy (Schiefelbein et al., 1998). Furthermore, the previous three techniques also measure the current and voltage difference via the same electrodes, thus consequently, a correction for the wire resistance is needed (Pommier et al., 2010). Note that the wire resistance is also temperature dependent. In order to circumvent this wire resistance correction, a four electrode configuration (Figure 1d) can be employed. This is because the current carrying and voltage sensing electrodes are separated as the outer electrodes provide the current while the inner electrodes measure the resulting voltage. Even so, this type of configuration still has a complex current path requiring calibration to determine the cell constant. For these so-called low accuracy techniques, experimental errors up to 10% are typically reported (Thibodeau & Jung, 2016). To avoid inaccuracies due to unconfined current paths within the calibration, some calibration free techniques have been developed. These set-ups involve the use of a coaxial cylinder technique (Schiefelbein et al., 1998) or of a measurement cell for which the current path can be defined using nonconductive parts to block uncontrolled spreading (Zhang et al., 2021). Unfortunately, the first technique is not usable for liquids with a conductivity above 0.1 S/cm (Fried, 1996), while the second requires post processing of the quenched sample geometry to determine

the cell constant. As a result of this post processing, a new crucible is needed for each experiment.



Figure 1 Overview of different configurations for electrical conductivity measurements. a) two electrode, b) central electrode, c) ring electrode and d) four electrode. Adapted from (Zhang et al., 2021)

A final consideration that has to be made is the crucible material. Commonly, a choice is made between metallic and oxidic crucibles. Metallic crucibles have the advantage that they can be made from inert materials such as Pt or Au, but as they are conductive, they may influence the measurement (Simonnet et al., 2003). On the other hand, oxidic crucibles are non-conductive but they may dissolve in the slag which alters the chemical composition of the slag and will also affect the measurement. Thus ideally, a slow/non-dissolving oxidic crucible should be chosen for a certain slag composition to prevent errors due to the crucible material. Unfortunately, this ideal situation is seldom an option.

3 Materials and methods

3.1 Electrical conductivity set-up

A schematic representation of the electrical conductivity measurement set-up is given in Figure 2. The set-up is constructed around a vertically mounted MTF 12/38/250 Carbolite resistance tube furnace with a length of 300 mm. A four electrode conductivity set-up is chosen as it circumvents the need for cable corrections associated with two electrode configurations as well as eliminating extensive measurement procedures related with calibration free methods. The electrodes are made of 450 mm long and 1 mm thick Pt wires which are inserted into alumina twin tubes. A schematic representation of the wire

geometry is also provided in Figure 2. In this figure, d_o is defined as the distance between the centres of both holes and was measured to be around 1 mm, while d_i is the distance between the central electrodes was equal to 5 mm. It was found that a small gap between the electrodes and twin tube holes is sufficient to keep the wires fixed at their position during measurements. Additionally, it provides a tolerance to still move the wires deeper into the tubes if the tips need to be replaced as a result of excessive bending or damage. The Pt wires are connected via extension wires to a Gamry Interface 1010E potentiostat which measures the slag's impedance. The immersion depth (h) of the electrodes in the slag bath is controlled via an EAS4X linear unit provided by Oriental Motor with a minimal step size of 0.01 mm. The crucible itself is positioned at a depth of 150 mm within the furnace on a ceramic insulation plug. A hole is made in this plug to allow a type K thermocouple to be inserted underneath the crucible to record the temperature.



Figure 2 Schematic overview of the constructed set-up and closeup of the crucible

