Light Metals 2012 *Edited by: Carlos E. Suarez*
TMS (The Minerals, Metals & Materials Society), 2012

ENERGY AND MAINTENANCE COST SAVINGS REVIEW AT SEVERAL US ALUMINUM DIE CAST MANUFACTURERS USING UNIQUE, NON-WETTING, MICRO-POROUS REFRACTORY PRODUCTS

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Keywords: Aluminum, Refractory, Furnace, Energy, Maintenance, Corundum

Abstract

Over the past several years, many aluminum processors in North America have used unique, inherently non-wetting, non-reactive, micro-porous refractory products from Westmoreland Advanced Materials, Inc. to line their melting and holding furnaces, as well as their molten metal transport systems. These manufacturers have experienced significant energy and maintenance cost savings through the use of this unique refractory technology. A review of the technology that was used to develop these unique refractory products, along with specific examples of the energy and maintenance cost savings from several customers are presented.

Introduction

Refractory Usage

Refractories are used in the production of aluminum to contain the thermal processes and to provide protection for personnel, furnace structures, and engineering components such as hydraulics. In order to be successful, the refractory must possess several beneficial properties, including resistance to the various wear mechanisms inherent to the process. It must also possess a thermal conductivity that suits the energy requirements of the process. Historically, dense, highly thermal conductive refractories have been used as working linings to provide wear resistance and process containment. Secondary layers of less dense, more thermally insulating materials have been used to reduce heat loss through the lining. This results in the metal freeze plane being located at or in these secondary layers; an inherently unsafe condition.

The energy efficiency of aluminum processing is greatly affected by the properties of the refractories used to line the processing equipment. This is true not only after initial installation, but throughout the refractory's service life. Thus, energy efficiency as a function of service time is a major component of the 'cost to produce' for aluminum processors. In February of 2003, the aluminum industry released its technology roadmap [1]. Six R&D needs were identified and one of these needs was Energy Efficient Technologies. Within this need, the top priority listed was the development and design of furnaces with improved cost effectiveness and energy efficiency.

Aluminum Production Issues

In addition to having a significant impact on energy efficiency, refractories can affect other aspects of the aluminum production process. These include: the quantity and quality of aluminum metal produced; the amount and frequency of furnace maintenance; safety and the overall service life of the furnace. This is due to the reactions which can occur between the refractory lining, the molten aluminum, fluxing agents and the atmosphere within the furnace. These reactions can: reduce the service life of the refractory lining; impede the desired production process; cause impurities in the metal; and/or cause unscheduled furnace maintenance outages. In a worse case; metal can be in contact with the shell or even released from the vessel.

Corundum Formation

One such reaction is corundum formation. Corundum is a form of aluminum oxide (Al_2O_3) also known as alpha alumina. This material can form as a result of oxidation of liquid aluminum metal in a furnace. Once the corundum build up reaches a certain size and volume, it can interfere with the physical operations of the furnace. It can impede the charging process; cause doors and ports to close improperly; deflect burner flames; insulate the metal from desired heat transfer; reduce the working volume of the furnace; and cause inclusions within the metal. Aluminum producers remove corundum by physically scraping the walls of the furnace with a mechanical device. In this process, the refractory can be damaged in several ways.

First, if the corundum is strongly bonded to the refractory surface and inside the refractory's open porosity, removing the formed corundum will also remove part of the refractory, thereby damaging the lining and causing metal inclusions. A study was conducted by WAM to evaluate the strength of formed corundum [2]. In this study, the strengths of corundum both at room temperature (cold cleaning) and molten aluminum processing temperatures (hot cleaning) was determined. The results indicated that corundum formed within a furnace is significantly stronger than any known refractory material at both of these temperatures. Therefore, when corundum bonded to the refractory is mechanically removed the weaker of the two materials will always fail and that will be the refractory.

Second, formation and penetration of corundum within the refractory lining can cause stress fractures. This results in the lining being more susceptible to thermal cycling and can increase the likelihood that mechanical cleaning will damage the lining and cause oxide inclusions.

