Key Aspects on Refractories for Molten Aluminium Long-distance Delivery

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The long distance (100–200 km) molten aluminum transportation (~8 Mt/trip) is a breakthrough process, which has benefits for both suppliers and customers. Among various advantages, the reduction in the customer's ingot inventory, in the energy costs and the benefits of not re-melting must be pointed out. Regarding energy savings, an increase in the delivering aluminum temperature is welcome as it reduces the homogenization time in the customer's furnace, increasing its productivity. In order to attain this objective, the refractory's thermal insulation design, the crucible's pre-heating profile and their maintenance procedure are key parameters. In this work, these aspects will be addressed, highlighting the relevant role of refractories in order to attain the customer's target. It will be shown that refractory projects involve a systemic analysis, comprising not only a suitable selection of material but also application and maintenance aspects.

1 Introduction

Molten aluminum purchasing can result in various advantages. According to *Peterson* and *Blagg* [1], molten metal transportation means energy delivery as two expensive steps are avoided: the production of aluminum ingots by the supplier and their re-melting at the customer. On the other hand, safety and technical issues must be addressed to handle molten metals and set suitable logistics, aiming to inhibit metal freezing in the crucible.

In order to attain a successful process, the refractory selection and design of the molten aluminum transportation ladles are key-issues. The main wearing mechanisms for this application are: chemical attack by the metal, mechanical damage during cleaning and thermal cycling [2]. Considering these aspects, the best refractory should be chemically stable, as well as being resistant to impact and thermal shock [3–5]. Besides this, a suitable thermal insulation is essential to save energy and provide high temperature molten aluminum to the customer.

Regarding the thermal properties [6–7], there are three different steps that must be considered:

(i) crucible pre-heating,
(ii) loading and transportation to the customer and
(iii) unloading and transportation of the empty crucible back to the aluminum producer.

Among them, the first one is of utmost importance to ensure a suitable delivering temperature (reduce heat exchange between the refractory and the metal) and also to minimize the refractory damage by thermal shock. The pre-heating schedule is designed to provide time for gradual heating of the refractory's internal lining surface up to a temperature close to the molten metal. Afterwards, a soaking time is required in order to make sure that the crucible is close to the equilibrium condition and ready for aluminum tapping. When this step is over, the molten metal is then loaded and the crucible is placed on a truck. On the road, the temperature of the molten metal starts to decrease as heat is transferred from the metal to the refractory and to the environment.

Alcoa-Poços operation has a long-term relationship with a customer located roughly 200 km far from the melting shop (4 h of transportation). Besides safety, the initial challenge was to ensure no molten metal freezing (<630 °C) due to thermal losses and arrival temperatures close to a target of 720 °C. However, from the learning attained by the customer and also by the producer, an outstanding improvement opportunity showed up as by increasing the arrival molten aluminum temperature from 720 °C to 740 °C would boost the customer's productivity (lower waiting time for aluminum temperature stabilization in their furnace) and reduce its gas consumption, directly affecting their operational

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Keywords: molten metal delivery, energy savings, thermal efficiency

Received: 14.01.2013
Accepted: 15.06.2013

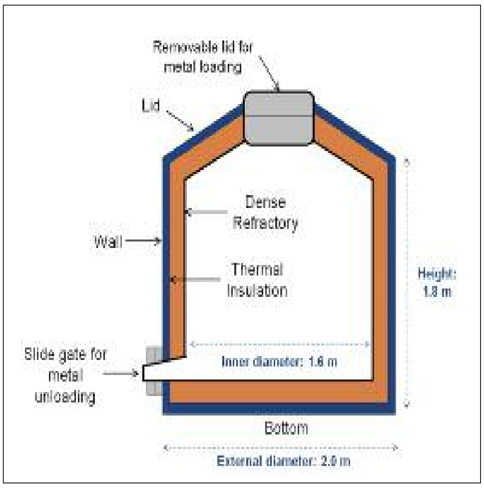

Fig. 1 **Schematic design of a molten aluminum transportation crucible [8]**

costs. This article points out how refractories affect this objective and the complexity of this issue, requiring a systemic view involving processing parameters and extensive team work to attain a successful performance.

2 Crucible design: refractory lining and insulation

Fig. 1 presents a schematic view of a molten aluminum transportation crucible [8], comprising of a dense refractory for aluminum contact, an insulating layer to inhibit heat loss and metal freezing, a removable lid (where the metal is loaded) and a slide gate valve (where the metal is tapped at the customer furnace's trough). Alcoa has four crucibles available by using this design (crucibles No. 1, 3, 4, 5) and also a different one, which besides these two layers (dense and insulating), a microporous one was added (3rd layer), with a very low thermal conductivity and better insulation effectiveness (crucible No. 2).

