# Practical Experience with an Energy Efficient, Micro-Porous Refractory Castable in Various Molten Aluminum Contact Applications

R.M. Cullen
Westmoreland Advanced Materials, LLC, Monessen, Pennsylvania

D.P. Hill
Airo Die Casting, Inc., Loyalhanna, Pennsylvania

## ABSTRACT

An energy efficient, micro-porous refractory castable was developed for use in molten aluminum contact applications under a grant from the U.S Department of Energy. Practical experience with WAM® AL II at an aluminum die cast facility, both after initial installation and 3 years of service, is discussed. Emphasis is placed on heat flux through the refractory lining, measured energy savings, corundum growth, ease of cleaning and other maintenance issues. Finally, practical experience in other molten aluminum contact applications, as well as additional refractory technology developments, is discussed.

## ORIGINAL RESEARCH STUDY

### DEVELOPMENT OF A MICRO-PORUOS REFRACTORY AGGREGATE

In 2003, Westmoreland Advanced Materials™ (WAM®) initiated a research study under the Department of Energy Small Business Innovative Research Grant DE-FG02-04ER84118[1] to develop a new type of micro-porous refractory aggregate and castable 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 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 a chemistry and mineralogy that were non-wetting to aluminum and would significantly reduce the attachment and growth of corundum and spinel. Several different aggregates were evaluated, and the physical and chemical properties for the preferred aggregate are listed in Table 1.

***Table 1. Physical and Chemical Properties for the Micro-Porous Refractory Aggregate***

| Description: | Micro-Porous Refractory Aggregate |
|---|---|
| Chemical Analysis, wt. %:<br>(Oxide Basis) | |
| Aluminum Oxide ($Al_2O_3$) | 71.8 |
| Calcium Oxide (CaO) | 27.0 |
| Silicon Dioxide ($SiO_2$) | 0.3 |
| Iron Oxide ($Fe_2O_3$) | 0.2 |
| Magnesium Oxide (MgO) | 0.4 |
| Sodium Oxide ($Na_2O$) | 0.3 |
| Physical Properties: | |
| Total Porosity | 57.65% |
| Total Pore Area | 0.56 $m^2/g$ |
| Average Pore Diameter | 3.75 µm |
| Bulk Density | 1.10 $g/cm^3$ |

## DEVELOPMENT OF A REFRACTORY CASTABLE

Once the appropriate refractory aggregate was determined, the development of a new refractory castable was initiated[2]. Specific objectives were set forth which focused on energy efficiency and suitability for molten aluminum contact, as well as ease of installation. The aggregate was screened into specific size fractions and additional fine materials were utilized to form the bonding phase. Several iterations of the castable were evaluated with Mix D-1 being chosen for further study. The physical properties for Mix D-1 were found in Table 2, and its unique combination of features are listed below:

- A high percentage of porosity, with an average effective pore diameter of less than 5 microns, which prohibits aluminum penetration and provides excellent insulating capacity.
- Less than 0.3% silica ($SiO_2$), eliminating one source of oxygen for corundum formation.
- A Coefficient of Thermal Conductivity of 1.0 W/m-°C at normal operating temperatures.
- Homogenous mineralogy resulting in uniform resistance to aluminum penetration and very good thermal shock resistance.
- Strengths exceeding those of most ceramic fiber board and other insulating products.
- Conventional castable type installation characteristics.

***Table 2. Physical Properties for Refractory Castable Mix D-1***

| Description: | Mix D-1 |
|---|---|
| Classification: | Aluminum Resistant<br>Standard Cement Castable |
| Installation Method: | Vibration Casting |
| Water Addition, wt. %: | 15 to 20 |
| Physical Properties: | |
| After Drying at 110°C | |
| Bulk Density, g/cm$^3$ | 2.07 |
| Modulus of Rupture, MPa | 7.1 |
| Cold Crushing Strength, MPa | 59.5 |
| After Heating to 816°C | |
| Bulk Density, g/cm$^3$ | 1.78 |
| Modulus of Rupture, MPa | 3.5 |
| Cold Crushing Strength, MPa | 24.1 |
| Permanent Linear Change, % | -0.1 |
| After Heating to 1371°C | |
| Bulk Density, g/cm$^3$ | 1.81 |
| Modulus of Rupture, MPa | 4.3 |
| Cold Crushing Strength, MPa | 18.0 |
| Permanent Linear Change, % | -0.4 |
| Thermal Conductivity, W/m-°C | |
| At 400°C | 1.02 |
| At 800°C | 1.02 |
| At 1200°C | 1.01 |
| Chemical Analysis, wt. %:<br>(Oxide Basis) | |
| Aluminum Oxide ($Al_2O_3$) | 66.3 |
| Calcium Oxide (CaO) | 24.9 |
| Silicon Dioxide ($SiO_2$) | 0.3 |
| Titanium Dioxide ($TiO_2$) | 0.1 |
| Iron Oxide ($Fe_2O_3$) | 0.1 |
| Magnesium Oxide (MgO) | 0.2 |
| Sodium Oxide ($Na_2O$) | 0.1 |
| Potassium Oxide ($K_2O$) | 0.1 |

