Optimization of Operational Practices to Increase the Working Life of Crucibles for Molten Aluminium Transportation

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This work addresses various aspects that affect the refractory lining performance of crucibles, as they play an important role in the aluminum production process by conveying molten metal from electrolytic cells (pots) to holding furnaces. Based on a systemic approach, the main objective of this investigation was to increase the working life of these crucibles and, consequently, reduce costs associated to aluminum production and refractory maintenance. According to practical results, the optimization of operational practices (i.e., castables' processing, placing, pre-heating of the lining, etc.) led to a significant increase (up to 83 %) in the average refractory working life. Moreover, after implementing the identified improvements, 91 % of the available crucibles were able to perform more than 400 metal runs and the maximum number of working cycles per equipment changed from 467 to 715. Therefore, in addition to the increase in the availability of crucibles, the enhanced performance of the refractories also resulted in financial benefits, reducing 47 % of the annual maintenance and pre-heating costs related to these materials.

1 Introduction

Crucibles are key components for molten metal transportation in the aluminum industry. They are usually comprised by a steel shell lined with ceramic refractories and present a vertical or horizontal (torpedo) cylindrical shape [1]. Another important feature is their robustness as, based on the working conditions that they are subjected to, these vessels must be able to withstand mechanical and thermal stress. When exposed to high temperatures, the wearing process of their metallic shell is mainly associated to creep, decarburization and oxidation mechanisms [2]. Aiming to minimize heat losses of the metal bath and reduce the temperature of the external wall (cold surface), refractory materials (dense and insulating) are commonly placed at the inner surface of these crucibles.

The partial or total (overall replacement) maintenance of these refractories is defined based on the detection of zones/areas with insufficient thermal insulation, which could induce safety risks for the operational process and staff. In order to prevent the need of unexpected lining repairing, some practices (i.e., pre-heating step) must be carried out in a suitable manner, as cracking and spalling of the refractory can take place during heating due to pressurization caused by the decomposition of hydrated phases and further release of a high amount of water vapour [3]. Additionally, special attention should be given to the installation procedure of these materials, as poor placing will have a direct and negative impact on the aluminum production process and the crucibles' working life.

1.1 Important refractory features

Refractory materials are commonly comprised by a mixture of coarse grains (aggregates), matrix components (fillers), binding agent (i.e., cement, hydratable alumina, phosphates, colloidal suspensions, etc.) and admixtures [4]. The performance of these products under service conditions depends directly on the resulting microstructure and physico-chemical transformations that take place during heating and at high temperatures. Some of the main parameters that

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have an impact on the refractories behavior are [4, 5]:

- The raw materials particle size distribution and shape;
- Chemical composition of matrix and aggregates fractions;
- Overall porosity content and pore size distribution of the cast/shaped product;
- Amount and distribution of the glassy and crystalline compounds in the formed microstructure.

In addition to the proper design of the formulations (based on the optimization of the raw materials selection and packing), the processing and placing procedures of the refractories must also be carefully carried out in order to avoid the generation of flaws during the materials curing and drying (pre-heating) steps [4–6]. The activities related to installation/maintenance and training staff responsible for this important stage are also essential to obtain the desired properties and performance of the refractory lining.

1.2 Maintenance procedures

Aiming to keep the equipment in service as long as possible according to project specifications, different maintenance procedures (corrective, preventive and/or predictive) can be implemented. Bernardes [7] and Lafraia [8] described such activities presented as follows:

- Corrective maintenance is the most expensive one, as it is usually conducted after identifying problems that can lead to inappropriate or unsafe operation of the equipment. In the case of crucibles, this procedure is required after reaching the refractories' working life or due to unexpected wearing of the lining.
- Preventive maintenance consists of efforts carried out to avoid premature failures that could result in low performance or even halt the equipment operation. This procedure is based on statistical data and information provided by the manufacturers (i.e., in order to schedule a further maintenance stop, the users may consider the overall production status, refractories' properties and reliability).
- Predictive maintenance is based on specific activities that could extend the continuous operation as long as possible. In order to identify the actions to be carried out, systemic monitoring and changing various operational parameters are required, leading to a suitable and controlled preparation of the vessels for the service (maintenance). When applied to the crucibles' operation, the decision to go ahead with a predictive maintenance procedure mainly depends on the data collected during the monitoring of the temperature of the external steel shell, as they can be used to foresee likely failures of the refractory lining.