3 Initial trials to improve thermal efficiency

Aiming to increase the delivering temperature at the customer, two attempts that could improve the thermal insulation in a short period of time and without a significant cost increase were carried out at the crucible's lid (Fig. 2):

(i) the application of a high-emissivity coating [9] that could inhibit the heat loss to the surroundings, reducing the molten metal temperature and

(ii) the addition of a calcium silicate insulating layer [10], which presents very low thermal conductivity and high chemical resistance to the aluminum contact.

Nevertheless, after these trials it was noticed that there was a large variability in the arrival temperatures, pointing out that before any improvement on the refractory lining, it was essential to reanalyze the processing steps in order to reduce the temperature scattering and increase the delivering temperatures.

4 Effect of the refractories life on the processing parameters

Among various evaluated parameters (crucibles' pre-heating, time to place the lid after loading the metal, temperature loss in the furnace's trough, volume of molten metal in the crucible, weather conditions and so on), the pre-heating step showed a close correlation with the exit temperature (at the supplier) and consequently arrival temperature (at the customer).

Considering this aspect, the crucibles' pre-heating curves were then evaluated for two different ladles: crucible No. 4, which had a new refractory lining, and crucible No. 3, in which the lining was in use for 5 years having only short repairing halts during this period in order to inhibit metal infiltration in its cracks. The analysis of the pre-heating curves generally indicated a remarkable difference between the theoretical pre-heater set point temperature and the actual crucible's one, measured by an inner thermocouple. Fig. 3a presents this behavior for crucible No. 3, but a similar profile was also detected for crucibles No. 1, 2 and 5, all of them having a long working life (>4 years). Conversely, the new refractory lining of crucible's No. 4 led to a different pre-heating profile, in which the theoretical curve was closely followed (Fig. 3b). In addition, the pre-heater gas consumption, shown in both Figures, pointed out a reduction of roughly 6 % for crucible No. 4, when compared to the others. These results indicated that a new refractory lining is an important aspect to better follow the heating curve profile, ensuring lower heat exchange between the molten metal and the refractory, whereas older and damaged refractories are not able to closely follow the theoretical curve, leading to higher gas consumption, poor soaking time, lower thermal stability and, therefore, less ability to keep the molten metal temperature, which leads to lower delivering temperature values.

Due to formal commercial agreement, in which a set volume of molten metal must be delivered to the customer per month, it was not possible to send all these old crucibles for a full refractory re-lining. Instead, a processing counteraction was conducted. Before this evaluation, four out of the five crucibles were available for transportation (every week, one of the five crucibles was halted for partial repairings in order to minimize the cracking effect and ensure safety during the process). Nevertheless, with four crucibles running, a shortcome was detected: while one crucible was transporting the molten metal (4 h journey) and the other one was on the way back from the customer (also 4 h journey), there were two other available ladles to start the pre-heating, but they were at room temperature. Conversely, by operating with three crucibles per week instead of four, this waiting running time was reduced (as the crucibles were then used more often), leading to a higher actual

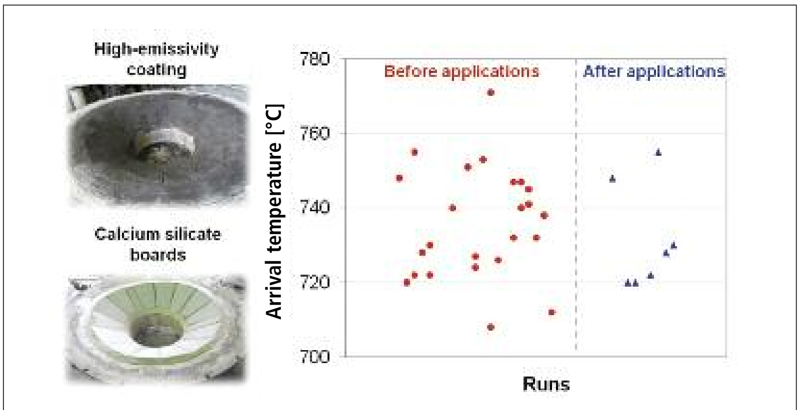

Fig. 2 **Applications at the crucible's lid and arrival temperatures' variability**

crucible's temperature when starting the pre-heating step (roughly 400 °C). Consequently, as the initial theoretical pre-heating temperature is 600 °C (it cannot start at room temperature, due to process time restriction to ensure the monthly molten aluminum volume delivery), the crucibles were more prone to follow the theoretical curve, even with a longer lining working life. Fig. 4 shows the new pre-heating profile of crucible No. 3 (old one), indicating almost no difference between the theoretical and actual curves and a reduction in the gas consumption, which also has a positive financial impact.