| | |
|---|---|
| Barium Oxide (BaO) | 8.0 |

Mix D-1 was essentially made up of the micro-porous aggregate (coarse particles) bonded together by cement (fine particles). Figure 1 is a scanning electron microscope photograph of Mix D-1 showing a micro-porous aggregate surrounded by the bonding matrix. It is apparent that the fine pores (dark grey to black spots) within the micro-porous aggregate were completely isolated by the bonding matrix. Figure 2 is a magnified view of the grain boundary interface. The surface of the micro-porous aggregate reacted to a depth of approximately 50 μm with the surrounding matrix, thus making the original grain boundary almost indistinguishable. This surface reaction is shown in Figure 2 by the line marked "Rxn depth." Therefore, Mix D-1 appeared to be a true monolithic material which was another unique feature for this refractory castable.

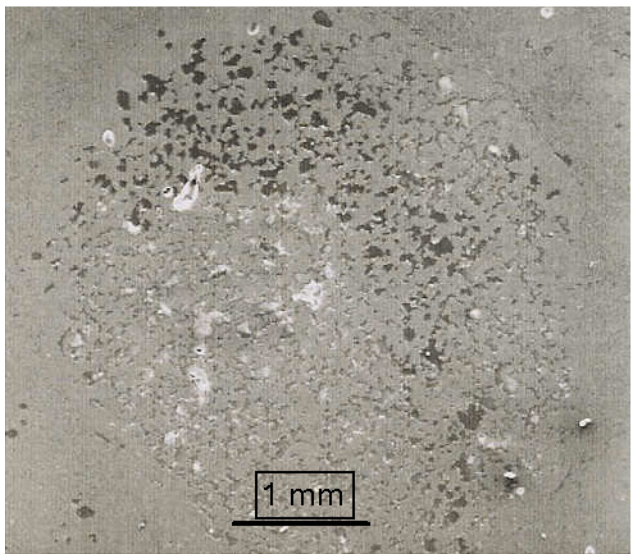


*Fig. 1. SEM Micrograph of Mix D-1*

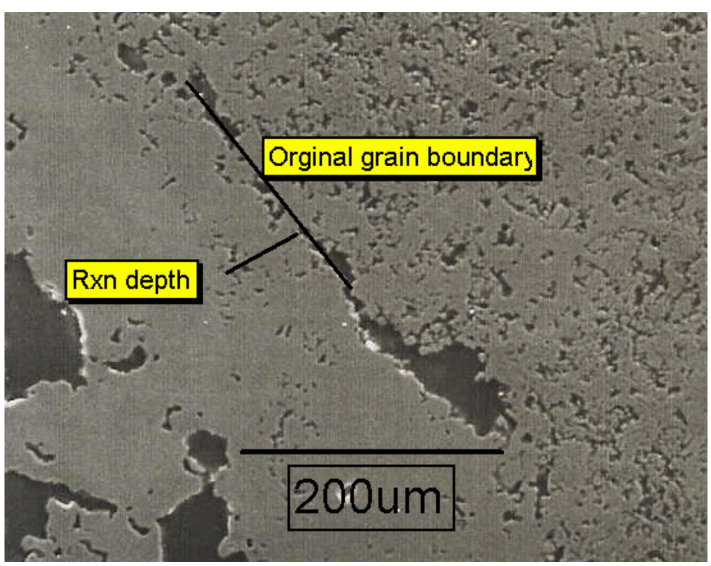


*Fig. 2. SEM Micrograph of Mix D-1*

## ORIGINAL SERVICE TRIAL RESULTS

In addition to the development of the refractory aggregate and castable, the research study also involved conducting service trials in various aluminum contact applications. WAM® enlisted the help of Airo Die Casting, Inc. (ADC), an aluminum die casting facility located in Loyalhanna, Pennsylvania. ADC 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 ADC[3]. The refractory linings in two identical high pressure die cast holding furnaces were completely removed. The new linings consisted of a 0.125 inch thick layer of insulating paper against the steel shell; followed by six inches of refractory block insulation; and a three inch thick hot face lining of either Mix D-1 or the Standard Refractory. The furnace containing Mix D-1 was designated DOE-1, while the one containing the Standard Refractory was designated DOE-2. Therefore, the only major variable between the DOE-1 and DOE-2 furnaces was the hot face refractory. A cross-sectional drawing of the holding furnace lining and is found in Figure 3.