1.3 Refractory drying (pre-heating) process

Among all refractory's processing steps, curing and drying (pre-heating) are the most relevant ones. Whereas the former is related to the development of green mechanical strength in order to ensure suitable demoulding, the latter is associated with water withdrawal, either physically (liquid up to 110 °C and as a vapour above this temperature) or chemically (by the decomposition of formed hydrates, depending on the original bonding system and processing conditions) at higher temperatures.

As the drying step is a time-demanding process, not only the costs related to the energy consumption, but also the impacts on the production halt (lost income) need to be taken into account. Moreover, any mechanical damage [9] caused during dewatering (that can even be the explosive spalling) would imply in a shorter lining working life and extra spending on maintenance and material, resulting in progressive and significant losses.

Considering that castables are usually bonded with hydraulic binders (calcium aluminate cement or hydratable alumina), the dry out process involves three stages occurring at different temperatures (typically up to 550–600 °C, depending on the material's permeability and applied heating rates): (i) evaporation, (ii) ebullition and (iii) dehydration (hydrate decomposition) [10, 11]. The relative amount of physical (free-water released during evaporation or ebullition) and chemically-bonded (CAC hydrates, for instance) H_2O depends on the total liquid amount added for mixing and the hydraulic binder content.

- Evaporation takes place when the installed refractory is exposed to temperatures lower than 100 °C, and it depends on: (a) the overall porosity of the generated microstructure (pore size and content, resultant permeability), (b) liquid features (viscosity, density and surface tension), and (c) environmental conditions (temperature, relative humidity and air flow). During this stage, H_2O is released from the region just beneath the surface without any change in pressure (adiabatic condition), as the temperature is usually constant. When such external film is withdrawn, solid/air interfaces are generated and, in order to keep the liquid cohesion, meniscuses are formed among the particles, due to the water surface tension. Under this condition, strong capillary forces pull the water from the inner region of the material to the surface. This is a continuous process, as long as the balance between the water dragging from deeper areas and its release to the atmosphere is constant.
- Ebullition starts when the castable's temperature reaches 100 °C, resulting in a higher mass loss rate than that observed during evaporation, as it is then ruled by the water vapour pressure [12] instead of the environmental features. This is a critical dewatering step and where most likely spalling takes place. As the vapour is quickly formed and usually located at a certain depth from the surface, it is not easy to attain a suitable and accurate balance between the amount of gas generated inside the body and its withdrawal rate at the surface (which is dependent on the heating rate, castable's permeability and thickness) [11].

The drying process can be carried out following two distinct heat up routines, based on a plateau or ramp profiles, in order to attain the best procedure to maximize the H_2O withdrawn during the evaporation stage. Relying on thermogravimetric measurements, Innocentini et al. [3] reported that the higher temperature gradient observed at the beginning of heating (based on the plateau method) sped up the heat transfer from the furnace to the body, increasing the mass loss. The gradual augment in the castable's temperature should also change the materials' drying rate profiles.

In industrial applications, as the dry out of various large monolithic blocks takes place simultaneously, a complex process is observed, where each individual product behaves according to its particular features (thickness, shape, permeability, thermal conductivity, amount of water, type and content of binder, porosity, mechanical strength, etc.) [13]. However, a unique drying schedule is usually applied in this processing stage. As a consequence, the resulting dewatering time/temperature profile (heating rate and holding periods) should be designed based on materials that present higher spalling likelihood and complex geometry.

Oil, gas-powered and electric heaters can be used to pre-heat (dry out) the crucible's refractory lining for conveying molten aluminum. Among the available options, gas-powered equipment is the most commonly applied, although the electric ones have proven to be an efficient alternative.

