INFLUENCE OF THE CaO, Al₂O₃ AND Fe₂O₃ CONTENT IN THE SLAG OF THE ISASMELT™ FURNACE AT SOUTHERN PERU ILO SMELTER

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ABSTRACT

Ilo Copper Smelter operates since 2007 with an ISASMELT™ furnace as a single smelting unit (1,200,000 tpy) associated with two Rotary Holding Furnaces for separation of matte and slag, and which directly produces a discard slag. Southern Peru continually has been improving the slag chemistry of its ISASMELT™ furnace in order to reduce copper losses, given its big economic impact due to large slag mass generation. The present paper describes the influence of the CaO, Al₂O₃ and magnetite content in the slag of the ISASMELT™ furnace correlated with the SiO₂/Fe ratio and its liquidus slag. Also it defines the best slag chemistry and operating practice in order to reduce the copper losses without compromise the bricks life of the furnace.
INTRODUCTION

Ilo Copper Smelter of Southern Peru (Grupo Mexico) is located on the southern coast of Peru, and treats mainly copper concentrates produced in its own mines (Toquepala and Cuajone).

The modernized smelter was commissioned in 2007 and operates with an ISASMELT™ furnace as a single smelting unit (1,200,000 tpy), which is associated with two Rotary Holding Furnaces (RHF) for separation of matte and slag. This slag is directly sent to the dump. Figure 1 shows the smelter flow diagram.

Figure 1 – Flow diagram of the Ilo Smelter

The ISASMELT™ process is a bath-smelting process using a single lance. The lance tip is immersed into a molten slag bath contained within the stationary, vertical, refractory-lined ISASMELT™ furnace. The injection of oxygen-enriched air, through the lance into the slag results in a highly turbulent molten bath. Feed material falling into the turbulent bath from above reacts rapidly, resulting in extremely high productivity for a relatively small bath volume.

Initial operating conditions for the ISASMELT™ furnace considered a slightly higher SiO₂/Fe ratio in the slag as well as lime addition (in form of seashell) to reduce the viscosity of the slag. This operational scheme with relatively high flux additions had the disadvantage of a large generation of slag mass.

In addition to the mentioned flux strategy, it was also important to develop an operating strategy for higher alumina contents in the ISASMELT™ slag that Southern Peru has from time to time.
METHODOLOGY

Based on CaO-SiO$_2$ interaction in the liquid slag being much stronger than the FeO-SiO$_2$ interaction (Coursol et al., 2007), which enhances the magnetite formation in the slag if there is not enough silica (see reactions below), Southern Peru had tested at the plant level, the progressive reduction of the flux lime addition to the ISASMELT™ furnace, until its total suspension.

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2\ [\text{CaO}]_{\text{slag}} + [\text{SiO}_2]_{\text{slag}} = [\text{Ca}_2\text{SiO}_4]_{\text{slag}} \tag{1}
\]

\[
2\ [\text{FeO}]_{\text{slag}} + [\text{SiO}_2]_{\text{slag}} = [\text{Fe}_2\text{SiO}_4]_{\text{slag}} \tag{2}
\]

\[
3\ [\text{FeO}]_{\text{slag}} + \text{O}_2\text{ gas} = (\text{Fe}_2\text{O}_3)_{\text{solid}} \tag{3}
\]

This change in the slag chemistry of the ISASMELT™ furnace (Herrera and Mariscal, 2009), was evaluated on basis of the ternary diagram that is shown in Figure 6, and that predicts the slag liquidus temperature in the Al$_2$O$_3$-CaO-"FeO"-SiO$_2$ system at oxygen partial pressure of 10$^{-8.4}$ atm and at fixed Al$_2$O$_3$ of 6 wt%. This model was developed using Factsage by the Pyrometallurgy Research Centre at the University of Queensland and Xstrata Technology.

Moreover and in order to assess the impact of levels of CaO and Al$_2$O$_3$ in the ISASMELT™ furnace slag, Southern Peru mundated XPS ("Xstrata Process Support") to prepare a mapping of the slag chemistry. The impact of these compounds in the ISASMELT™ slag chemistry also was evaluated with using the Factsage software, considering a matte composition of: % Cu = 62, % Fe = 12.35, % S = 23.6; and P (SO$_3$) = 0.45 atm.

Operational Control of the ISASMELT™ Furnace

In the ISASMELT™ bath-smelting chemistry process, the phases involved are the molten matte, molten slag and gas. If we disregard the minor elements present in copper concentrates and flux, then there are essentially five components, Cu, Fe, S, O, and SiO$_2$, then according to the Gibbs phase rule, the number of degrees of freedom will be 4 in a system in equilibrium. For practical reasons, the following independent variables are chosen: slag composition, matte grade, bath temperature, and SO$_2$ partial pressure.

