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Development of a simulation procedure for the evaluation of new refractories for aluminium furnaces

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ABSTRACT

Refractory materials for aluminium industry are designed to be resistant to different degrees of thermal, mechanical and chemical wear. The refractory wall thickness reduction during service life increases the heat losses through walls decreasing the thermal efficiency of the furnace. Last developments are focused on obtaining refractories with better performance and improved insulation properties.

On this regard, a simulation procedure has been developed to compare the thermal and chemical performance of different refractories during end use. This procedure includes measuring the internal and external wall temperatures of a testing furnace using thermography, and comparing the resistance to liquid aluminium determining the corundum and cracks appearance. Two refractories have been tested by this procedure for comparative purposes; a commercial alumina castable and an improved alumina castable with better insulation properties.

Keywords: Refractories, Aluminium furnaces, simulation, end use properties, corrosion resistance, insulation behaviour.

INTRODUCTION

Refractory degradation and failures in aluminium melting furnaces can be caused by several mechanisms [1, 2] such as: chemical reactions between the molten aluminium and the refractory material (corrosion); mechanical degradation of the material by the process environment (erosion and abrasion) or by ingot loading (impact) or thermal shock. All these mechanisms reduce the energetic efficiency of the process because lining degradation promotes heat losses (insulation of the furnace is reduced) and also increases the refractory maintenance and repairing [3]. In order to have a good efficiency of the furnace, low thermal conductivity refractories are being continuously developed.

In the furnace, there is an area where the aluminium is in contact with the furnace atmosphere (Bellyband). In this area there is a triple interface (Gas atmosphere, refractory and molten metal), with the presence of a thermal gradient between them. In the area over the molten metal, corrosion of the refractory is produced by the action of the corundum growing from the metal line. [4]
In the area of contact between refractory and liquid Aluminium is where corundum is created by an oxidation and/or corrosion mechanism, but also by the mechanical cleaning and de-drossing of the furnace. At the surface of the liquid Aluminium, Aluminium is oxidized with the oxygen presented in the furnace atmosphere [5]:

$$4/3\ Al_2 + O_2 \Rightarrow 2/3\ Al_2O_3$$

Liquid aluminium and its alloys react with refractories to form corundum by reducing the silica present in them:

$$4\ Al + 3SiO_2 \Rightarrow 2Al_2O_3 + 3Si$$

We can observe in Figure 1 the corrosion of the refractory in the bellyband area.

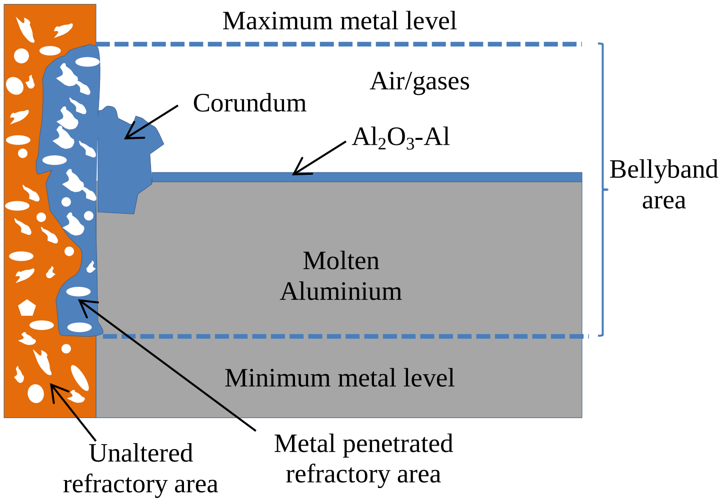

Figure 1. Bellyband area with corrosion of the refractory.

In some cases the performance of a refractory material can be predicted from the results of different laboratory tests. However, in other cases, due to a lack of direct correlating test, some other properties are predicted by experience. Hence, it is of a great importance to have validation tests that closely simulate the performance of refractories. A common standard procedure to test the new refractories implies the introduction of refractory test samples, at a specific temperature, in a closed furnace where the temperature is equal over the sample. In this procedure, the thermal stress and the thermal conductivity are not determined as in real industrial conditions, neither is the chemical corrosion resistance.

The most important properties to essay for a refractory are:

- Density and porosity.
- Mechanical resistance.
- Thermal conductivity.
- Thermal shock resistance.
- Chemical resistance.

Density is sometimes used as a "rule-of-thumb" indicator of the insulating ability of a refractory, but this can be misleading [6] since other material properties can also affect this behaviour.

