MECHANISM OF BUILDUP FORMATION IN AN ELECTRIC FURNACE FOR COPPER SLAG CLEANING

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ABSTRACT

The copper slag cleaning in an electric furnace is based on slag reduction and settling of copper matte inclusions. Copper recovery depends on the slag temperature, degree of magnetite reduction and slag residence time. The formation of solid buildup on the furnace hearth leads to the decrease of furnace volume and slag residence time, affecting copper recovery and furnace capacity.

The formation of buildup in the electric furnace of Codelco Norte Smelter creates the fundamental questions about the mechanisms of solid layer creation.

Three major hypothetical causes of solid layer formation have been taken under consideration: precipitation of magnetite from saturated copper matte, precipitation and solidification of metallic copper and solidification of copper matte at the hearth/matte interface.

Complex multi-physics modeling of heat generation, fluid flow and heat transfer allowed for determination of the temperature distribution. For processing of the slag from copper concentrate smelting in Teniente Converter the temperature distribution does not show the conditions for magnetite precipitation and/or matte solidification. However, during Teniente Converter stop over the solid reverts and converter slags, with high content of cuprous oxide, have been processed only in the furnace leading to the formation of the layer of a liquid copper on the furnace hearth. Infiltration of the liquid copper into hearth refractories resulted in dramatic change of thermal conductivity of chromo-magnesite bricks. It leads to the change of temperature distribution, creating conditions for magnetite and copper precipitation. Continuous growth of buildup reached semi-equilibrium conditions after a long period of time, corresponded to the decrease of the operational volume of the electric furnace about 50%.

INTRODUCTION

The formation of buildup on the electric furnace hearth occurs frequently in copper slag cleaning and melting processes [1, 2, 5]. The thickness of the buildup, which consists mainly of magnetite, varies from 100 to 300 mm.

The buildup formed in the electric furnace of the Codelco Norte Smelter reached over 1 m in thickness generating a deep concern about the impact on the furnace performance and the questions about the mechanisms of formation of so thick deposit on the furnace hearth. The furnace operated correctly from start-up to November 2004, when the bottom deposit started to grow up to 1.0-1.4 m in height, then stabilized. Schematically, the proportion of buildup, copper matte and slag is shown as a furnace cross-section in Figure 1. The operating volume of the electric furnace decreased about 50% affecting furnace capacity.

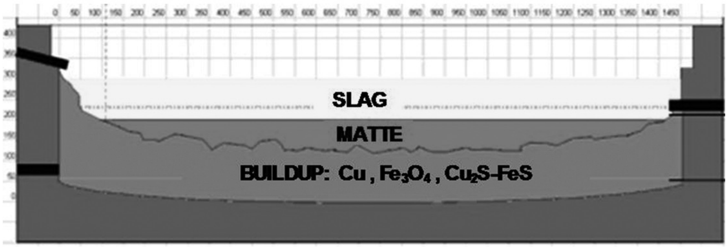

Figure 1: Schematic cross-section of electric furnace with bottom buildup

There are three components, which can deposit from a copper matte on the surface of the hearth: magnetite, copper and solid matte. Concentrate smelting in the Teniente Converter produces high-grade matte (72-74% Cu) and fayalite-base slag containing 12 to 20% of magnetite (Fe_3O_4) and 4 to 10% of copper. The produced copper matte in electric furnace contains from 68 to 70% Cu.

The general mechanism of the magnetite solubility in high-grade matte is relatively low and strong temperature dependent [4], and can be summarized as: i) the magnetite from slag is reduced by carbon of electrodes and coke according to (Equation 1), ii) the magnetite partially settles down and dissolves in copper matte (Equation 2), and iii) co-reduction of cuprous oxide leads to settling of metallic copper and its dissolution in copper matte (Equation 3).

$$(Fe_3O_4)_{slag} + C \Rightarrow 3\ (FeO)_{slag} + \{CO\}_{gas} \tag{1}$$

$$(Fe_3O_4)_{slag} \Rightarrow [Fe_3O_4]_{matte} \tag{2}$$

$$(Cu_2O)_{slag} + C \Rightarrow 2\ [Cu]_{matte} + \{CO\}_{gas} \tag{3}$$

Any temperature drop results in precipitation of magnetite on the furnace hearth. On the other hand, based on Cu-Fe-S phase diagram illustrated in Figure 2, the saturation of copper matte with copper causes the precipitation of copper and the formation of blister copper layer at the bottom. Thus, the aim of this work is to evaluate the mechanisms of buildup formation on the electric furnace hearth.