3.2 Methodology

A binary PbO-SiO₂ slag system with a PbO/SiO₂ weight ratio of 85/15 was desired because this composition was investigated by several authors using either a two electrode setup (Ashizuka & Ohtani, 1969; Bockris & Mellors, 1956; SAITO H et al., 1969; Schellinger & Olsen, 1949) or a ring electrode setup (Ejima et al., 1968; Ito & Yanagase, 1960). Even though different setups are used, comparing the conductivity values from our setup with literature data should already provide a first indication whether the current setup can provide reliable results. The slag was prepared from high purity (> 99.9 pct) powder chemicals (PbO, SiO₂) provided by Sigma Aldrich. The powders were first premelted in a high-frequency induction furnace (Hüttinger TIG 20/ 100) at 800 °C in an Al₂O₃ crucible. To minimize dissolution of Al₂O₃ into the slag, the holding time at high temperature was limited to 30 minutes after which the slag was quenched in water. During this time, air was blown (24 l_n/h) through the slag bath to ensure sufficient mixing. Several quenched pieces were then cold embedded using Epofix resin and were then ground and polished up to a 1 µm abrasive particle size. The slag composition was then analyzed via a scanning-electron microscope (SEM, JEOL, JSM-7600, FEG-SEM) which is equipped with an energy-dispersive X-ray spectroscopy detector (EDS, Oxford Instruments, x - Maxⁿ Silicon Drift Detector). The used acceleration voltage during these measurements was 15 kV. To prevent charges building up on the sample, it was first carbon coated using physical vapor deposition. Conductivity experiments were carried out in chemically inert gold а crucible. It was found that metallic crucibles were most commonly used for the binary system under consideration (Ashizuka & Ohtani, 1969; Bockris & Mellors, 1956; Ejima et al., 1968; Ito & Yanagase, 1960; SAITO H et al., 1969) and thus a metallic crucible was chosen for comparison with literature. The gold crucible was made from 0.2 mm thick foil and folded into a beam shaped crucible with a ground plane of dimensions between 20 mm x 20 mm and 25 mm x 25 mm. The crucible had to be refined and remade between both experiments leading to a variation in dimensions. For the experiments, a slag bath of 10 mm and an immersion depth for the electrodes of 3 mm was desired. This shallow cell set-up was also used for conductivity measurements by Barati and Coley (Barati & Coley, 2006) and Hundermark (Hundermark, 2003).

The set-up was calibrated using standard 1 and 0.1 D KCl solutions at room temperature. During calibration, the temperature was recorded to take into account the temperature dependency of the conductivity. From preliminary experiments, it was found that the cell constant was rather sensitive to the reconstruction of the set-up after an experiment. Differences of 5 - 7% in the cell constant for the different experiments were observed and thus it was decided that a calibration is necessary before each high temperature experiment. Measurements were made galvanostatically with an applied current amplitude of 100 µA. Before measurements were carried out at a single frequency, a frequency sweep between 1 Hz and 500 kHz was carried out to determine a frequency region where the real impedance was constant. This region was found to be quite narrow around 100 kHz and thus a single frequency impedance measurement was carried out at 100 kHz for the calibration.

For the high temperature experiments, the mass of slag necessary to obtain a bath height of 10 mm was calculated via the slag's density. For a PbO/SiO₂ ratio of 85/15, a density of 6.2 g/cm^3 was found in literature (Cnockaert et al., 2021). After inserting the slag into the gold crucible, the furnace was heated to 800, then 850 and finally 900 °C at a heating rate of 5 °C/min. Once the initial temperature of 800°C was reached, the slag was kept at this temperature for one hour to ensure a fully molten bath. The electrodes were then inserted at an immersion depth of 3 mm through a slow descent of the electrodes with the linear unit. The slag surface could be located due to a sudden drop in the impedance and less fluctuating values as opposed to readings in air. For the high temperature measurements, a frequency sweep was also carried out between frequencies of 0.1 Hz to 500 kHz. It was found that the real impedance was independent of the frequency between 10 and 100 kHz. As such, single frequency impedance measurements were carried out at frequencies of 10, 50 and 100 kHz. The impedance measurement procedure was then repeated at 850 and 900 °C but the residence time before the actual measurement was reduced to 40 minutes. After the final measurement, the electrodes are lifted, the top plug is removed which allows the crucible to be pushed upwards. It is then grasped with stainless steel pliers to allow water quenching . The electrodes and crucible were then cleaned in a 37% HCl solution at 80 °C to remove any remaining slag. The high temperature experiment was carried out twice allowing to estimate the reproducibility of the conductivity set-up.

4 Results

The determined cell constants for the first and second experiment are provided in Table 1. For both calibrations, a slight difference in the cell constant for different calibration fluids was observed which is related to the current path being dependent on the used solution as mentioned earlier (section 2.2). However, between both experimental runs, a significant difference between both average cell constants was observed as well. This difference could be explained via a difference in geometry between both runs as the crucible had to be remade after the first run which resulted in a crucible with a larger ground surface for the second run. Hence, the distance between the electrodes and the crucible walls became larger, explaining the increase in cell constant.