Air is the most readily available source of oxygen for the formation of corundum. Since aluminum furnaces are constantly being opened and closed for charging and cleaning, and due to poor sealing around doors and ports, it is difficult to completely eliminate oxygen from the process. A second source of oxygen is attributed to the reduction of metal oxides such as phosphorous pentoxide (P_2O_5), silica (SiO_2), titania (TiO_2), iron oxide (Fe_2O_3), etc... which are often components of refractory materials. Aluminum metal can penetrate the porosity of the refractory and reduce certain metal oxides to metal by preferentially bonding with the oxygen to form corundum within the refractory pore structure. This corundum formation results in physical damage to the refractory, in the form of cracks. The cracks are caused by the shear stresses set up within the refractory due to the thermal expansion differences between the corundum and the other mineralogical phases present. These cracks exacerbate the problem by allowing further penetration of aluminum metal and continued repetition of this process. Eventually, this causes the refractory lining to wear to the point of having to be replaced. The physical erosion of the refractory lining can also cause refractory inclusions to be present within the metal. Finally, in addition to the physical damage it can cause, aluminum metal penetration as well as corundum formation increases the average thermal conductivity of the refractory lining. This is important because metal penetration results in more heat loss through the furnace lining as time goes on. This will increase the energy required to maintain temperature, or worse, make it impossible to hold temperature in the furnace. In either case, the energy efficiency is compromised even though the refractory lining may still be physically intact.

Spinel Formation

Another reaction that can occur between the refractory and the environment within an aluminum furnace is the formation of spinel. A magnesium-aluminate spinel mineral ($MgAl_2O_4$) can be formed by the reaction of aluminum and magnesium at elevated temperatures in the presence of oxygen. Certain alloys of aluminum, such as 7075, contain magnesium metal. When these alloys are exposed to free oxygen, spinel can form. The formation of this crystalline phase is an expansive one, and if it takes place within the porosity of a refractory, physical damage in the form of cracking can occur. Spinel formation can cause similar operational problems as those described for corundum formation such as: physical damage and erosion of the refractory lining; inclusions being trapped in the metal; and increased thermal conductivity due to metal penetration into the refractory lining.

Freeze Plane Placement

In all cases where a dense, highly thermal conductive hot face lining is utilized the freeze plane of the molten metal is typically located at the interface between the dense hot face and a more thermally insulating backup or secondary lining. This situation enhances the wear and reaction mechanisms described in the previous paragraphs by allowing highly reactive molten metal to penetrate deep within the refractory via the refractory's inherent porosity (commonly referred to as 'wicking') or by following stress fractures created by mechanisms described previously.

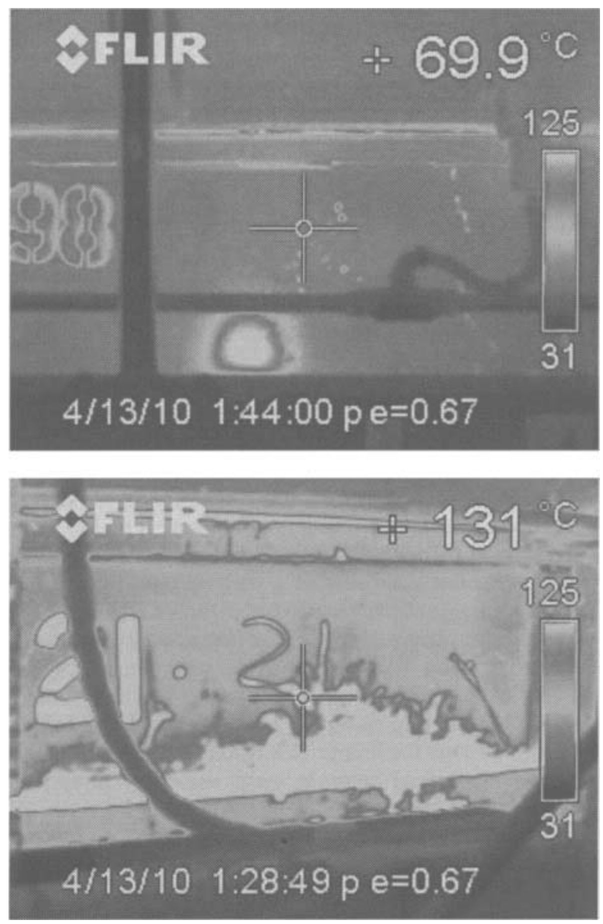

Figure 1: top is a FLIR image of a launder showing metal reaching shell (hot spot); bottom is a FLIR image of launder where the metal eventully enlarged the hot spot and ran into the bottom of the shell.