Fig. 1 Gas-powered pre-heater in operation (a) without and (b) with a crucible

Fig. 2 Electric pre-heater (a) before and (b) during operation with crucibles

1.3.1 Gas-powered pre-heater

In the process of gas combustion, the flames are continuously generated according to the reagents discharge at the burner nozzle. However, the fuel combustion only takes place when specific conditions are achieved (i.e., suitable air/fuel ratio) after igniting the pre-mixed reagents in the heater. As gas fuels are comprised by a mixture of different compounds (methane, various alkanes, and even carbon dioxide, nitrogen and hydrogen sulfide in minor contents), it is possible to estimate the air flow to induce a complete combustion of these components [14]. Unburned reagents represent a potential heat loss, as well as a safety hazard. By knowing the fuel chemical composition and by analyzing the combustion products, the efficiency of this process can be calculated based on the reaction stoichiometry. Thus, considering these data, one may infer:

- Whether a suitable air flow is being introduced into the burner;
- The heat loss due to the addition of an excessive amount of fuel into the system;
- The presence of CO, unburned reagents and hydrogen among the combustion products.

In order to illustrate the operation of a gas-powered heater, Fig. 1 shows one of these pieces of equipment before and after its coupling with a crucible.

1.3.2 Electric pre-heating

An electric pre-heater is a device that converts electric energy into heat, according to the Joule effect. This phenomenon is based on interactions between the moving electrons from a current and the atomic ions of the conductor material as, after their collision, a fraction of kinetic energy is released. The increase in the kinetic or vibrational energy of the ions is detected by a further rising of the conductor temperature [15, 16]. Thus, energy is transferred from the electrical power supply to the heating elements of the pre-heaters. The generated heat is then used to dry out and keep the refractory lining of crucibles at a suitable temperature level, before its contact with molten metal.

As highlighted in Fig. 2 a, the electric pre-heaters can present various heating elements in order to provide the required thermal dissipation (heat generation) to induce an effective drying process of the refractory lining. These elements are commonly connected to a mobile and metallic cover that is placed over the crucible, as shown in Fig. 2b.

Comparing the two presented heaters (gas-powered or electric), the latter system has the following advantages:

- No risk of explosion (as no flammable gas is used);
- Improved, more reliable/efficient temperature control;
- Lower wearing of the refractory lining due to no direct contact with flames;
- Lower noise level during operation.

2 Optimization of operational practices and the drying process (pre-heating) of crucibles – case study

In order to analyze the performance of crucibles for molten aluminum transportation at the Alcoa plant in Poços de Caldas/BR, a systemic evaluation of the maintenance process and the refractory lining behaviour

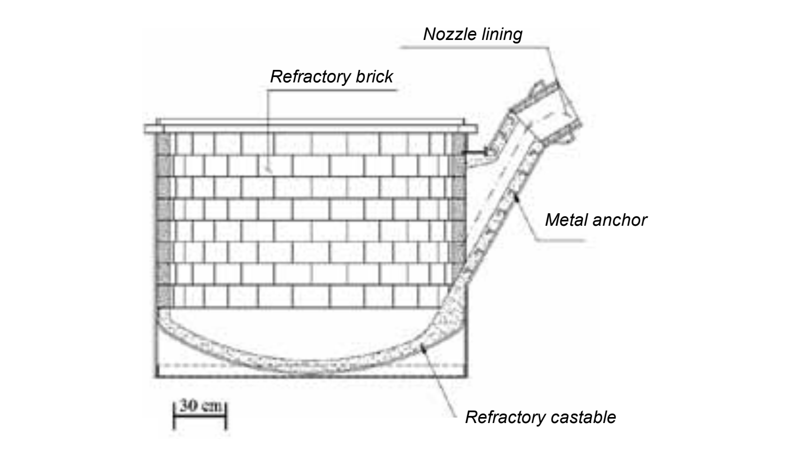

Fig. 3 Sketch of a crucible used at Alcoa plant in Poços de Caldas (Brazil), highlighting the shaped (bricks) and castable refractories lining this equipment

Tab. 1 Metal runs carried out by the repaired crucibles after corrective maintenance [1]

Crucible number	1	2	3	5	6	7	9	10	11	12	13
Number of metal runs	303	195	261	265	360	366	213	467	329	355	198

was carried out, aiming to identify which operational practices could be optimized to increase the working life of this equipment. Fig. 3 illustrates the crucibles' features with a volume capacity of roughly 9 t of molten aluminum, pointing out the presence of two different types of refractories (brick or castable) placed on three distinct regions (bottom, internal walls and nozzle). Bricks are installed on the walls, whereas castables line the bottom and nozzle areas.