The thermal properties of refractories such as Thermal conductivity and Thermal shock resistance can be measured following different standards (EN-993, ASTM C-182, ASTM C-1171). Thermal data from commercial refractories given by producers have several drawbacks to estimate the real behaviour of refractories on working conditions, being difficult to make comparisons for the selection of the refractories because the lack of information about the test procedures and complete characterization of properties at different temperatures. Same situation happens when comparing the chemical resistance of the refractories. In this case, only laboratory scale qualitative methods are available (i.e. PRE/R34) which not always totally replicate the real behaviour of the material during service conditions.

This work deals mainly with the determination of the real behaviour of refractories during end use. The objective is to obtain a better refractory testing procedure to determinate by comparison their chemical attack resistance, their thermal shock resistance and thermal conductivity. The resistance to liquid aluminium will be evaluated by determining the corundum and crack's appearance on the refractory. For the thermal behaviour, it will be measured the internal and external temperatures of the furnace walls to determine an equivalent thermal conductivity of the refractory that can be translated to a heat loss during real application and therefore to an energy and refractory cost.

DESIGN OF EXPERIMENTS

A method to simulate the behaviour and properties of refractories is described. An iron vessel with a total capacity, once the refractory lining installed, of 60kg of aluminium works as a container for testing 4 identical walls with different refractories. By using a top cover with electrical resistances, a temperature of 750ºC is obtained in the liquid aluminium, with an internal room temperature of 850ºC, in order to promote corundum formation like in industrial conditions. As the external wall of the vessel is in contact with air, there is a gradient of temperature, like in the industrial furnaces.

MATERIALS

The molten material for the tests have been chosen from the typical material used for die casting aluminium, which is alloy $AlSi_9Cu_3(Fe)$ according to standard EN AC-46.000, included in the EN 1706:2010 standard.

The refractories selected for the study are dense alumina castables containing a hydraulic binder. Two different refractory formulations were chosen for comparative purposes. On one hand, RCAST A, this is a standard refractory castable used in contact with molten Aluminium. On the other hand, RCAST B, which is an improved refractory castable designed to obtain better insulation properties and a positive impact on energy savings. Both castables must resist the chemical wear caused by being in contact with molten aluminium but also their thermal properties must be appropriate to endure the thermal and mechanical shocks during service operations.

The refractories tested in the furnace are summarized on table 1.

Table 1: Refractory materials tested.

	Material	Thickness
1	RCAST A-Reference	80 mm
2	RCAST B- Improved mat.	80 mm

The base composition for the dense castable are summarised in table 2.

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Table 2: Composition of tested refractories.

Chem. Comp.	RCAST A- Reference	RCAST B- Improved mat.
Al2O3 (%)	60	68
SiO2 (%)	21	22
Other (%)	19	10
Density (g/cc)	2.50	2.50

On a first stage, several formulations were developed in REFRACTARIOS KELSEN with the aim of obtaining a new refractory castable with improved insulation properties while maintaining its chemical resistance. Modifications on composition and adjustments on the manufacturing procedures were done to obtain an improved refractory castable. Figure 2 and figure 3 show the manufacturing process and the final product obtained at REFRACTARIOS KELSEN.

Figure 2: Industrial equipment to produce the new refractories

Figure 3: Refractories prepared to install into the test unit.

EXPERIMENTAL

Once the vessel is prepared, a polystyrene cubic mould is introduced into the centre of the vessel to help create the refractory walls. The different refractories are prepared and poured into the vessel's walls. After one day, the polystyrene is removed and the refractory curing process starts. Refractory is cured during 2 days at 180ºC and after the temperature is increased, at a rate of 100ºC per day, until a maximum temperature of 1.000ºC is reached. In Figure 4 we can observe the refractory after the curing process.

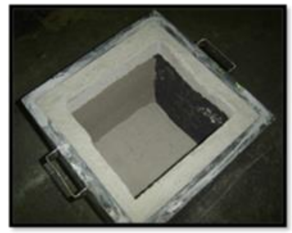

Figure 4: Refractory lining after sintering.

Solid Aluminium is introduced in the furnace, and it is melted. The holding temperature for liquid Aluminium is set to 750ºC. Every day the furnace is cleaned and de-drossed. Every week the furnace is emptied and the lining is revised for crack detection. Pictures are taken to each of the walls and different behaviours between materials are checked.