Once molten metal can access the backup or secondary materials, the metal will almost always continue to the shell where it will finally freeze in contact with the highly thermal conductive steel shell. This creates a 'hot spot' (Fig 1) on the shell and represents a major cause of energy loss during the operation of the vessel. This also causes the 'heaving' seen in many furnace walls and hearths, especially in dry hearth operations where the cyclic thermal conditions exasperate the problem of stress fractures. A major cause of concern is if there is no steel shell present to contain and freeze the metal. This can result in hot metal breaching containment.

Refractory Development

Refractory Aggregate Development

In 2003, Westmoreland Advanced Materials™ (WAM®) initiated a research study under the Department of Energy Small Business Innovative Research Grant DE-FG02-04ER84118 [3] to develop a new type of micro-porous refractory aggregate and subsequent monolithic refractory products for use in molten aluminum contact applications. The desired characteristics of the aggregate included:

- a very fine pore structure small enough to prevent molten aluminum metal from penetrating into the refractory
- a large volume of very fine pores well distributed throughout the aggregate to provide improved insulating capability;
- a low coefficient of thermal conductivity to reduce heat loss and energy consumption;
- a chemistry and mineralogy that were non-wetting to aluminum metal; and
- a chemistry and mineralogy that would significantly reduce or eliminate the formation, attachment and growth of corundum and/or magnesium aluminate spinel within the aggregate.

The details of the refractory aggregate development can be found in an earlier publication [4].

Refractory Castable Development

Once the appropriate micro-porous refractory aggregate was discovered, the development of a new refractory castable based on this raw material was initiated. Specific objectives were set forth in the research study which focused on energy efficiency and suitability for molten aluminum contact. Ease of installation was also determined to be an important objective. The details of the refractory castable development can also be found in an earlier publication [4]. In summary, Mix D-1 from this study had a unique combination of features including:

- A high percentage of porosity, with an average effective pore diameter of less than 4 microns.This average diameter prohibits metal penetration due to the surface tension of molten aluminum. It also provides excellent insulating capacity as the overall pore volume is approximately 45%.
- Less than 0.3% silica (SiO_2), and phosphorous pentoxide (P_2O_5) eliminating two major sources of oxygen that can contribute to corundum formation on and within the refractory.
- A Coefficient of Thermal Conductivity of < 1.0 W/m-°C at normal operating temperatures, allowing for a significant improvement in energy efficiency. And placement of the metal freeze plane in the working lining.
- Homogenous mineralogy resulting in uniform resistance to aluminum penetration, uniform thermal expansion and very good thermal shock resistance comparable to that of amorphous silica compositions.
- Strengths approaching those of low cement castables, and exceeding those of most ceramic fiber board and other insulating products, thus limiting degradation of the lining because of damage due to mechanical cleaning operations.
- Conventional castable type installation characteristics requiring only blending with water and vibration casting for proper placement.

Service Results

Pace Industries, Airo Division

In addition to the laboratory work conducted to develop the refractory aggregate and castable, the research study also involved conducting service trials of the castable in various aluminum contact applications at manufacturing facilities. Pace Industries, Airo Division (Airo), an aluminum die casting facility located in Loyalhanna, Pennsylvania. Airo agreed to perform a side-by-side comparison of Mix D-1 versus a standard, 80% alumina, phosphate-bonded, two component refractory composition (Standard Refractory) typically used by Airo. This side-by-side evaluation was conducted using two identical high pressure die cast holding furnaces with identical insulating back up linings. The only difference was the three inch thick hot face lining consisting of either Mix D-1 (DOE-1) or the Standard Refractory (DOE-2). Details of this study can be found in prior literature [4, 5]. The results of this evaluation found in Table I show an energy savings of 15.6%.