The values of these operating parameters were fixed by operational experience and considerations of productivity, refractory wear and copper losses in slag, and are described below:

- The matte grade was set at 62 – 63% on account of conversion capacity available. The matte grade is controlled by adjusting the amount of oxygen that is injected by the lance, based on the chemical assays of samples taken during tapping.
- The bath temperature depends on the slag chemical composition and it is set approximately 20 °C lower than the slag liquidus. For a typical mineralogy and chemical composition of the Southern Peru concentrates, the bath operating temperature was set at around 1180 °C.
- The SO$_2$ partial pressure (-0.45 atm) depends on the oxygen enrichment of process air that must be injected into the bath according to mass & energy balance of the furnace.
- The chemical composition of the ISASMELT™ slag is defined to get a smaller mass and a proper viscosity. The SiO$_2$/Fe ratio is adjusted on the basis of the magnetite results obtained by the magnetic saturation method using a Satmangan analyzer from slag samples taken on a spoon at the start of each tap and cooled to room temperature. The CRO (control room operator) also monitors the slag viscosity via "tapping duration" and from feedback of the field operators.

The historical magnetite content in the slag that is produced in equilibrium with the operating parameters defined above is set between 8 – 10%. In this range a good balance is achieved between the losses of copper in the slag and the brick life of the ISASMELT™ furnace.
RESULTS AND DISCUSSION

Impact of % CaO on the ISASMELT™ Slag Chemistry

The results of plant tests consisting of eliminating lime addition to the ISASMELT™ are shown in Figure 2 (Herrera and Mariscal, 2010).

![Graph showing the impact of CaO on ISASMELT™ slag chemistry](image_url)

Figure 2 – Silica to iron ratio versus % CaO content in the ISASMELT™ furnace slag

It can be seen that the reduction of lime addition to the ISASMELT™ furnace until its total elimination and to keep within the required slag properties that the SiO$_2$/Fe% ratio was significantly reduced. This also meant less consumption of silica flux, which led to a further reduction of the slag mass. It also highlighted the strong interaction between silica and CaO.

The impact of CaO in the ISASMELT™ slag chemistry was also evaluated using the Factsage software, considering a slag with 4% Al$_2$O$_3$, 0.7% ZnO, 0.3% Na$_2$O, 0.3% Cu = 62, % Fe = 12.55, % S = 23.6, and P (SO$_2$) = 0.45 atm. Figure 3 shows the slag liquidus against % SiO$_2$/Fe at various % CaO levels.
In this Figure it can be seen that higher levels of CaO raises the magnetite liquidus and lower the SiO₂ liquidus, in agreement with the trial results shown above. The analysis demonstrated that the CaO consumes some SiO₂ in the slag by the formation of soluble calcium silicates, hence the presence of more CaO in slag force an operation with higher % SiO₂/Fe ratios for similar slag properties.

Impact of Alumina on the ISASMELT™ Slag

When a concentrate higher in alumina is fed to the furnace, the slag chemistry changes in a meaningful way since Al₂O₃ can promote magnetite formation (spinel). This forces the smelter to use more SiO₂ at higher presence of Al₂O₃ in slag to avoid excessive magnetite formation. This could lead to having too viscous a slag potentially foaming the furnace, and increasing the mechanical losses of copper in the slag.

To prevent a high slag viscosity due to occasional increases in alumina content in the concentrates mapping of the slag chemistry for the ISASMELT™ furnace was carried out, to study the impact of the higher Al₂O₃ on the slag liquidus and on the operating SiO₂/Fe ratio. The following was used for the calculation: a slag composition of: % CaO = 0.9, % ZnO = 0.7, % Na₂O = 0.3, matte composition of: % Cu = 62, % Fe = 12.55, %S = 23.6; and P (SO₃) = 0.45 atm. Figure 4 shows the result.

In this graph it can be seen that higher levels of Al₂O₃ raise the magnetite liquidus and lower the SiO₂ liquidus. In order to avoid excessive magnetite formation in the ISASMELT™ slag, every 2% Al₂O₃ requires an increase to the % SiO₂/Fe ratio by approximately 0.05, but this will increase slag viscosity due increased SiO₂ addition.

Because of this fluxing with CaO was evaluated to counteract the impact of high Al₂O₃ without increasing operating slag temperature. This hypothesis was tried by performing liquidus calculations at different % CaO/Al₂O₃ ratios to see if lime addition could help maintain a reasonably low % SiO₂/Fe ratio in slag at high % Al₂O₃. The graph shown in Figure 5 displays these results, and in all the calculations, the % Al₂O₃ in slag was kept at 8 wt%.
Figure 4 – Slag liquidus versus % SiO₂/Fe in slag at % various Al₂O₃ levels

Figure 5 – Slag liquidus versus % SiO₂/Fe in slag at % various CaO/Al₂O₃ ratios

Figure 5 shows that a higher level of CaO raises the magnetite liquidus and lowers the SiO₂ liquidus at high levels of Al₂O₃ in slag. Addition of CaO does not allow maintaining a low operating % SiO₂/Fe ratio in slag.