Tab. 1 presents the arrival temperature results before and after this process change. For the old crucibles (No. 2 and 3) a considerable increase in the average temperature was detected, pointing out that working with 3 crucibles/week instead of 4 was a suitable alternative to provide higher energetic efficiency (in terms of pre-heating and delivered temperature) and lower gas consumption during pre-heating, resulting in cost savings.

4.1 Evaluation of the arrival temperature per crucible

Considering the relevant impact of the refractories' working life on the pre-heating curves and the correlation between the pre-heating step and the arrival temperature, the percentage of temperatures below the initial customer's target (720 °C) was calculated for each crucible for 5 months before the pre-heating adjustment (Tab. 2).

Comparing crucibles No. 1, 3 and 5, the longer the working life the higher the percentage of temperatures below 720 °C was, as expected. Nevertheless, the results of crucible No. 2 must be highlighted, as no temperature below the target was observed. This ladle has a third layer of insulating material (microporous board), pointing out that the thermal insulation materials also play a relevant role on the arrival temperature. Based on these observations, from now on all crucibles will be designed with a similar thermal project as No. 2.

Due to this work, an additional procedure was established: every 6 months, the older crucible will be subjected to an overall refractory and insulation re-lining in order to ensure constant high temperature delivery to the customer.

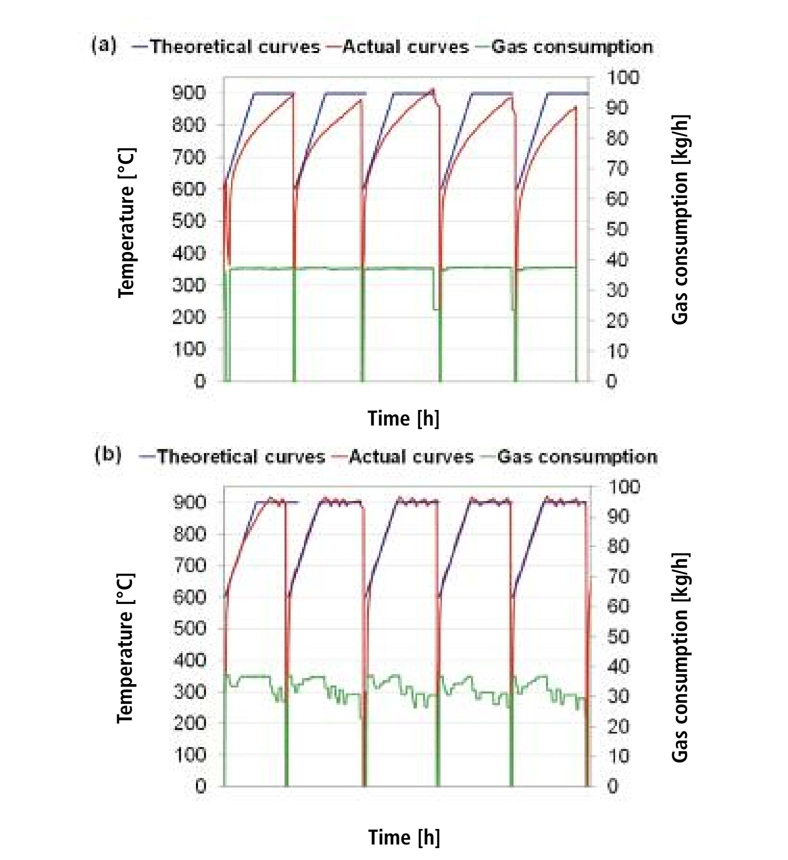

Fig. 3a–b Pre-heating curves (theoretical and actual) of: (a) crucible No. 3 (5 years of operation) and (b) crucible No. 4 (new refractory lining)

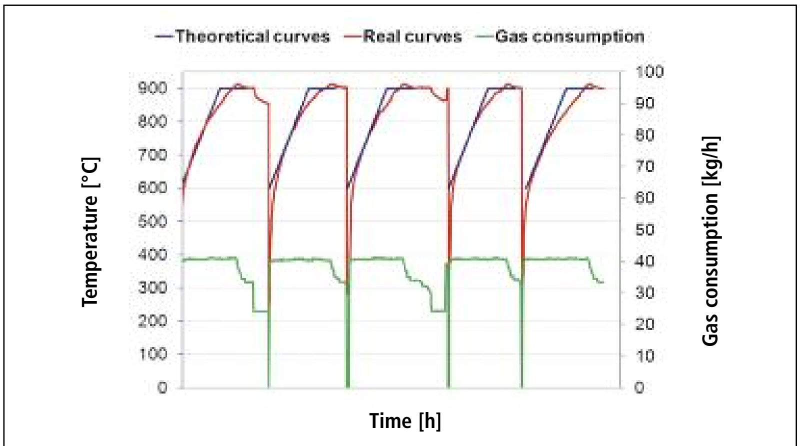

Fig. 4 Pre-heating curves (theoretical and real) of crucible No. 3 (5 years of operation), after establishing a new process procedure

Tab. 1 Temperatures attained before and after pre-heating evaluations and counteraction*

Arrival Temperatures [°C]		
Crucible*	**Before**	**After**
2	741 ± 15	751 ± 17
3	734 ± 8	746 ± 11
4	741 ± 14	742 ± 9

* Crucible 1 and 5 were on maintenance the week before or after testing, respectively.