Table I. Original Energy Consumption Comparison for the DOE-1 and DOE-2 Holding Furnaces

Furnace Designation:	DOE-1	DOE-2
Data Collection Time Frame:	November of 2004	
Hot Face Refractory:	Mix D-1	Standard Material
Metal Temperature:	682°C	682°C
Energy Usage for 7 Days:	2,920 kWh	3,460 kWh
Energy Usage Difference:	540 kWh per week	
Energy Savings:	15.6%	

In addition to being a more energy efficient hot face lining refractory, the personnel in charge of furnace maintenance at Airo found that Mix D-1 exhibited less corundum buildup and was much easier to clean than the Standard Refractory. Photographs of the DOE-1 and DOE-2

Furnaces during a cold cleaning after approximately one year of service can be seen in Figures 2 and 3.

Figure 2. DOE-1 Furnace during a cold cleaning after ~1 year of service.

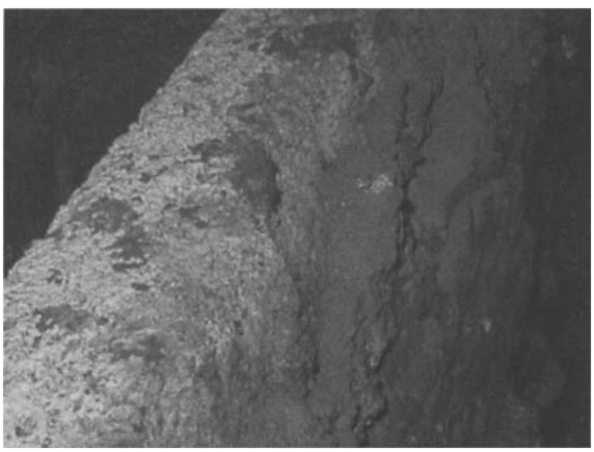

Figure 3. DOE-2 Furnace during a cold cleaning after ~1 year of service.

The service life and performance of these holding furnaces continued to be monitored by Airo and WAM® over the next three years. In the fall of 2007, Airo determined that the DOE-2 furnace containing the Standard Refractory was no longer "holding temperature" and the refractory lining would have to be replaced. However, at the same time it was determined that the DOE-1 furnace containing the Mix D-1 was still performing well. It was decided to take updated energy measurements from both the DOE furnaces prior to removing the DOE-2 furnace from service. Details of this study can be found in prior literature [5]. It was determined that the energy savings per pound of metal produced by using Mix D-1 as the hot face lining had increased to 53% (see Tale II). Note, because of the thermal loss with DOE-2 the metal throughput of the two furnaces could not be kept identical. Therefore, energy use was measured as a function of metal processed is this later evaluation.

Table II. Updated Energy Consumption Comparison for the DOE-1 and DOE-2 Holding Furnaces

Furnace Designation:	DOE-1	DOE-2
Data Collection Time Frame:	December of 2007	
Hot Face Refractory:	Mix D-1	Standard Material
Metal Temperature:	686°C	686°C
Energy Usage in 27 hours	458 kWh	516 kWh
Amount of Metal Processed	6778 lbs	3529 lbs
Energy per Metal Processed	0.068 kWh/lb	0.146 kWh/lb
Energy Savings	53%	

The increased energy usage of the DOE-2 furnace lined with the Standard Refractory was a result of aluminum metal penetration and corundum growth within the lining resulting in a higher average thermal conductivity of the lining and as a result, greater heat loss. It was also a result of reduced overall lining thickness due to refractory damage resulting from the cleaning process required to remove bonded corundum. In either case, the results in Table II show that the use of Mix D-1 as a hot face lining continued to provid and actually significantly increased energy savings as a function of time compared to that of the Standard Refractory after 3 years of service. This highlights the importance of considering the energy efficiency of the refractory over the lifetime of the vessel as opposed to only at installation.

In light of the positive service trial results obtained during the original DOE research study, Airo switched to using Mix D-1 in the hot face refractory linings for all subsequent holding furnace re-builds. Airo also relined both its central melt reverb furnaces with Mix D-1 as the primary hot face lining material, one in 2006 and the other in 2010. Both of these furnaces have shown significant energy and maintenance cost savings compared with the same furnaces previously lined with competitive refractory materials. One previous wear issue, heaving of the furnace walls, was completely eliminated. More details regarding the 2006 central melt furnace reline and subsequent cost savings can be found in an earlier publication [5].