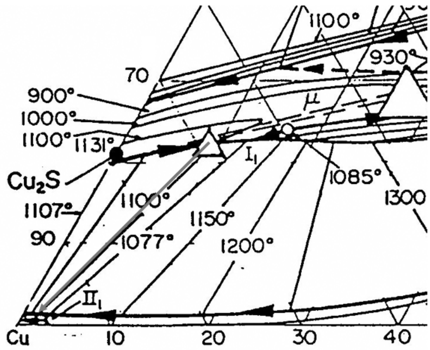

Figure 2: Cu-Fe-S System [6]

METHODOLOGY

Modeling of the electric furnace operation has been carried out using commercial software COMSOL. Geometry of the Codelco Norte electric furnace as 2D cut through two electrodes is shown schematically in Figure 3.

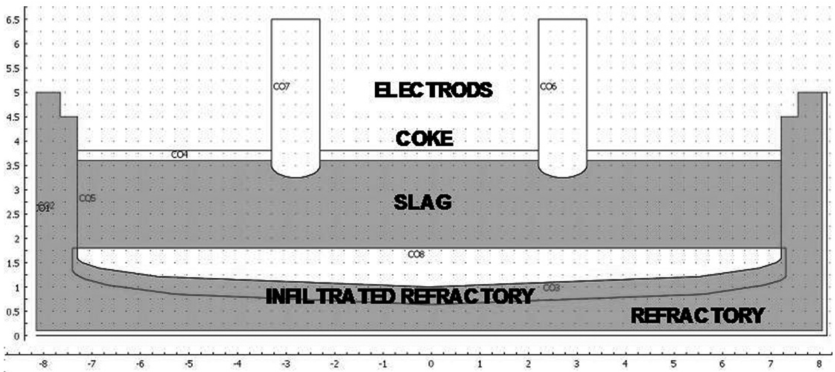

Figure 3: Cross-section of the 2D electric furnace model at the beginning of buildup formation

Using simultaneously three solvers: potential and current distribution profile, Navier-Stokes incompressible fluid and heat transfer the temperature distribution profile was determined in the electric furnace. First, the temperature distribution profile was calculated for original furnace structure using average voltage range and slag conductivity determined experimentally [7]. Second, the metallic copper infiltration into the furnace hearth at the depth of first layer of refractory lining was assumed and calculation repeated. Third, the furnace with uniform buildup thickness of 1 m as simplified case of real deposit together with infiltrated refractory was modeled. The geometry of above case is shown in Figure 4.

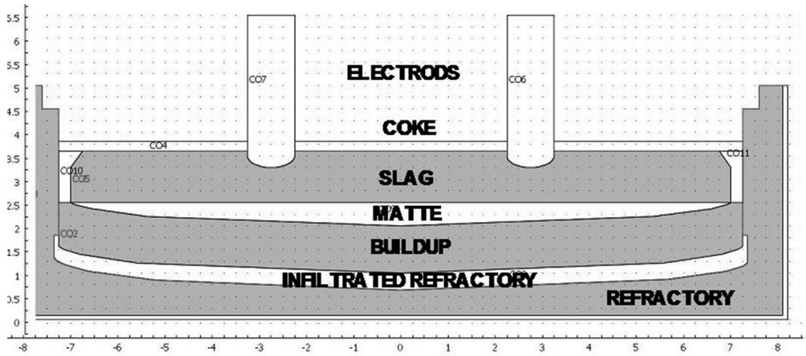

Figure 4: Cross-section of the 2D electric furnace model with infiltrated refractory

RESULTS AND DISCUSSION

The typical distribution of power input is illustrated in Figure 5. It can be seen the dominating Joule heat liberation at electrode/slag interface. Overheated slag flows along the coke to the side walls, cooled down and return along the slag matte/interface as it is shown by the model diagram of slag velocity distribution profile in Figure 6. Convection slag movement is very important for homogenization of slag temperature, rate of magnetite reduction by mass transfer onto reductant surface and inclusions coalescence. Calculated temperature distribution profile in the furnace cross-section is shown in Figure 7.