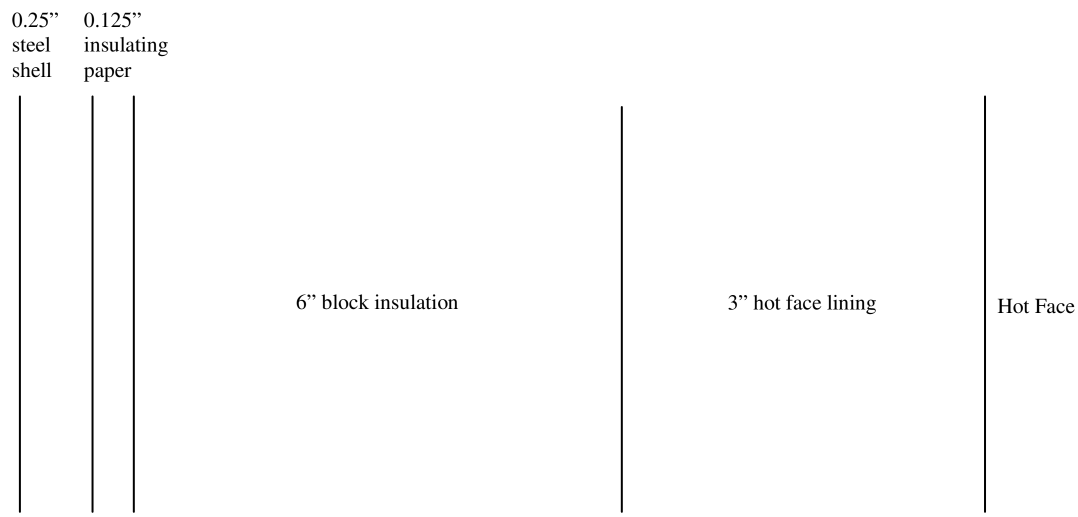


**Fig. 3. Cross-sectional Drawing of the Holding Furnace Lining Configuration**

The holding furnaces were put into service at the same time during November of 2004. In order to measure the energy efficiency, power meters were attached to both furnaces and the energy consumption was monitored. Over a seven day period, the same aluminum alloy and metal temperature were maintained in both furnaces. The energy consumption for the DOE-1 furnace was 2920 kWh, while the energy consumption for the DOE-2 furnace was 3,460 kWh. The difference was 540 kWh which translated to energy savings of 15.6%.

*Table 4: 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 Material: | Mix D-1 (Micro-Porous Aggregate Based Castable) | Standard Material (80% Alumina, Phosphate-Bonded, 2 Component Castable) |
| Aluminum Metal Temperature: | 682°C | 682°C |
| Energy Consumption for 7 Days | 2,920 kWh | 3,460 kWh |
| Energy Consumption Difference | 540 kWh per week | |
| Energy Consumption Savings | 15.6% | |

In addition to being a more energy efficient hot face refractory, the personnel in charge of furnace maintenance at ADC found that Mix D-1 exhibited less corundum buildup and was much easier to clean than the Standard Refractory. The head of furnace maintenance at ACD stated, "The (Mix D-1) furnace was much easier to clean and you only need to scrape the sidewalls with a pry bar to remove the corundum, whereas you need a 30 pound jackhammer to remove the corundum from the (Standard Refractory) furnace[4]." The reduced corundum buildup and ease of cleaning of Mix D-1 significantly reduced the amount of time and energy spent on furnace maintenance over the life of this furnace. Figures 4 and 5 are photographs taken of the DOE-1 and DOE-2 furnaces, respectively, during a "cold cleaning" after about one year of service. It is apparent from these photographs that Mix D-1 was not penetrated and was much easier to clean than the Standard Refractory.