High Metal Temperature and Corrosive Application

A variant of Mix D-1 was evaluated at a customer who employed an unusually high metal temperature of greater than 1150°C and an aluminum alloy that was typically very corrosive to the hot face refractory lining. Prior to the use of the Mix D-1 variant, the refractory linings used in this application were high purity, tabular alumina based materials which only lasted about 6 months. The hot face refractory and back up material would be severely penetrated and disrupted by the aluminum alloy and subsequent corundum. Therefore, the thermal and safety protection normally supplied by the refractory was severly compromised, and the lining would have to be replaced.

After switching to the use of the Mix D-1 variant, the service life of the furnaces have been extended to 3 years. Also, significant energy and maintenance cost savings have been obtained by this customer, since the original thermally conductive alumina was replaced by the termally insulating Mix D-1 varient. This customer solved his reactivity issue and gained an energy efficiency benefit.

Southeast Automotive Die Caster

An Automotive Die Caster located in the southeastern part of the United States first trialed Mix D-1 in several lauder sections at its facility. A 25% energy savings was experienced in these lauders and they were significantly easier to clean and maintain. Due to this success, this facility lined one of its holding furnaces with Mix D-1, Within 2 months it was experiencing 20% energy savings and after 14 months it was experiencing 46% energy savings with the use of Mix D-1 compared to a furnace lined with a standard competitive refractory material. In light of the successful results obtained during these initial trials, this facility has converted all but one of its holding furnaces to Mix D-1. The final furnace will be converted once the current lining has reached the end of its life. In addition to the energy saving, this facility has documented a 65% reduction in maintenance costs and has extended its maintenance frequency from 6 months to 12 months per holding furnace. This reduced down time has improved the overall plant efficiency by eliminating a significant amount of lost production.

Midwest Automotive Die Caster

After hearing about the success at the first Automotive Die Caster, another Automotive Die Caster located in the Midwest lined one of its gas fired reverb furnaces with Mix D-1. It had also relined a duplicate furnace using the same lining configuration, except a 70% mullite based competitive refractory containing an industry standard aluminum penetration additive was used as the hot face lining. This facility experienced a 32% reduction in gas usage as well as significant maintenance savings. In addition to the use of Mix D-1 in its reverb furnace, this facility began to use another variant of Mix D-1 in one of its stack melters. Prior to the use of this variant, this facility experienced major corundum growth and penetration in the stack as well as corundum penetration in the holder. This required approximately $50,000 in repair costs and 100 hours of furnace downtime. With the use of this variant, the cold cleaning time has been reduced to one 8 hour shift, saving a documented $30,000 in repair costs. Furthermore, the maintenance frequency has been extended from 6 months to 12 months in the stack melter thereby reducing lost production capacity.

Second Midwest Automotive Die Caster

A second Midwest Automotive Die Caster has used Mix D-1 in the holding sections of its stack melters. So far this facility has experienced a 10% reduction in energy costs and approximatley 45% reduction in repair and maintenance costs with the use of this material. This facility has also encountered some issues with major corundum growth and penetration in the stack sections of its melters. In order to elevate this problem, this facility is running a trial of a pressed and burned refractory brick based on the same technology used in Mix D-1. It is still relatively early, but thus far the brick are performing very well in this highly corrosive and erosive area.

AL-REC LLC

A second trial of the pressed and burned refractory brick based on the same technology used in Mix D-1 is currently being run at AL-REC LLC in Millwood, WV. The brick are in an impact area at the head of a trough system that sits underneath a rotary-type, aluminum recycling furnace (see Figure 4). The aluminum metal cascades down about 5 feet from the mouth of the furnace to the impact area of the trough at a rate of 1500 pounds per minute. This impact area represents a very corrosive and erosive refractory application. Service trial reports thus far indicate that the brick linded impact area exhibits a flat surface and no apparent concavity or loose material. The general manager of AL-REC LLC has relayed that "the brick are doing great... and holding up better than anything tried before![6]"