In conclusion and according to Factsage calculations, lime addition to the furnace does not help in allowing more Al₂O₃ in the slag and leads to higher silica addition. According to Figure 4 even without lime addition, more silica is required to process higher Al₂O₃. High additions of silica to the ISASMELT™ furnace tend to increase the slag viscosity.
Southern Peru, based on these findings, has decided only to increase the bath temperature when the content of Al$_2$O$_3$ in the ISASMELT$^\text{TM}$ slag is more than 6%, in order to obtain a suitable viscosity of the slag.

**Impact of Magnetite on the ISASMELT$^\text{TM}$ Slag**

The magnetite content control in ISASMELT$^\text{TM}$ furnace slag is very important for the operation of the furnace. High magnetite content causes high slag viscosity which increases the tap times and results in poor phase separation in the RHF, which increases the copper losses mainly due to greater mechanical entrapment of matte in the slag. On the other hand, lower magnetite contents affect the bricks life of the furnaces.

The magnetite activity in the molten slag depends on the operating temperature, oxygen potential or matte grade, the SiO$_2$/Fe ratio, as well as on the CaO and Al$_2$O$_3$ contents in the slag as seen in previous topics.

On the basis of the ternary diagram shown in Figure 6, the slag liquidus is evaluated considering an alumina content of 6% in the ISASMELT$^\text{TM}$ furnace. After elimination of the lime flux addition to the furnace, the resulting % CaO/SiO$_2$ ratio was around 0.04 because of the lime contained in the concentrate, and the % SiO$_2$/Fe was set around 0.74 in order to maintain a magnetic content in the slag between 8 to 10%. This slag composition is represented by the white circle, shown in the ternary diagram in Figure 6.

![Figure 6 - Liquidus in the system Al$_2$O$_3$-CaO-FeO$'$SiO$_2$ at P$_{O_2}$ = 10$^{-5.4}$ atm and Al$_2$O$_3$ = 6 wt %](image)

According to the Factsage model, the liquidus temperature for this slag composition (white circle) is predicted to be close to 1200 °C, and since the bath operating temperature was set at 1180 °C, a slag superheat of -20 °C is operated with which allows enough "solid fraction" in suspension to form a layer of magnetite that protects the furnace refractory lining.

However, this slag viscosity led to high formation of accretions at the entrance of the boiler because of splashing of slag projected by the lance operation. In order to reduce this build-up in the boiler, it was decided to test the furnace operation with a lower content of magnetite in the slag (7.5 – 9%), but
keeping the bath temperature in 1180 °C in order to reduce the slag viscosity, and monitor the bricks wear very closely.

This new slag composition is represented by the red circle that is shown in the diagram of Figure 6. The new SiO₂/Fe ratio was around 0.76 and the corresponding liquidus temperature is close to 1180 °C.

Figure 7 shows the magnetite content and the SiO₂/Fe ratio in the ISASMELT™ slag in this current third campaign. A reduction of the magnetite content in slag can be seen after increasing the SiO₂/Fe ratio; this means that the furnace has operated with a lower fraction of solids in suspension, but there has been no reported higher rate of brick wear.

![Graph showing SiO₂/Fe ratio and Fe₃O₄ content in ISASMELT™ slag](image1)

**Figure 7 – SiO₂/Fe ratio and Fe₃O₄ content in ISASMELT™ slag**

Figure 8 shows the magnetite and copper contents in the ISASMELT™ slag. It can be seen that there is a significant reduction of the copper losses in slag after increasing the SiO₂/Fe ratio, in this way the reduction of the magnetite, has led to better matte–slag separation.

![Graph showing %Cu and %Fe₃O₄ content in the ISASMELT™ slag](image2)

**Figure 8 – % Cu and % Fe₃O₄ content in the ISASMELT™ slag**

**CONCLUSIONS**

The strong interaction between SiO₂ and CaO was highlighted to show that the presence of more CaO in slag forces an operation with higher SiO₂/Fe ratios, and therefore increases the slag mass generation in the furnace. On basis of this finding Southern Peru has decided to suspend lime addition to the ISASMELT™ furnace.
The presence of more Al₂O₃ in slag requires the addition of more SiO₂ to prevent magnetite formation, but adding more SiO₂ to the furnace also increases the slag viscosity, therefore, Southern Peru decided to increase the operating temperature when feed with higher alumina is fed to the ISASMELT™ furnace.

The slight reduction of magnetite by increasing the SiO₂/Fe ratio in slag reduces its slag liquidus and therefore its viscosity if the operating temperature is not changed, for Southern Peru this practice led to achieving a significant reduction of mechanical losses of copper in the slag, without affecting the brick life of the ISASMELT™ furnace.

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REFERENCES