Figure 5: Power input profile

Review of the operation of the electric furnace in showed the untypical operation of electric furnace processing only solid reverts and small amount of liquid slag from Teniente slag cleaning furnace [3] due a programmed maintenance of the Teniente Converter. The processing of reverts with high cuprous oxide and metallic copper contents resulted in formation of the metallic copper layer on the furnace hearth.

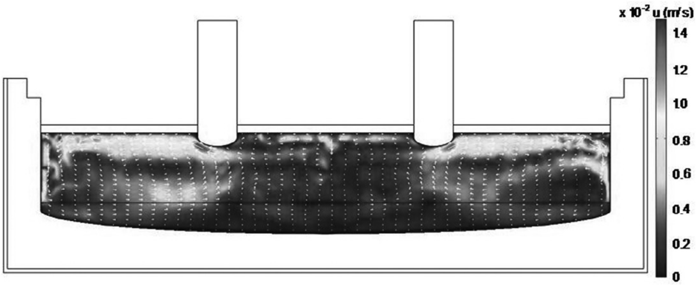

Figure 6: Slag velocity profile. arrows indicate direction of the convective flow

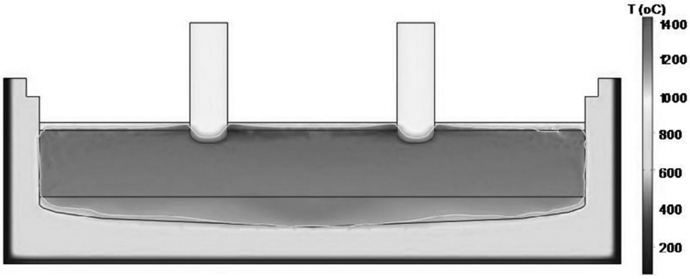

Figure 7: Temperature profile – original furnace

Chromo-magnesite bricks open porosity is about 16%. If only 2/3 of open porosity is filled by copper (10% of the brick volume) the average thermal conductivity of infiltrated bricks is equal:

$$k_{IB} = 0.1 \cdot k_{Cu} + 0.9 \cdot k_{CB} = 0.1 \cdot 400 + 0.9 \cdot 4 = 40 \frac{W}{mK} \qquad (5)$$

Thus, the thermal conductivity of infiltrated bricks increases 10 times from 4 to 40 W m^{-1} K^{-1}.

The model calculations for infiltrated bricks presented significant change in temperature distribution, particularly in copper matte layer, as it is shown in the diagram of Figure 9. The white line represents the 1100ºC isotherm line. It results in the increase of heat transfer from a liquid matte downwards to the displacement of the isotherm of copper solidification.

The modeling results for the electric furnace with and without infiltrated refractory are shown in Figure 10 as vertical temperature in the furnace center. It can be seen strong temperature drop in the coke layer due to endothermic Boudouard reaction and slag temperature decrease as the result of endothermic reaction of magnetite and cuprous oxide reactions (Equations 1 and 3). The maximal slag temperature is close to 1400ºC. Along the slag height the temperature decreases approximately 200ºC. In the upper part of copper matte layer the temperature is similar for original furnace without infiltrated refractory and for furnace with copper infiltration to the first refractory lining layer. In lower part of the matte layer the temperature is about 50ºC lower for the case of refractory infiltration (red line) comparing to the case of the furnace without copper infiltration (black line). Higher thermal conductivity of infiltrated refractory causes the increase of heat flux downwards making steeper the temperature gradient in the copper mate layer.

The decrease of matte temperature about 50ºC in its lower part affects the solubility of magnetite causing precipitation of solid magnetite. Simultaneously, the copper matte is saturated with copper and blister copper separates from matte. The temperature at the hearth surface is close to melting point of copper (1083°C). So, the solid magnetite traps a liquid copper, which solidifies and forms solid deposit with magnetite, what can be seen in Figure 8. Analysis of buildup samples showed that the major components are magnetite and blister copper with some amount of copper matte and speiss (Cu-Fe alloy with As-Sb-S-Pb). The precipitation of magnetite and metallic copper from the copper matte is a slow process due to low solubility in a high-grade matte and fluctuation of temperature and furnace charge.