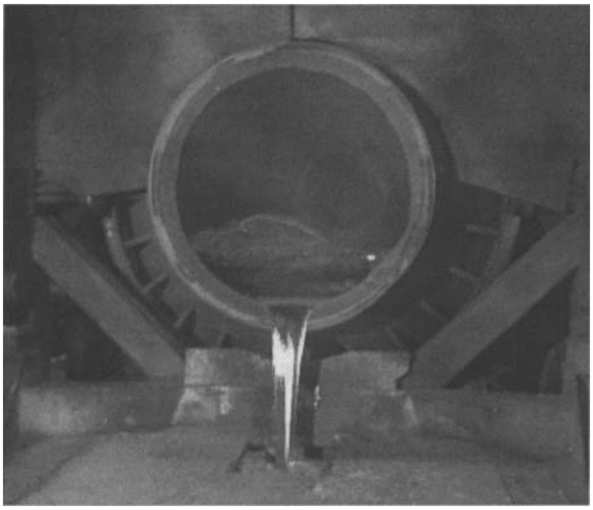

Figure 4. AL-REC Rotary-Type Aluminum Recycling Furnace discharging molten aluminum onto an impact pad made with Mix D-1 type brick.

Additional Product Developments

In addition to the new castable compositions and the variants discussed above, other refractory products based on the same technology as Mix D-1 have been developed. A gunning mix variant was developed and a service trial was conducted in a holding furnace at an aluminum producer in Ontario, Canada. After approximately 6 months of service the material was evaluated. The customer reported that the gunned lining was performing very well. Significantly improved penetration resistance and reduced corundum formation was noted. It was also reported by the maintenance staff that this furnace was much easier to clean compared to other furnaces utilizing industry standard refractory linings.

After 5 years of service Airo used this gunning mix variant to replace refractory in a slightly dished out bellyband area in one of its reverb furnace previously lined with Mix D-1. It was reported that during the cold cleaning the aluminum and surface corundum was easily cleaned off of the original lining after which a skim coat of the gunning mix was applied to the bellyband and roof sections. After several months of service the repair material has performed as well as the initial installed lining. Periodic hot cleaning remains easy and the energy efficiency is equivalent to the castable counterpart.

A stronger and denser castable variant based on the unique technology of Mix D-1 was developed for use in highly corrosive and erosive applications. This variant has been used in areas of furnaces such as ramps, sills, jambs and lintels or similar areas that experience a high degree of mechanical abuse or impact. Additional examples include transfer ladles, troughs and launders that experience impacts of high velocity steams of molten aluminum eminating from melting or holding furnaces. This stronger and denser material has proven to be an excellent performer and problem solver for these adverse conditions. It should be noted that although the dense variant provides excellent resistance to chemical reaction, abrasion and impact, it does not provide the energy efficiency achievable with the original micro-porous Mix D-1. Therefore, when designing a furnace lining the use of the high density variant should be limited to high wear areas or in highly chemical reactive environments (high flux or salt bath applications for example) in order to retain the best overall energy efficiency for the process equipment of interest.

Future efforts are being expended on the development of a a lighter weight variant of Mix D-1. Application areas for this variant include furnace roofs and over-the-road crucibles. A complete family of products has been developed around this unique and patented technology. However, we will continue to refine the physical properties and installation characteristics for these products as aluminum processing demands dictate. Applications for this unique refractory technology are not limited to aluminum. Other industry applications are being explored relating to zinc, lead and magnesium production, as well as minerals processing, pulp and paper and power generation.

Conclusion

A unique refractory technology was developed to answer a specific need identified by the aluminum industry. This effort was identified as urgent and was supported by the U.S Department of Energy. Over the past several years, many aluminum processors and manufacturers in North America have implimented and evaluated the unique, inherently non-wetting, non-reactive, micro-porous refractory products which were developed based on this technology. Processors evaluated these products in all aspects of their process including primary melting and holding furnaces, transfer ladles and molten metal transport systems such as troughs and heated launders. When utilizing these products manufacturers have measured and documented significant energy and maintenance cost savings. They have also greatly improved manufacturing efficiencies by significanly reducing lost production due to down time required for furnace maintenance. Several U.S. and international patents have been awarded and several additional compositional and methods patents are pending for this technology. Westmoreland Advanced Materials, Inc. is the sole owner of this family of technologies.

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