DEGRADATION OF CRUCIBLE PROPERTIES AND IMPACT ON ENERGY CONSUMPTION DURING OPERATION

Mirco Pavoni[1], Heinrich Ebhardt[2], Dieter Heumannskaemper[2], Martin Ng[2], Arjoon Vohra[2], Ramdas Chitalkar[3]

Morgan Advanced Materials, Molten Metal Systems, Noltinastrasse 29, Berkatal-Frankenhain, Hessen, 37297, Germany

Keywords: Energy, Properties, Consumption, Crucibles, Aluminum, Costs

Abstract

Considering the increase in global energy prices, Morgan Advanced Materials has undertaken this study to understand the impact of the degradation of crucible properties on the energy consumption of foundries, during operation. The following study is based on crucibles being utilized in melting and holding of aluminum alloys in electrical resistance furnaces. Crucibles were installed in furnaces that were equipped with energy tool(s) in order to measure the energy consumption throughout its operational period. It was observed that the energy consumption per hour was steady for the first 3 months. Thereon the energy consumption per hour increased up to 100% for another 2 months. It was recorded that the energy consumption per kg of aluminum increased by 93%. The data was further analyzed to calculate the financial costs to the foundry and how better operating practice can provide significant financial savings for a foundry.

Introduction

Morgan Advanced Materials is an advanced materials company providing technically complex, bespoke solutions to its customers, enabling them to address global trends such as energy demand, environmental sustainability and other such trends. Molten Metal Systems (henceforth mentioned as MMS), a subsidiary of Morgan Advanced Materials, has observed that aluminum casters are concerned with the rise in energy costs/prices over the next few years, globally. According to American Foundry Society, energy costs contribute to 55% of the total costs for an average aluminum foundry. Therefore casters and MMS have established that there is significant potential to reduce the energy costs of these foundries.

Crucibles in Aluminum

Aluminum casters are typically using electrical resistance or fuel fired furnaces to melt their aluminum and hold it at a required temperature for their castings. Some foundries are carrying out their melting and holding operation in separate furnaces and some use one furnace, depending on the operating practice and the demand of aluminum. The furnaces installed in such foundries require MMS crucibles to hold and contain the aluminum from its solid state till its melting (for melting applications) and/or it is used to keep the aluminum at a particular holding temperature (typically 700-800ºC for holding applications). MMS crucibles are used in energy intensive applications and therefore there is scope for understanding and analyzing the various aspects of this process to understand how energy costs can be minimized.



Figure 1: Crucible (left) installed in an electrical resistance furnace (right) at an aluminum foundry.

Crucibles that are used in aluminum applications are generally comprised of clay, silicon carbide, carbon, and other ceramic or refractory materials. The 3 point transverse bending strength is approximately 10MPa for a crucible with density ranging from 2,100 to 2,200kg/m^3 and a porosity ranging from 8 – 15% (see Table 1).

Table 1: Chemical, Physical and Mechanical Properties of a Crucible in Aluminium Applications

Chemical Composition	
Silicon carbide	25-35 %
Carbon	35-45 %
Clay with other materials	25-35 %
Physical & Mechanical Properties	
3 Point Transverse Bending Strength	10 – 12 MPa
Density	2,100 – 2,200 kg/m^3
Porosity	8 – 15 %

One of the main properties for this study that we will consider is the thermal conductivity of the crucible. The crucible conductivity is defined by its raw materials, binding agent and the processing mechanism. The thermal conductivity is a function of temperature and this is showed in Figure 2.