*Fig. 4. Cold Cleaning of DOE-1 Furnace after 1 Year of Service*

***Fig. 5. Cold Cleaning of DOE-2 Furnace after 1 Year of Service***

**UPDATED SERVICE TRIAL RESULTS**

The service life and performance of both the DOE-1 and DOE-2 holding furnaces continued to be monitored over the next three years. In the fall of 2007, ADC determined that the DOE-2 furnace containing the Standard Refractory was no longer "holding temperature." Therefore, this furnace needed to be removed from service to replace the refractory. However, the DOE-1 furnace containing Mix D-1 was still performing well.

In order to determine if the energy efficiency of Mix D-1 was maintained, new energy measurements from both furnaces were taken. In December of 2007, power meters were re-attached and the energy consumption was monitored. Over a 27 hour period, the same aluminum alloy and the same metal temperature were maintained in both furnaces. The results of this evaluation are found in Table 5. The energy consumption for the DOE-1 furnace was 458 kWh, while the energy consumption for the DOE-2 furnace was 516 kWh. However, this time the amount of aluminum processed through each furnace was also recorded. Using this information, it was determined that the energy savings per pound of metal produced was 53%. The increased energy usage of the DOE-2 furnace lined with the Standard Refractory could have been caused by aluminum penetration and corundum growth within the lining resulting in higher thermal conductivity and heat loss. Also, it may have resulted from reduction of the lining thickness during the cleaning process. In either case, the results in Table 5 showed that the use of Mix D-1 as a hot face lining provided significant energy savings compared with that of the Standard Refractory, even after 3 years of service.

A comparison of the original and updated service trial results is important to note since they demonstrate the use of Mix D-1 not only provided significant energy savings during initial start up of the furnace, but these savings actually increased over time due to penetration and/or thinning of the Standard Refractory lining. It is speculated that other lighter weight refractories used in similar applications may provide similar or even slightly better energy saving initially. However, with time these materials would be penetrated by aluminum metal and/or be thinned during the cleaning process used to remove the corundum build up. Therefore, these lighter weight refractories would lose their energy efficiency over time. It is the unique combination of the micro-porosity (energy efficiency) and the mineralogy (non-wetting to aluminum) of Mix D-1 which allow it to perform so well in molten aluminum contact applications.

***Table 5. 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 Material: | Mix D-1 (Micro-Porous Aggregate Based Castable) | Standard Material (80% Alumina, Phosphate-Bonded, 2 Component Castable) |
| Aluminum Metal Temperature: | 686°C | 686°C |
| Energy Consumption for 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% | |

## ADDITIONAL APPLICATION RESULTS FROM ADC

In light of these results, ADC also decided to reline one of three central melt furnaces in January of 2006 using Mix D-1 as the hot face refractory. Two years later this furnace is considered quite well insulated compared to a similar furnace lined with the Standard Refractory. A recent temperature survey on the shells of these two furnaces yielded an average temperature of 76°C on the furnace lined with the Standard Refractory and 64°C on the furnace lined with Mix D-1. The furnace lined with Mix D-1 still exhibits corundum growth due to the reaction of atmospheric oxygen with the large surface area of the molten metal bath. However, the corundum does not adhere to furnace walls and is easy to scrape off with a manual rake. Figure 4 shows how the wall of the furnace has held up after 2 years of service. It is believed that if the furnace had been relined with the Standard Refractory, it would soon be time to do a belly band patch. Such patches have been performed on the other central melt furnaces at ADC at around 24 to 36 months. The use of Mix D-1 also requires no zoning in the belly band area so it can be used in both the lower and upper sidewalls.