Tab. 2 **Percentage of delivering temperatures below the target for each crucible in use***

Percentage of Delivering Temperatures Below 720 °C [%]				
Months	Crucible No. 1 (5 years of operation)	Crucible No. 2 (4,5 years of operation)	Crucible No. 3 (5 years of operation)	Crucible No. 5 (4 years of operation)
1	14	0	11	6
2	14	0	13	3
3	0	0	8	0
4	4	0	9	4
5	4	0	19	5
Average	7	0	12	4

* Crucible No. 4 was not in operation and was undergoing overall maintenance at this period due to safety reasons (molten metal leakage)

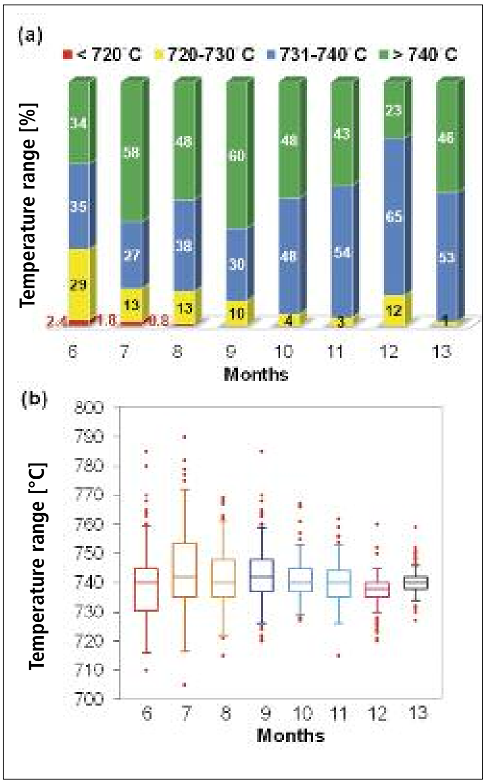

Fig. 5a–b **Percentage of molten metal delivering temperatures for different temperature ranges, before (months 6 and 7) and after (8–13) process adjustments (a), and "box plot" evaluation of molten metal delivering temperatures (b)**

5 Effect of the systemic evaluation on the arrival temperature

After the improvements carried out and due to the constant operational training and better process control, it was noticed that there was a remarkable reduction in the percentage of temperatures below the initial target of 720 °C (after month 9, no temperature was lower than this) and also an outstanding increase in the temperatures above the new challenging target established by the customer (740 °C), as shown in Fig. 5a.

In order to better evaluate these results, a "box plot" statistical analysis was conducted and the results are presented in Fig. 5b. Except for month 12, which is considered the coldest one in Brazilian Southeastern region (where transportation takes place), all average temperature was above 740 °C. Regarding the temperature decrease in the winter due to weather conditions, an improvement was detected: no crucibles were delivered with temperatures below 720 °C, whereas previously for the same month, 26 % of the crucibles arrived at the customer plant with temperatures <720 °C. Additionally, the temperature average also increased: 737 ± 6 °C (2012) versus 724 ± 15 °C (2011). Furthermore, the overall results indicate a decrease in the standard deviation (lower temperature scattering), solving the initial drawback of high variability, which was hiding the benefits of better insulation systems. By keeping this narrow variability, an additional increase in the arrival temperature can now be aimed at, by improving the crucibles' refractory lining design.

6 Final remarks

The main learning from this study is that when working with refractories, one must not only focus on their selection and design, but rather draw attention to the importance of a systemic overview, which also involves their processing, application and maintenance in order to attain an expected performance. Initial trials to improve the thermal efficiency pointed out that improvements could only be noticed if a standardized and controlled process is carried out. Therefore, before suggesting any novel material, the main process parameter (crucibles' pre-heating step) that was affecting the arrival temperatures' variability was evaluated and a counteraction was able to improve it. As a result, both lower heat exchange and heating gas consumption were ensured, leading to higher molten metal arrival temperatures and attaining the customer need (target temperature of 740 °C). As the process is now under full control, the next step will be the change of the refractories and insulation design, leading to even greater temperatures and resulting in lower energy consumption (and costs) and higher productivity for the customer.

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