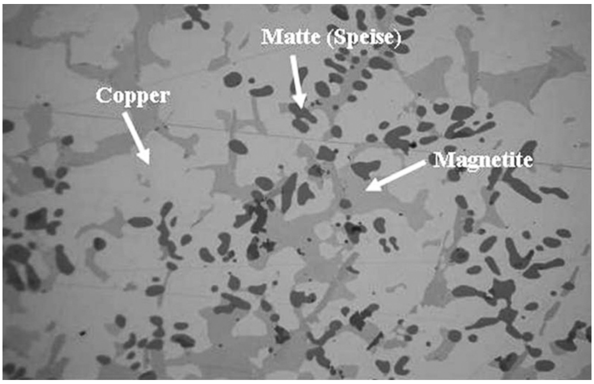

Figure 8: Microphotograph of buildup sample from electric furnace

However, the precipitation proceeds up to the moment of steady-state situation, where the thickness of matte layer and the temperature gradient inside are small enough to maintain the matte temperature at which precipitation stops. The bottom buildup in the electric furnace grew up from during 36-38 month, when rich the stable situation, which corresponds to the buildup thickness 0.8-1.4 m.

The results of modeling of the furnace in current situation with infiltrated refractory and simplified uniform thickness of buildup 1 m demonstrates in Figure 10 the 1100°C isotherm line at the interface copper matte/solid buildup pointing out the steady-state operational situation of the electric furnace. More intensive slag motion in this thinner slag layer (Figure 11) helps in temperature homogenization and the decrease of temperature gradient.

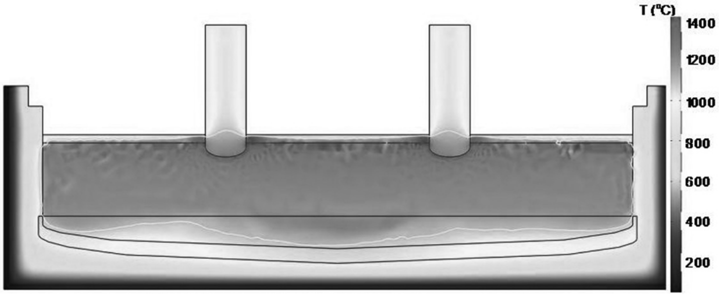

Figure 9: Temperature profile infiltrated refractory

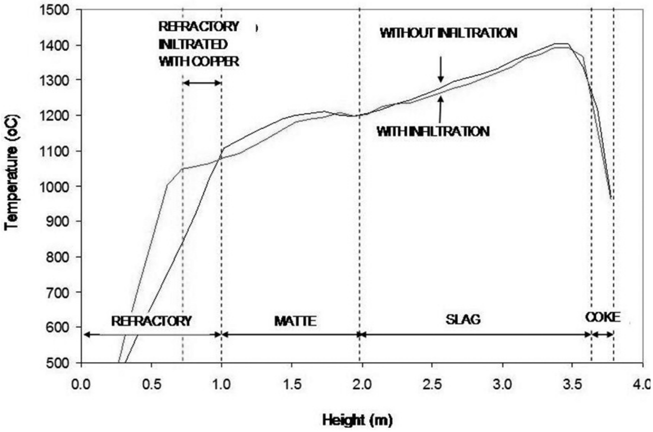

Figure 10: Vertical temperature profile in the center of the furnace with/
without infiltration of copper into hearth refractory

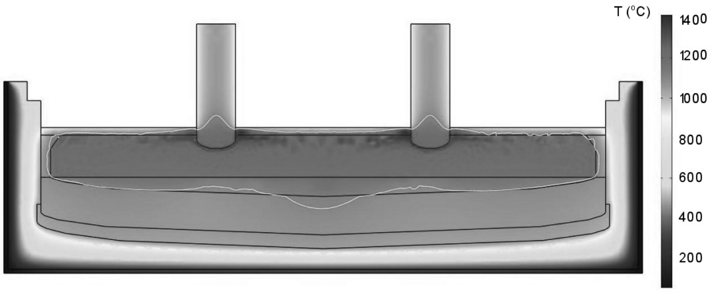

Figure 11: Temperature profile – infiltrated refractory and buildup

The vertical temperature distribution in the furnace center is presented in Figure 12. The thermal conductivity of a buildup was estimated as weighted average of copper and magnetite conductivity. Slag and matte temperatures show smaller gradient. Even temperature gradient inside the buildup is relatively low due to high thermal conductivity.

