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Ultrasonic Degasing and Processing of Aluminum Part II

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ABSTRACT

At the TMS conference in 2013 the paper Ultrasonic Degasing and Processing of Aluminum was presented (Rundquist & Manchiraju, Ultrasonic Degasing and Processing of Molten Aluminum, 2013). The focus of the paper was the removal of dissolved hydrogen from molten aluminum using Ultrasonics. In this paper we will present a brief overview of the earlier work. Our continued work using ultrasonics in molten aluminum both in the foundry and continuous casting has demonstrated that not only were we removing hydrogen efficiently from molten aluminum but there was a significant reduction in inclusion levels as well. The main focus of this paper will be to present the effectiveness of the ultrasonic degassing process at removing hydrogen and inclusions from the molten aluminum. Such inclusions include oxide films, carbides, refractories etc... Data from both the continuous casting and foundry process(s) will be presented and discussed. Finally, based on the ideas advanced in the previous sections, conclusions will be drawn on the overall ability of ultrasonic processing of molten aluminum along with the improvements in casting quality.

INTRODUCTION

The Southwire process of Ultrasonic Degasing and Processing of Molten Aluminum (Rundquist & Gill, 2013) continues to be refined and optimized. Throughout the process of optimization, hydrogen and inclusion removal data were obtained.

The goal of a degasing system is to remove dissolved hydrogen from the molten metal as well as reduce the amount of impurities in the melt. Currently most aluminum cast shops and foundries use a combination of purge gas and corrosive chemicals to remove these impurities. These corrosive chemicals are usually chlorine, fluorine or a combination of the two. Delivery methods range from direct gas injection into the melt or salt fluxing via pucks and powder (Totten & MacKenzie, 2003).

The goal of the Southwire Ultra-D degasing process is to efficiently remove hydrogen and reduce the amount of impurities from the melt without corrosive chemicals that are generally used in the conventional degassing process.

This paper will present the data obtained from Southwire's alloy continuous casting rod line as well as selected foundry data. Hydrogen removal efficiencies will be presented based on casting temperature and inclusion removal data will be presented via standard ABB PoDFA analysis. Finally a short discussion on the benefits of not using corrosive chemicals like chlorine to degas and clean aluminum, will be presented.

It is appropriate at this time to summarize the fundamentals of ultrasonic degasing. Ultrasonic degassing (Xu *et al*, 2004, 2007, 2008), (Han, 2014), an environmentally clean and relative inexpensive technique that uses high intensity ultrasonic vibrations to remove hydrogen in molten aluminum. An ultrasonic wave propagating through a liquid metal generates alternate regions of compression and rarefaction. When the intensity of the ultrasonic vibration is high enough, a large number of tiny vacuum cavities are generated in the melt. The dissolved gas diffuses into these vacuum bubbles and is removed out of the melt as the bubbles escape from the melt surface. The Southwire Ultra-D degassing process improves the ultrasonic degassing approach by utilizing a small amount of inert gases to assist the survival of cavitation cavities. The idea is to use high intensity ultrasonic vibration to break up larger inert gas bubbles into tiny bubbles. The bubbles then collect cavitation cavities and hydrogen collected by those cavities.

Compared to conventional degasing, the uniqueness of ultrasonic degassing includes:

1. No chlorine.
2. Small cavitation cavities that ensure a fast degassing.
3. Less dross formation, because less of the melt surface is disturbed.

Before this work, it was unclear if these tiny cavitation cavities were capable of removing small inclusions and impurity elements. However, we have conclusively demonstrated that the small cavitation bubbles effectively remove inclusions.

HYDROGEN REMOVAL EFFICIENCIES

<u>Continuous Casting and Rolling</u>

Throughout the process of testing the Ultra-D degasing process the Alspek H (ALSPEK H - Applications) unit was employed in testing the dissolved hydrogen in the molten aluminum. Table 1 shows a selection of the after Ultra-D degasing hydrogen levels and the corresponding average and standard deviation.

Table 1. After Ultra-D degasing Hydrogen Levels

Date	Alloy	H2 mL/100g After Ultra-D Degasing
8/28/2013	5052	0.12
10/1/2013	5052	0.13
10/22/2013	5154	0.14
2/24/2014	5052	0.12
3/24/2014	5154	0.11
	Average	0.124
	Std Dev	0.0101

The data in Table 1 was obtained using a 4 head Ultra-D degasing system running on Southwire's alloy rod line at approximately 8000 pounds per hour production rate. Through extensive testing the per head capacity for the Ultra-D degasing process has been determined to be 3000 pounds per hour in a launder fed casting system.