On that basis, once per month a Thermographic Camera is used to measure the internal and external temperature of the furnace. The thermal image is adjusted by measuring wall temperatures with a calibrated thermocouple. A FLIR Systems ThermoVision A320 camera is employed to obtain the thermal images, and a calibrated contact pyrometer to determine the real temperature of the internal and external walls of the furnace. In order to analyse the images and to adjust the images with real temperatures, the IR monitoring and Thermo Cam researcher professional 2.9 software packages are employed. We can observe in Figure 5.a. how is recorded the internal temperature and the adjusted thermal image in Figure 5.b.

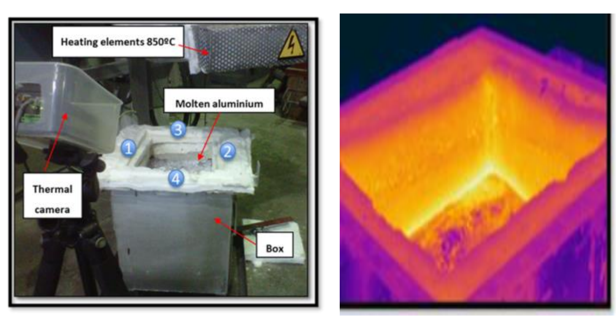

Figure 5: a) Test equipment. b) Thermal image.

This methodology is applied during 3months, and the test is stopped if important cracks are detected in the lining before that time.

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RESULTS AND DISCUSSION

The disclosed procedure was used to evaluate the two aforementioned refractory materials which were installed on opposite walls of the testing vessel.

The results in the external area of the furnace are summarized in table 3:

Table 3: External average temperature of the furnace

Reference	Temperature (ºC)
RCAST A-Reference	397ºC
RCAST B- Improved mat.	385ºC

The emissivity parameter was established with a value of 0.4 in the thermal analysing software. With this value, the difference between pyrometer measured temperature and temperature obtained with the thermal camera was less than 1ºC. The minimum fluctuations of temperature in function of time are also available.

In figure 6 we can observe how the external temperature of the refractory, the average internal temperature, the standard deviation and the distribution of temperatures can be determined.

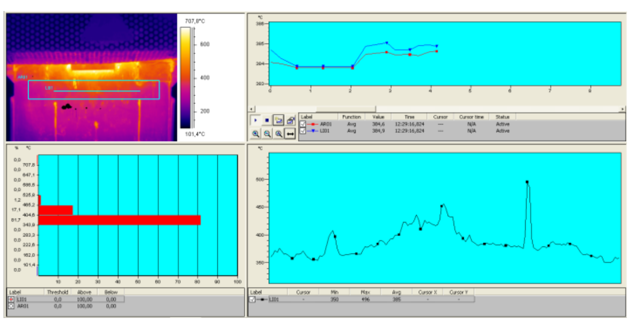

Figure 6: External refractory temperature determination

Depending on the surface quality of the steel surface of the vessel, some points showed punctually higher or lower temperatures. In order to equilibrate these variations a square analysis area is defined to obtain the average temperature values and compare them with the linear values.

The results in the internal area of the furnace are summarized in table 4:

Table 4: Internal average temperature of the furnace

Reference	Temperature (ºC)
RCAST A-Reference	714ºC
RCAST B- Improved mat.	750ºC

We can observe in figure 7 how is determined the internal temperature of the refractory, the average internal temperature and the standard deviation. In this case, the emissivity parameter is established as 0.88. With this value the difference between the pyrometer measured temperature and the temperature obtained with the thermal camera is less than 2ºC. We can observe the fluctuations of temperature in function of time.

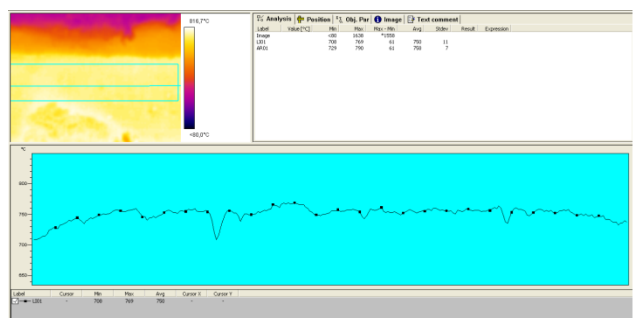

Figure 7: Internal refractory temperature determination

The best results are obtained with the new improved castable refractory, based on the smaller external temperature and the higher internal temperature that this material showed during tests in the furnace.