*Fig. 6. Photograph of the Sidewall of the Central Melt Furnace*

## OTHER ALUMINUM INDUSTRY APPLICATIONS

In light of these successful service trials, other aluminum metal contact applications were solicited for Mix D-1, which has since been branded WAM® AL II. One such application involved a customer who employed an unusually high metal temperature of 1150°C and an aluminum alloy that was very corrosive to the refractory. Previous linings consisted of 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. Therefore, the thermal efficiency and safety protection normally supplied by the refractory would be gone, and the lining would have to be replaced. A small research furnace was initially installed with a variant of WAM® AL II in November of 2004, followed by the re-lining of a production furnace in January of 2005. According to this customer, as of January of 2008 both furnaces were still in service and performing very well. The energy savings originally calculated by this customer was 16%, and both furnaces have maintained this energy savings over the past 3 years.

Another customer, an automobile manufacturer located in the Southeast USA, has used WAM® AL II for the past few years to line several launder sections and die cast holding furnaces at its facility. This customer measured the energy usage of the furnaces lined with WAM® AL II and compared these results with those of similar furnaces lined with other refractory compositions. The customer initially determined an energy savings of 50% with the furnaces lined with WAM® AL II. However, the customer found this number hard to believe, so the measurements were repeated. This second set of measurements indicated an energy saving of 46%. This customer has also experienced a significant reduction in the amount of time and effort needed for furnace maintenance.

Other aluminum contact applications where WAM® AL II has been successfully used include: holding furnaces, launders and trough sections at various aluminum die cast facilities; covers and metal lines in over-the-road crucibles; lids for pot line transfer ladles at primary aluminum facilities; jet stirrers for secondary aluminum producers; and in certain applications at both zinc and lead producers. Additional trials are currently being conducted in several other applications, as well.

## ADDITIONAL PRODUCT DEVELOPMENTS

In addition to WAM® AL II, other refractory compositions based on this technology have been developed. A service trial for a gunning mix was run in a holding furnace at an aluminum producer in Ontario, Canada. As of January 2008, the material was in service for 6 months and the customer reported that the furnace was much easier to clean. Also, a very fine variant was developed for use as a coating for new and existing refractory linings; a patch or putty for cracks and holes in refractory linings; and as a parting medium for cast iron molds and troughs. A dense variant was developed for areas where high mechanical erosion or physical abuse are encountered. It provides the same "ease of cleaning" as the original formulation, but the energy savings is not as apparent due to its increased density. Finally, a lighter weight variant for use in over-the-road crucibles is currently under development.

## PRACTICAL CONSIDERATIONS

Development of a furnace lining refractory that is mineralogically non-wetting to aluminum and provides significant long term reduction in energy consumption can provide several practical advantages for aluminum producers. The measurable savings in energy cost per pound of finished product can contribute to a competitive advantage in the marketplace. Operationally, the time spent on furnace maintenance will be reduced, damage to furnace linings as a result of maintenance will be reduced and personnel will spend less time in proximity to molten metal to remove buildup. During scheduled maintenance, the downtime required to clean a lining in preparation for repairs will be reduced, which should result in shorter, less expensive outages.

## CONCLUSION

A micro-porous refractory aggregate and castable were developed under a grant from the U.S Department of Energy for use in molten aluminum contact applications. Practical experience with WAM® AL II at Airo Die Casting, Inc. demonstrated improved energy efficiency and required less time and effort to clean than the Standard Refractory. It resulted in lower furnace shell temperatures; significant energy savings; less corundum growth; and reduced maintenance costs. In light of these results, WAM® AL II has been used by several customers in various molten aluminum applications with similar success. Further refinement of this technology has resulted in the development of additional refractory products for the aluminum industry. U.S. Patent Number 7,368,010 was granted to Westmoreland Advanced Materials, LLC for this invention, and international patents are pending. Additional information regarding WAM AL II and other products offered by Westmoreland Advanced Materials, LLC can be found at www.westadmat.biz, or by calling 724-684-5902.

## REFERENCES

[1] U.S. Department of Energy Grant Number DE-FG02-04ER84118, Westmoreland Advanced Materials, LLC, pp 1-98 (April 2005)

[2] R.M. Cullen, Research Report R 0043, Westmoreland Advanced Materials, LLC, pp 1-10 (August 20, 2003)

[3] Beaulieu, P. and McGowan, K.A. “Micro-Porous Castable Refractory for Molten Aluminum – Parts I and II,” Industrial Heating Vol. 73, Nos. 2 and 4 (2006).

[4] Private conversation between R.M. Cullen and the Head of Furnace Maintenance at Airo Die Casting, Inc. (December 2007)