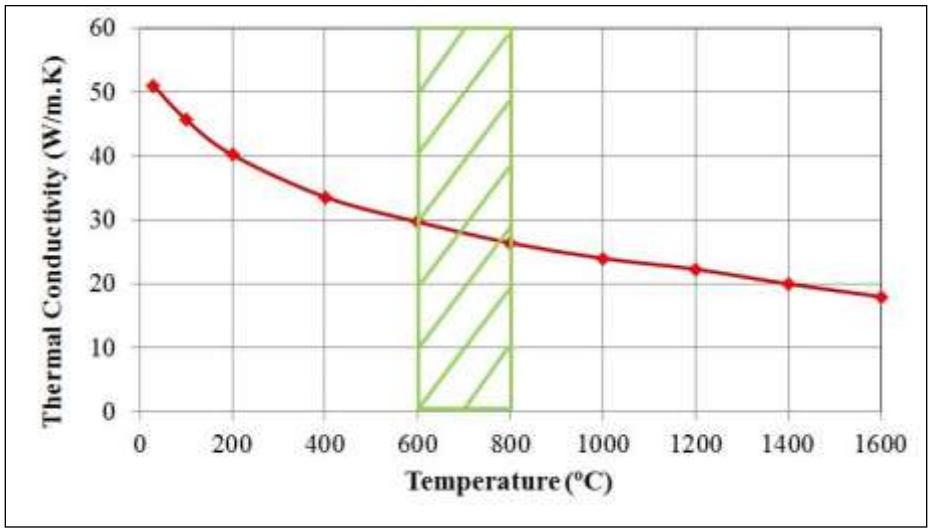


Figure 2: Thermal conductivity of a crucible as a function of temperature and the green area showing the operating temperature range in aluminium application.

However, as the thermal conductivity of a crucible cannot be measured directly during operation, we need to use an alternative approach to obtain the energy consumption for the crucible in the furnace.

End of Crucible Life

The crucible is used as a consumable and therefore it has a defined operating period, also known as lifetime. The crucible life is determined by various factors in the foundry processes as well as the crucible manufacturer's processes. Therefore the range in crucible lifetime is determined by looking at various foundries, globally, that are casting aluminium and using electrical resistance furnaces for their melting and holding applications (See Table 2).

Table 2: Range in crucible lifetime for various modes of operation in aluminium application

Mode of Operation	**Min. Average Lifetime**	**Max. Average Lifetime**
Melting	2 months	4 months
Holding	6 months	12 months
Melting and Holding	3 months	6 months

Without considering unexpected failures, such as bottom cracks or catastrophic failures, due to mechanical stresses as a result of faulty practice, harsh handling, insufficient sintering, etc., foundries have various ways to determine the end of the crucible life. Some of them use the crucible till visible cracks appear along the walls of the crucibles (see Figure 3). Some foundries have a statistical measure by reflecting on their past experience with the crucibles. For example, if the initial crucibles start cracking after 5-6 months, the foundry will determine that the crucible should be removed after 4-5 months to avoid unexpected failures and loss of production time. Other foundries measure the heating time for the aluminium from the beginning till the end. Generally, the aluminium melting period will increase after a certain time period and after a certain limit, the foundry decides to change the crucible. This is mainly due to oxidation of the carbon present in the crucibles.



Figure 3: cracks on the crucibles in the middle (left); top to bottom (middle) and top wall (right).

The phenomenon of the oxidation can be easily recognized in a broken crucible by the brownish color versus the grayish of a new one (see figure 3). When the crucible material starts oxidizing, it changes the properties like porosity, chemical composition and mechanical resistance.

Experimental

2 crucibles were installed at an aluminium foundry with electrical resistance furnaces (see Table 3). The crucibles were monitored throughout its operating period at the foundries visually as well as through energy consumption. Data loggers were attached the furnaces to collect the kWh units being consumed. The crucibles will be uninstalled at the end of its life to analyse the crucible failure and the deformation that the material has undergone over its operating period.

Table 3: Furnace information and casting procedure of Foundry A

Parameters	**Foundry A**
Type of Furnace	Electrical Resistance
Power	46kW
Operation Method	Melting and Holding
Casting Method	Gravity Die Casting
Crucible Capacity	300

Results

Energy Analysis

Foundry A recorded the energy consumption per unit hour and per unit kg of aluminium from October 2013 (Month 1) to March 2014 (Month 6) (see Figure 4) with the crucible. It is clear that the energy consumption was approximately constant for the first 4 months (0.4kWh/kg), till January 2014 and then almost doubled for February and March (0.77kWh/kg). From the end of January, the customer had longer heating times with a maximum of 1.5 hours, which accounted to more than 80% compared to the initial heating times.