	G _{1 D KC} (cm ⁻¹)	G _{0.1 D KCI} (cm ⁻¹)	Gaverage (cm ⁻¹)
1 st calibration	0.497	0.481	0.489
2 nd calibration	0.546	0.544	0.545

Table 1 Cell constant G for the different experimental runs

From SEM-EDX measurements, the composition (in wt% \pm standard deviation) of the slag was determined as 85.4% \pm 0.1%, PbO, 14.10% \pm 0.09% SiO₂ and 0.53% \pm 0.07% Al₂O₃. The presence of a small amount of alumina was attributed to the initial slag preparation in the induction furnace. The measured electrical conductivity as a function of temperature is plotted in Figure 3 a) along with the data from literature for compositions near 85 wt% PbO. It was found that the conductivity did not deviate significantly between the measured frequencies thus the average value of frequencies 10, 50 and 100 kHz is shown. In addition, the Arrhenian activation energy is provided in Figure 3 b). Figure 3 a) shows reasonable agreement between our data and those from other studies with the closest match being

the data of Ashizuka et al. (Ashizuka & Ohtani, 1969). The calculated activation energy of both experiments also lies within the range of 60 – 90 kJ/mol as found in literature. This also confirms that the four electrode set-up is able to predict the temperature dependency well. Comparison between both runs shows good agreement between the values at 800 and 850 °C for which a deviation of 4.33 and 2.77%, respectively was observed, which agrees with the usually quoted experimental error below 10% (Thibodeau & Jung, 2016). Only at 900 °C, the deviation between both runs was slightly higher at 13.02%.. Given the large difference in cell constant after calibration between both runs, it is evident that calibration before each new measurement is required to obtain accurate and reproducible results.



Figure 3 a) Conductivity values of the present experiments (blue) and values obtained from literature (black) and b) calculated activation energy

Finally, the impedance spectrum of the high temperature frequency sweeps are shown as a Nyquist plot in Figure 4. In addition, the average values of the real and imaginary impedance at 10, 50 and 100 kHz for each temperature are plotted as well. The impedance values of the single frequencies agree well with those from the initial sweep, indicating that the measurement is stable over the measurement time. In addition, the real impedance of each single frequency measurement lies in the zone where $Z_{real}(f) = Z_{real}(f^0)$ with f^0 being the frequency for which the imaginary impedance Z_{imag} equals 0. Nyquist plots were also made by Sun et al (2011) for SiO₂-Al₂O₃-CaO-MgO-FeO/NiO slags using a two-electrode configuration (Sun & Guo, 2011). They recorded the impedance between frequencies of 100 kHz and 10 Hz. Their Nyquist plots also show a constant Z_{real} for frequencies up to f^0 . For frequencies below f^0 , they also report a curving of the Nyquist plot to the right, similar to our findings. However, the emergence of a region for which - Z_{imag} is a constant was not reported by Sun et al. It does give the impression, however, that this region coincides with frequencies below 10 Hz. This correspondence in Nyquist plots further confirms the validity of our set-up and methodology.



Figure 4 Nyquist plot of the high temperature experiments along with the average real and imaginary impedance of the single frequency measurements at 10, 50 and 100 kHz

5 Conclusion

To reduce metal losses in slags, an additional slag cleaning operation via a submerged electrical arc furnace can be utilized. For the furnace operation, the slag's electrical conductivity is an important parameter. Unfortunately, slag conductivity data is scarce. A schematic overview of the designed set-up and measurement procedure were discussed indicating that a four electrode configuration seemed optimal, as it leads to faster measurements compared to the calibration free methods while also negating the need for cable correction associated with set-ups that require calibration. Hence, an experimental set-up was built using four Pt wires as electrodes connected to a potentiostat, while controlling the immersion depth via a linear unit. The set-up was validated via a binary SiO₂-PbO slag system in an inert Au crucible. It was found that the conductivity, the activation energy and the impedance spectra were similar to literature data. In addition, the reproducibility of our measurements was also below the usual experimental error of 10%, except for the slightly higher value found at 900 °C.