Figure 1. 4 Head Ultra-D degasing system in operation at Southwire alloy rod line

As we have previously observed, the degasing efficiency is affected by the casting temperature of the molten aluminum. As the temperature of the molten aluminum increases the solubility of hydrogen also increases (See Figure 2).

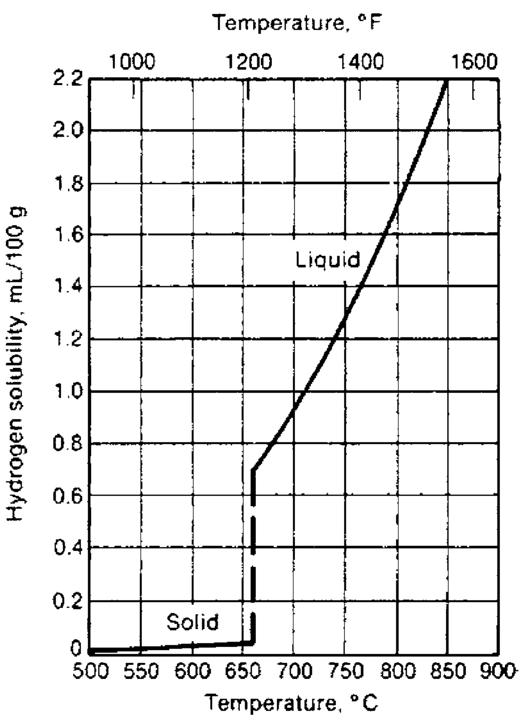

Figure 2. Hydrogen max solubility in aluminum (ASM)

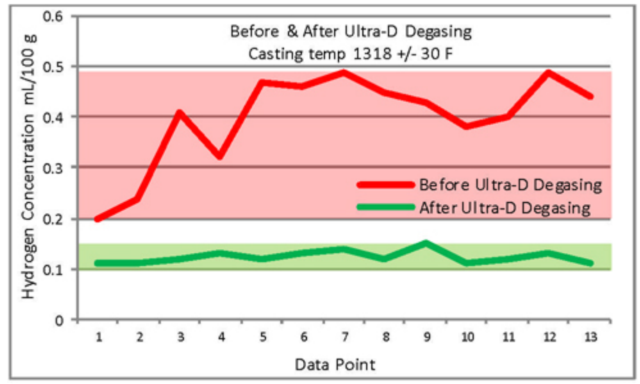

Figure 3. Hydrogen concentration before and after Ultra-D degasing

Analysis of the Ultra-D degasing (See Figure 3) indicates that the final hydrogen value is independent of the amount of dissolved hydrogen before the degasing. The final hydrogen value after degasing is at or below .15 mL/100g, leading to the conclusion that the degaser is able to reduce the hydrogen levels to equilibrium or below equilibrium levels consistently.

Figure 4 details the efficiency of Hydrogen removal. Efficiency of hydrogen removal is calculated as follows:

$$E\% = \frac{(H_i - H_f)}{H_i} x100 \qquad (1)$$

Where:

- H_i = initial hydrogen concentration
- H_f = final hydrogen concentration at casting (after Ultra-D degasing)
- E% is the efficiency of removal expressed in percent

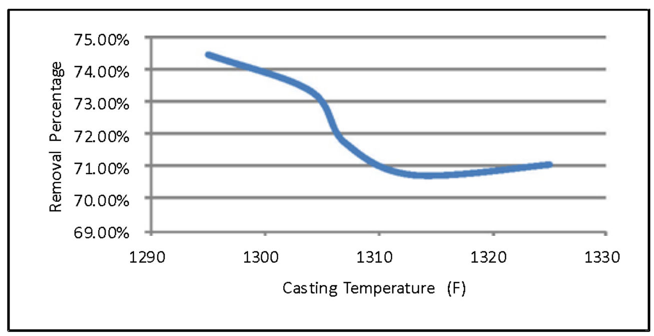

Figure 4. Degasing efficiency vs. casting temperature for 5xxx alloys

As can be seen from the data above, there is direct correlation between temperature of casting and hydrogen removal efficiency. It is interesting to note that the degasing efficiency of the Ultra-D degasser is between 70% and 74%. This leads to the conclusion that even though the degasser is more efficient at lower casting temperatures; at high casting temperatures the Ultra-D degaser is very efficient (~ 70% efficient). It is notable that using this information the Southwire plant is able to control the casting temperature within the most efficient range of the degasing process. Keeping the casting process operating within the optimum range ensures high levels of Hydrogen removal.