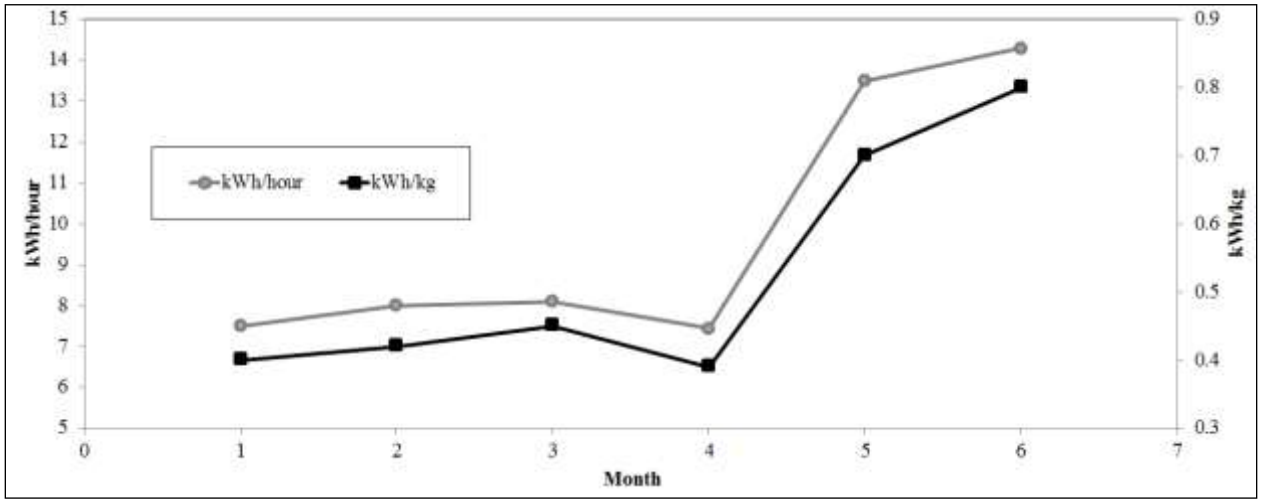


Figure 4: values of kWh/hour and kWh/kg of energy consumption at Foundry 1 throughout crucible operating life.

We can further analyse Figure 4, by considering the output and the operating conditions at Foundry 1 to obtain monetary significance of this study. The foundry operates 8 hours per shift, 2 shifts per day and 5 days per week. Therefore they are operating 320 hours per month. Considering the kWh/hour, the kWh consumed per month is calculated. The unit cost of kWh in this foundry is €0,19, which is approximately $0,21. Therefore the energy cost per month was calculated (see Table 4). Observing the values of energy costs per month in Table 4, it was important to see the difference between successive months compared to the first month of operation (ΔE). This will show the financial losses the customer is making by continuing the crucible operation in terms of energy consumption. The energy costs of February and March are almost double compared to October. This implies that the foundry is incurring heavy energy costs as well as losing on production time due to decreased heating rates.

Table 4: Monthly energy costs calculated for Foundry 1 from October 2013 to March 2014.

	October	**November**	**December**	**January**	**February**	**March**
kWh/hour	7.5	8.0	8.1	7.4	13.5	14.3
kWh/month	2,400	2,560	2,592	2,381	4,320	4,576
Energy Cost/month	$ 511	$ 545	$ 552	$ 507	$ 919	$ 974
ΔE		$ 34	$ 41	$ -4	$ 409	$ 463

Considering the value of the crucible to be approximately $600, the foundry can effectively install a new crucible at the end of January leading to a total cost of $1.800, an energy savings of $1.950. In this manner, the foundry will have improved savings as well as increased heating rates, leading to a higher output of aluminium.

Oxidation Analysis

The crucible was uninstalled and cut to observe the inner material and the degree of oxidation (see Figure 5). As expected, the brown colour indicated that most of the carbon was oxidized.



Figure 5: Images of crucible after operation (left); cut piece from crucible showing the brown oxidized layer (right).