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References

- Ashizuka, M., & Ohtani, M. (1969). The Measurement of the Electrical Conductivity of Silicate Melts Containing PbO and Na2O. *Journal of the Japan Institute of MetalsJournal of the Japan Institute of Metals and Materials*, *33*(4), 498–503. https://doi.org/10.2320/jinstmet1952.33.4_498
- Barati, M., & Coley, K. S. (2006). Electrical and electronic conductivity of CaO-SiO2-FeO x slags at various oxygen potentials: Part I. Experimental results. In *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science* (Vol. 37, Issue 1). https://doi.org/10.1007/s11663-006-0084-x
- Bellemans, I., De Wilde, E., Moelans, N., & Verbeken, K. (2018). Metal losses in pyrometallurgical operations - A review. Advances in Colloid and Interface Science, 255, 47–63. https://doi.org/10.1016/j.cis.2017.08.001
- Bockris, J. O., & Mellors, G. W. (1956). Electric Transport in Liquid Lead Silicates and Borates. *The Journal of Physical Chemistry*, *60*(9), 1321–1328. https://doi.org/10.1021/j150543a040
- Cnockaert, V., Bellemans, I., Crivits, T., Vrielinck, H., Blanpain, B., & Verbeken, K. (2021). Determination of the Fe3+/ Σ Fe Ratio in Synthetic Lead Silicate Slags Using X-Band CW-EPR. *Journal of Sustainable Metallurgy*, 7(2), 519–536. https://doi.org/10.1007/s40831-021-00348-0
- Ejima, T., Watanabe, Y., & Kameda, M. (1968). Electric Conductance in the Liquid PbO-SiO2 Binary System (Electric Conductance in Liquid Lead Silicates(I)). *Journal of the Japan Institute of MetalsJournal of the Japan Institute of Metals and Materials*, *32*(12), 1250–1256. https://doi.org/10.2320/jinstmet1952.32.12_1250
- Fried, N. (1996). *Electrical properties of binary solutions of molten titanium dioxide-barium oxide*. https://dspace.mit.edu/handle/1721.1/10600
- Fried, N. A., Rhoads, K. G., & Sadoway, D. R. (2001). Transference number measurements of TiO2-BaO melts by stepped-potential chronoamperometry. *Electrochimica Acta*, 46(22), 3351– 3358. https://doi.org/10.1016/S0013-4686(01)00531-X
- Friedrich, B., Kalisch, M., Friedmann, D., Degel, R., Kaußen, F., & Böhlke, J. (2018). The Submerged Arc Furnace (SAF): State-of-the-Art Metal Recovery from Nonferrous Slags. *Journal of Sustainable Metallurgy*, 4(1), 77–94. https://doi.org/10.1007/s40831-017-0153-1
- Hundermark, R. (2003). *The electrical conductivity of melter type slags*. University of Cape Town. http://hdl.handle.net/11427/5316
- Ito, H., & Yanagase, T. (1960). Studies on Lead Silicate Melts. *Transactions of the Japan Institute of Metals*, 1(2), 115–120. https://doi.org/10.2320/matertrans1960.1.115

- Pommier, A., GAillArd, F., Malki, M., & PichAvAnt, M. (2010). Methodological re-evaluation of the electrical conductivity of silicate melts. *American Mineralogist*, *95*(2–3), 284–291. https://doi.org/10.2138/am.2010.3314
- SAITO H, GOTO K, & SOMENO M. (1969). Electric Conductivity of Liquid Pbo-Sio2, Pbo-Geo2, Pbo-P2O5, Pbo-B2O3 and Pbo-Sio2-Geo2 System. *Iron & Steel Inst Japan-J (Tetsu-To-Hagane)*, 55(7), 539–549. https://doi.org/10.2355/tetsutohagane1955.55.7_539
- Sarkis, J. (2019). Sustainable Transitions: Technology, Resources, and Society. *One Earth*, 1(1), 48–50. https://doi.org/10.1016/j.oneear.2019.08.018
- Schellinger, A. K., & Olsen, R. P. (1949). The relationship between electrical conductivity and composition of molten lead silicate slags. *JOM*, 1(12), 984–986. https://doi.org/10.1007/BF03398417
- Schiefelbein, S. L., Fried, N. A., Rhoads, K. G., & Sadoway, D. R. (1998). A high-accuracy, calibrationfree technique for measuring the electrical conductivity of liquids. *Review of Scientific Instruments*, 69(9), 3308–3313. https://doi.org/10.1063/1.1149095
- Schlesinger, M., King, M., Sole, K., & Davenport, W. (2011). Extractive Metallurgy of Copper. *Extractive Metallurgy of Copper*. https://doi.org/10.1016/C2010-0-64841-3
- Simonnet, C., Phalippou, J., Malki, M., & Grandjean, A. (2003). Electrical conductivity measurements of oxides from molten state to glassy state. *Review of Scientific Instruments*, 74(5), 2805–2810. https://doi.org/10.1063/1.1564272
- Sun, C. Y., & Guo, X. M. (2011). Electrical conductivity of MO(MO=FeO, NiO)-containing CaO-MgO-SiO 2-Al2O3 slag with low basicity. *Transactions of Nonferrous Metals Society of China* (*English Edition*), 21(7), 1648–1654. https://doi.org/10.1016/S1003-6326(11)60909-6
- Thibodeau, E., & Jung, I. H. (2016). A Structural Electrical Conductivity Model for Oxide Melts. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*, 47(1), 355–383. https://doi.org/10.1007/s11663-015-0458-z
- Zhang, L., Malfliet, A., Blanpain, B., & Guo, M. (2021). In Situ Electrical Conductivity Measurement by Using Confocal Scanning Laser Microscopy. *Metallurgical and Materials Transactions B* 2021 52:4, 52(4), 2563–2572. https://doi.org/10.1007/S11663-021-02210-W