It is important to note that the electric furnace in Codelco Norte Smelter was designed originally as a slag/matte separator and slag cleaning unit. For various reasons the furnace operates as a classical slag cleaning reactor creating the conditions that the furnace is over-dimensioned for the amount of slag from Teniente Converter together with charged solid reverts.

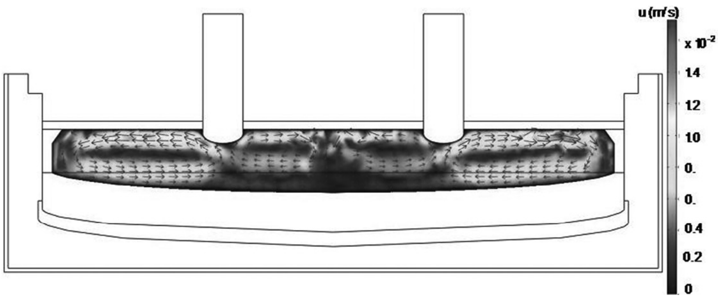

Figure 12: Slag and matte velocity profile – infiltrated refractory and buildup

Thus, in the current situation, the electric furnace decrement of about 50% of its original operating volume is suitable for processing the 800-1200 t/day of liquid slag form the Teniente Converter along with 100 t/day of solid reverts. The furnace operation with low capacity limits power input and intensity of slag motion by natural convection. However, for an eventual intensification of TC smelting rate plan it would need a larger volume to ensure the proper residence time for reduction and settling.

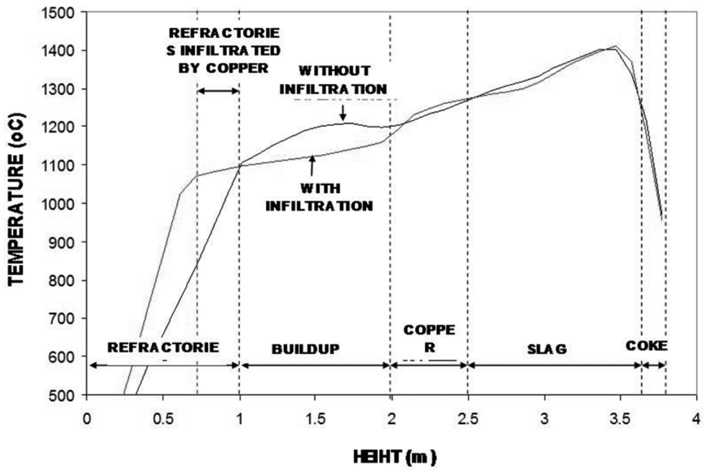

Figure 13: Vertical temperature profile in the center of the furnace with infiltration of copper into hearth refractory and formed buildup

Various proceedings have been prepared for partial removal of buildup by magnetite reduction with iron and washing out with lower grade matte linked with precise control of matte temperature [3].

The simple overheating of matte layer by the increase of the depth of electrodes immersion has strong limitations. The high electric conductivity of the slag causes the increase of the current intensity to its maximal value. The operation with tapping hole at high metallostatic pressure and increased temperature is difficult.

CONCLUSIONS

Treatment of a slag and solid reverts with high cuprous oxide contents leads to the precipitation of metallic copper on the furnace hearth. The copper infiltrates open porosity and joints of the refractory bricks changing dramatically the thermal conductivity of the upper part of the hearth. It increases heat flux downwards creating stronger vertical temperature gradient in the copper matte layer.

The temperature decrease of lower part of copper matte layer causes the precipitation of magnetite and metallic copper from the copper matte, which form buildup on the furnace hearth. The formation of buildup is slow, but in the long period of time the thickness of bottom deposit can be very high decreasing furnace volume.

Large electric furnaces have predisposition for formation of strong vertical temperature gradients due to low thermal conductivity of a slag. The furnaces should operate at full load ensuring high power input and intensive convectional stirring.

NOMENCLATURE

k_{IB} = Thermal conductivity of infiltrated bricks , W m^{-1} K^{-1}.
k_{Cu} = Thermal conductivity of copper , W m^{-1} K^{-1}.
k_{CB} = Thermal conductivity of chromo-magnesite bricks , W m^{-1} K^{-1}.

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