Samples were taken for optical microscopy examination. The sample was taken at the interface between the oxidised and the unreacted regions of the crucible. The microstructures (see Figure 6) clearly show the difference in the oxidised layer and the unreacted layer. In the unreacted layer, the blue needle shaped structure is the carbon that was used in the crucible. The microstructure has a significant amount of carbon, which correlates with the chemical composition give in Table 1. Observing the microstructure of the oxidised layer, there are needle shaped pores. The morphology of the pores is similar to the graphite. This implies that the graphite was oxidised resulting in pores within the crucible. The pore structure correlates to the graphite structure at the beginning of the crucible's operation, leading to a decrease in thermal conductivity.

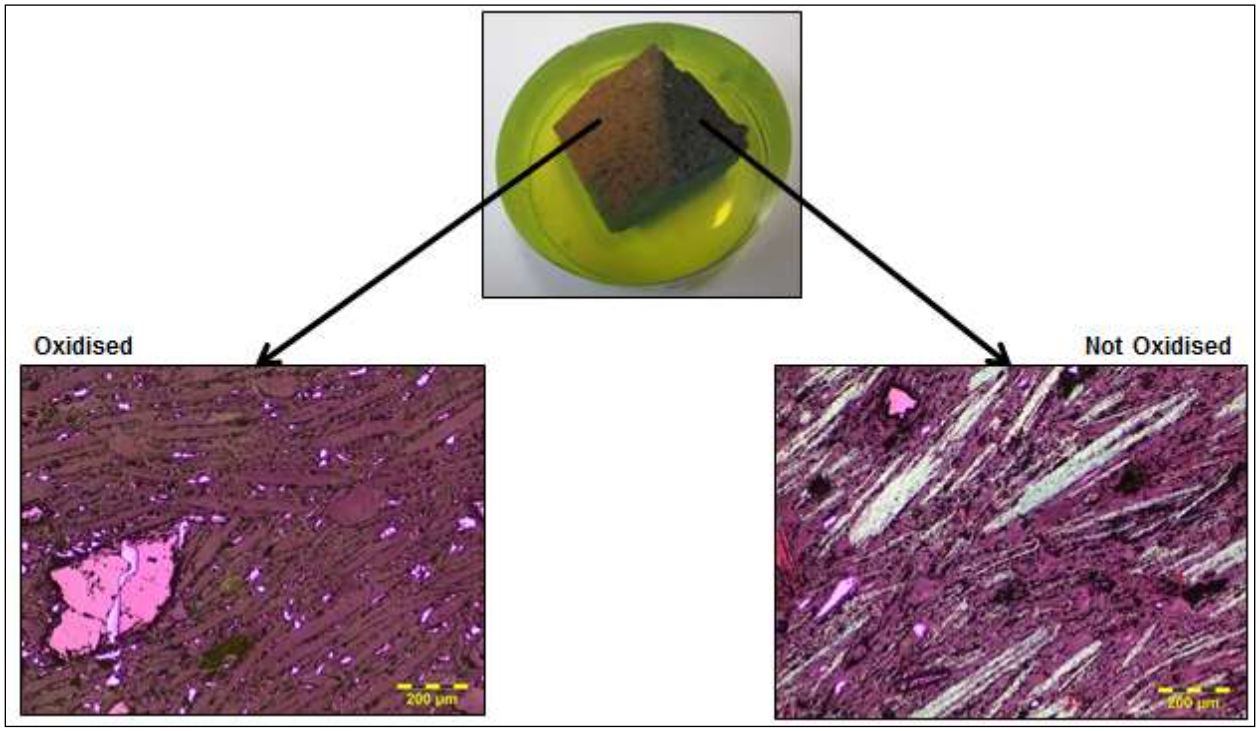


Figure 6: Sample taken from the interface (top); the microstructure of the oxidised layer (left) and microstructure of the unreacted layer (right).

Conclusion

The study concludes that the degradation of crucible properties through the oxidation of the carbon does have a great impact on the energy consumption of aluminium foundries. The crucible that was installed operated for 6 months. The last two months had an energy consumption that was almost double compared to the first month of operation. Calculating the costs for the additional energy consumption, it is profitable to remove the crucible before the oxidation starts.