Foundry: Sand and Die Casting

As discussed previously, the Ultra-D degasing process was operated in a foundry environment. In the sand casting foundry, the temperatures in the processing furnace are considerably higher than that in the die cast shop and the continuous cast process. Most of the trials were run at temperatures in excess of 1350 F. Further analysis is done using density measurements and an industry standard RPT (reduced pressure test) to verify degasing of the melts.

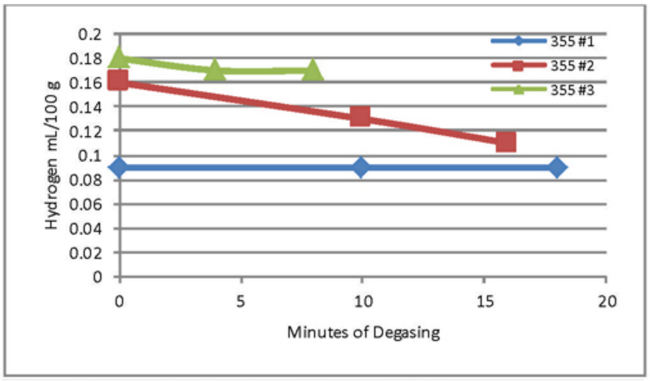

Figure 5. Degasing time for 3 trials of 355 alloy

Figure 5 shows the data from a 1000 lbs. electrically heated holding furnace that has been degased with a single head Ultra-D degasing system. The hydrogen level was continuously monitored with the Alspek H unit. As the hydrogen is reduced the metal temperature is maintained at the starting value. The first experiment, 355 #1, already had the hydrogen at the atmospheric equilibrium point and therefore could not be reduced further. The other two experiments do show hydrogen reduction. To further understand the degasing and cleaning process an RPT[1] test was performed before and after the degasing cycle. Table 2 shows the results of the RPT tests. Figure 6 is a typical polished RPT sample set of before and after degasing.

Table 2. Before and After Density Measurements

Alloy	Start Density g/cc	End Density g/cc	% of theoretical[2]
355 #1	2.512	2.65	97.79%
355 #2	2.447	2.667	98.41%
355 #3	2.489	2.66	98.15%

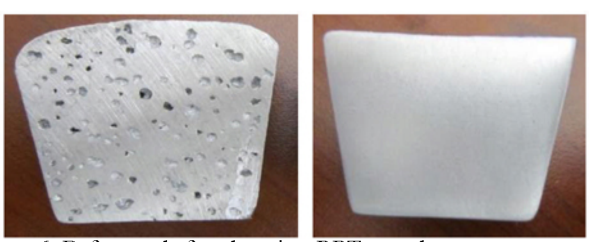
Figure 6. Before and after degasing RPT samples

After degasing the 355 alloy melts all three experiments achieved greater than 97% theoretical density. The average over the three experiments was a 7.08% increase in density from the starting value.

As has been reported extensively in the literature, as referenced well by (Samuel, 1993), the RPT test is not a very accurate measurement technique. Generally only the bulk properties can be determined using RPT. However, RPT is extensively used since it does indicate the overall quality of the degased casting. Once the metal meets density specification via an RPT test it is ready for casting and subsequently the melt is poured into production molds.

At this time it is important to reiterate that the goal of the degaser is not just to remove the hydrogen from the aluminum, but rather to deliver the highest density metal to the casting process. This is accomplished by reducing the amount of dissolved hydrogen and reduction in the number of inclusions.

INCLUSION & ALKALI REMOVAL

Inclusion removal before casting is the second part of delivering the highest density metal to the mold or casting machine. Typical cast house and foundries rely on both rotary degasers and filters to remove inclusions. Many papers have been published on the traditional methods to remove inclusions and the industry has standardized on a few methods to measure melt cleanliness (Totten & MacKenzie, 2003).

The Southwire Kentucky plant uses the ABB PoDFA inclusion analysis method (ABB PoDFA Analysis). A sample of the melt is drawn through a small filter under vacuum. The amount of metal drawn through the filter is weighed and discarded. The metal in the filter is allowed to solidify. The filter is then cut from the remaining sample and sent to the laboratory for metallurgical analysis.

The Southwire alloy rod line primarily focuses on the removal of Na and Li alkali metals during the casting and hot rolling of 5xxx alloys. The importance of keeping these impurities low in hot rolling is well known in the literature to prevent hot tearing during the hot rolling process (Totten & MacKenzie, 2003). Standard spectrum analysis was carried out both before and after the Ultra-D degasing process to gauge the effectiveness of alkali removal.

Continuous Casting and Rolling

During the operation of the Ultra-D degasing process samples were taken before degasing, immediately following the degaser and finally after the CFF (ceramic foam filters) just before the casting machine. Figure 7 is an overhead picture of the alloy rod line showing the sample locations.