These temperature measurements make possible to estimate the thermal conductivity of the refractories by means of a simple analytical calculation. The heat transfer across the wall is determined by equations (1) to (3); and the equation (4), derived from these, permits to estimate the value of the thermal conductivity.

$$Q_{across\ wall} = K(W/mK) \cdot \frac{A\,(m^2)}{L(m)}\,[T_{int\ wall} - T_{ext\ wall}](K) \qquad (1)$$

$$Q_{ambient\ dissip} = h\,(W/m^2K) \cdot A\,(m^2)\,[T_{ext\ wall} - T_{ambient}](K) \qquad (2)$$

$$Q_{across\ wall} = Q_{ambient\ dissip} \qquad (3)$$

$$K\,(W/mK) = L(m) \cdot h\,(W/m^2K)\,\frac{(T_{ext\ wall} - T_{ambient})(K)}{(T_{int\ wall} - T_{ext\ wall})(K)} \qquad (4)$$

A first estimation for the case of the newly developed refractory is done considering the measured temperatures ($T_{int\ wall}$ = 750 ºC, $T_{ext\ wall}$ = 385 ºC), a wall thickness of 80 mm, and typical values for the ambient temperature (20 ºC) and the convection coefficient (h = 5 W/m^{2}K). Equation (4) provides a thermal conductivity value equal to 0.4 W/mK, which is lower than the expected by physical characterization. The analysis was adjusted modifying the value of the convection coefficient, taking into account that the typical values for natural convection are comprised between 5 and 25 W/m^{2}K. Assuming a new higher h value, the thermal conductivity predicted by equation (4) matches well with the measured thermal conductivity in laboratory scale. So, once the analysis has been adjusted, it can be used to predict the thermal conductivity of the rest of refractories during their degradation process.

In addition to this simple calculation a steady state heat transfer simulation with NX Nastran thermal software package using finite elements (FEM) is performed to evaluate the thermal gradient across the wall (see figure 8). This model has been set up taking into account the same values used in the previously adjusted analysis and it will be also useful to evaluate the thermal behaviour of the rest of refractories.

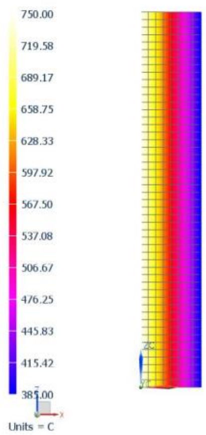

Figure 8: Temperature results from FEM simulation for RCAST B.

Finally, an example of the measurement of the corrosion by image comparison method an example is shown on figure 9.

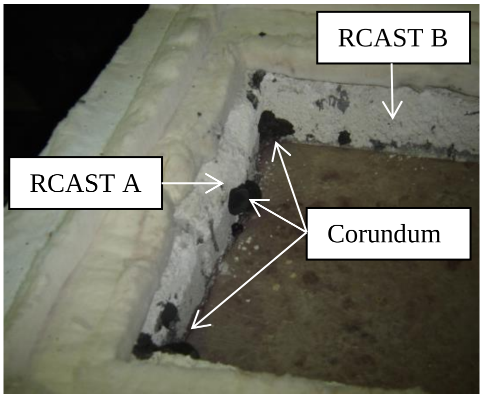

Figure 9: Corundum and cracks formation comparison between different walls

We can observe that corundum formation is higher in the reference material RCAST A, and that the improved refractory RCAST B has a better resistance to chemical attack and a lower corundum formation.

CONCLUSIONS

There are standard tests in order to determinate refractories' properties, but they are not always capable of determining their behavior in real end use conditions. The work reported in this paper has permitted to develop a test procedure that can compare different refractories in semi industrial operation. The main properties that can be compared are:

– Thermal conductivity.
– Corrosion resistance.
– Thermal stress resistance.

For that purpose, a special vessel that replicates the real operation conditions of an Aluminum furnace has been used to carry the refractories and test them.

By using and adjusting a thermal camera with real measured temperature it's possible to determinate the internal and external temperature distribution and quantify differences between different refractories. This way thermal conductivity of materials is tested. The results clearly showed the improved insulation properties of a newly developed refractory castable.

The system permits also to adjust simulation models with the real data, increasing the accuracy of simulation results and providing a good designing tool for the development of new refractory linings.

Finally, and using the same testing vessel, the chemical corrosion resistance of the installed refractories can also be evaluated by determining the corundum formation and crack's appearance on the refractory surface. The newly developed refractory castable was this way validated on its improved chemical resistance.

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