Considering the available data concerning the bricks and castables' replacement carried out in previous corrective maintenance process of this equipment, the crucibles' performance is presented in Tab. 1.

Based on these data, the working life of the crucibles varied in a large range, as presented in Tab. 1: (i) 45 % of the crucibles presented between 190 and 265 metal runs, (ii) 45 % showed an increased service life time, reaching 303–366 runs, (iii) whereas only 10 % withstood 466 runs.

Analyzing the whole situation and data in order to understand this unsuitable and scattered performance, the following aspects were highlighted:

- There was no standard procedure defined for the installation of these materials;
- There was no control of the water's dosage and temperature, and an inconsistent mixing of the formulation components resulted in a non-homogeneous castable mixture;
- After placing the castable at the bottom of the crucible, the applied heating schedule did not meet the suppliers' recommendations.

Instead of selecting and installing novel refractory products with higher performance (and most likely with higher costs), a suitable alternative would be to optimize the placing and drying steps of the materials currently in use. Therefore, the following procedures were implemented:

- Preventive and predictive maintenance of the refractory lining;
- Definition of a standard placing method for the castables to be applied at the bottom region of the crucibles;
- Adjust the pre-heating schedule of the refractory lining according to the suppliers' recommendations.

Considering the data presented in Tab. 1 and a statistical study based on the reliability of the applied refractory castable [7, 8], a preventive maintenance plan was developed. Additionally, thermographic inspections were carried out on the crucibles' steel shell in order to monitor the refractories behavior and help to define when a corrective maintenance of the lining would be required.

Aiming to ensure a suitable preparation and placing of the castable, the staff responsible for this activity was also trained according to ISO 9000 and ASTM standards [17]. A specific and detailed procedure describing how the monolithic products should be processed (pointing out the amount of water to be added during mixing, curing temperature, etc.) and placed at the bottom region of the vessels was prepared and then checked by the technical team during maintenance of these crucibles. Furthermore, a removable metallic structure was designed, so that the thickness of the cast refractory lining could be adjusted during the installation of the vibratable monolithic products.

Another important action focused on the optimization/maintenance of the heating system. When analyzing the drying profile of various crucibles (before the improvements highlighted above), it was noticed that the actual temperature of the lining was very different from the one suggested by the refractory's supplier and programmed in the heater equipment (Fig. 4 a). In order to solve this problem, some damaged valves were exchanged, the air and fuel flows used in the gas-powered heaters were adjusted (considering the combustion reaction stoichiometry), preventive maintenance of the heating system was carried out more often and the refractories' drying profile was closely monitored.

In a further step, the performance of the crucibles was analyzed over the next six months in order to identify the effects of such improvements in their working life. Fig. 4 shows the changes in the actual and recommended drying schedules, before (a) and after (b) adjusting the pre-heater system. As summarized in Tab. 2, by using a suitable heating curve and also conducting other optimizations in the installation procedures (amount of water added during mixing, curing temperature, etc.), longer castables' working life and higher availability of crucibles were attained.

For example, according to the collected data, the following aspects can be highlighted:

- Average increase of 83 % in the refractories' working life;
- 91 % of the evaluated crucibles were able to carry out more than 400 metal runs (which is markedly higher than only 10 % obtained before implementing the enhanced operational practices);
- 73 % of the crucibles (total of 9) withstood more than 500 metal runs;

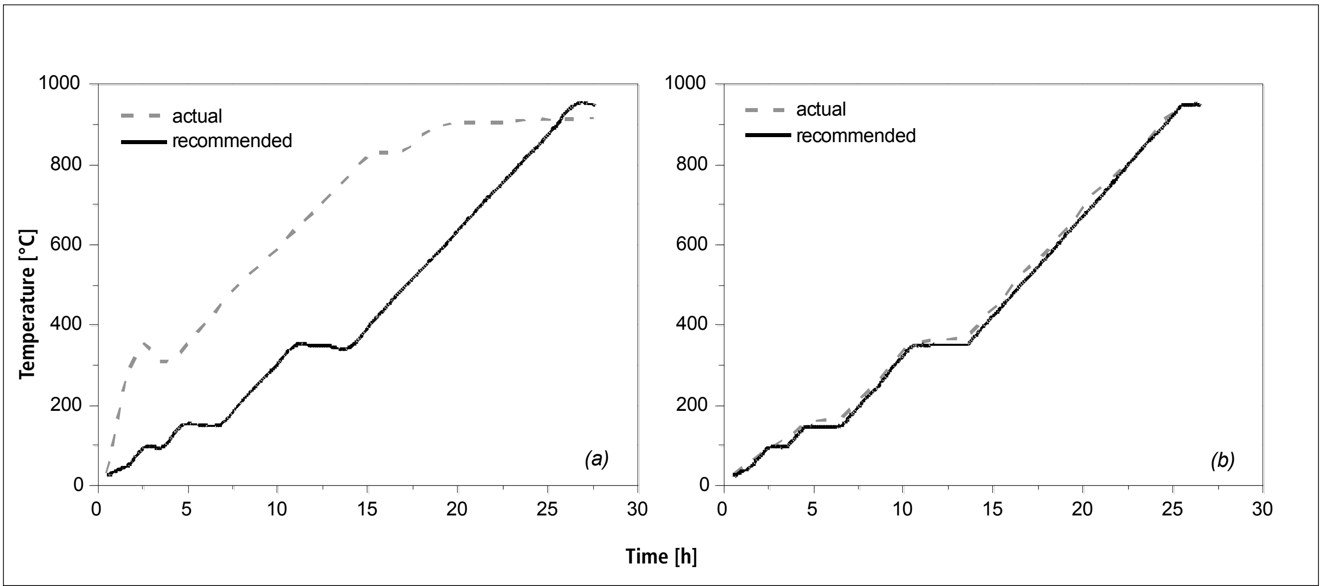

Fig. 4 Heating profile for castable's drying (a) before and (b) after improvements in the pre-heating system of molten aluminum crucibles

- The maximum number of runs per crucible increased by 53 %, changing from 467 to 715.
- Reduction of 47 % of the annual maintenance and drying costs related to refractory materials.
- An additional benefit was the overall decrease in energy consumption.

3 Final remarks

This work pointed out that by applying the theoretical concepts related to the refractory´s drying process and using operational practices (preventive and predictive maintenance schedules, training of technical staff, etc.), the working life of crucibles for conveying molten aluminum can be significantly enhanced. Not only the training of the staff responsible for the refractory castable placing, but also the definition of a standard procedure containing all the required information for processing these materials were fundamental for attaining a lining with improved quality. Furthermore, the design of a specific device to help the control of the placing step of the castables at the bottom of the crucibles and the optimization of the heating system resulted in a reduction in the maintenance costs and overall energy consumption. Consequently, a higher availability of crucibles was attained, as this equipment was able to carry out up to 550 metal runs (average value).

Tab. 2 Benefits of a suitable drying schedule concerning improvements in a refractory castable's performance used in molten aluminum crucibles [1]

Crucible Number	Number of Metal Runs between Two Consecutive Repairs		Increase in the Number of Runs	Increase in the Crucible's Life [%]
	Before Drying Control	After Drying Control		
1	303	514	211	70
2	195	523	328	168
3	265	669	404	152
5	261	609	348	133
6	360	568	208	58
7	366	534	168	46
9	213	446	233	109
10	467	514	47	10
11	329	715	386	117
12	355	652	297	84
13	198	301	103	52
Average	**301**	**550**	**248**	**83**

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