1 RPT includes solidification at 27” Hg gauge, sectioning, polishing, density measurement

2 Theoretical density of C355.0 T6 Sand Cast 2.71 g/cc (Aluminum C355.0-T6)

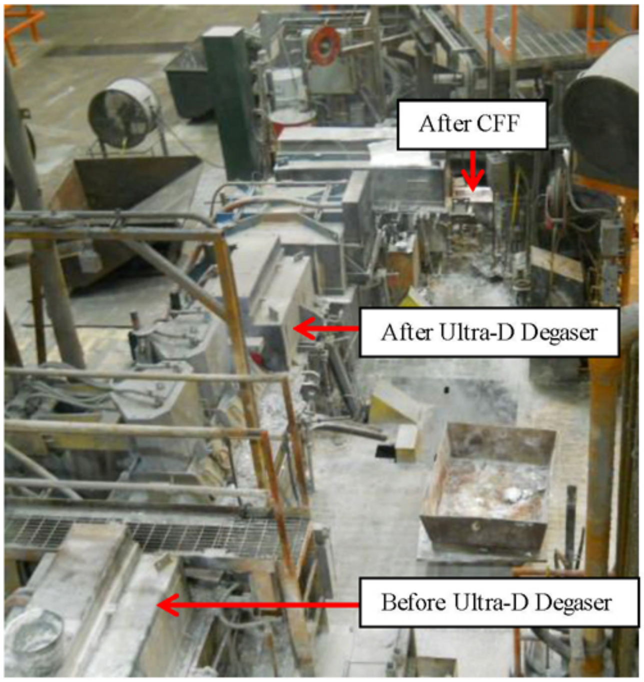

Figure 7. Sampling locations for PoDFA analysis (Ultra-D degaser removed for clarity)

In Figure 8 the full PoDFA results are presented.

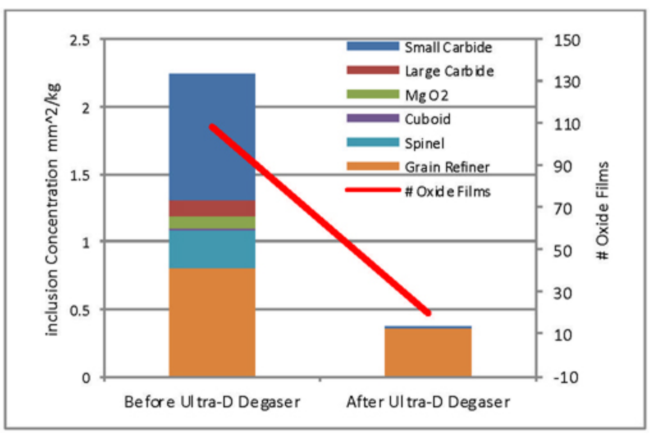

Figure 8. PoDFA results from 5052 at 8000 pounds/hour on Southwire Alloy rod line

The Southwire plant receives liquid metal from a nearby smelter. The smelter's reduction cells are the main source of the carbides (Totten & MacKenzie, 2003) in the feed stock for the process. It is crucial to have the carbides removed prior to casting. Any inclusions that are not removed prior to solidification will have significant negative implications in downstream processing as well as a negative impact on the physical and mechanical properties of the castings. Table 3 below details the inclusion removal efficiency of the Ultra-D degasing process where efficiency is determined as outlined in Hydrogen removal efficiency section (see above).

Table 3. Inclusion Removal Efficiencies

Alloy	Total Inclusion Removal Efficiency by Ultra-D Degaser
5052	98.47%
6201	80.23%
4047	55.68%

Inclusions concentrations for various compounds are given in mm^2/kg of aluminum. Aluminum oxide films that are folded and mixed into the melt are not counted for *area per mass* of metal, rather they are individually counted per sample and are classified by size and shape. Table 4 shows a typical oxide removal for 5052 alloy using the Ultra-D degasing process.

Table 4. Oxide film removal by Southwire degasing process

	Before Ultra-D Degaser	After Ultra-D Degaser
# of Oxide Films	108	20
Length	Short, Med, Long	Short
Thickness	Thin, Med, Thick	Thin

As can be seen by the data in the table, passing the metal through the Ultra-D degasing process removes most of the oxide films and the remaining films are only of the short and thin variety[3].

Figures 9 & 10 show the progression of the samples through the process of inclusion removal. Figure 9 is directly out of the furnace (before degasing) with a multitude of oxide films and inclusions, figure 10 is after the Ultra-D degasing process where the presence of oxide films is significantly reduced.

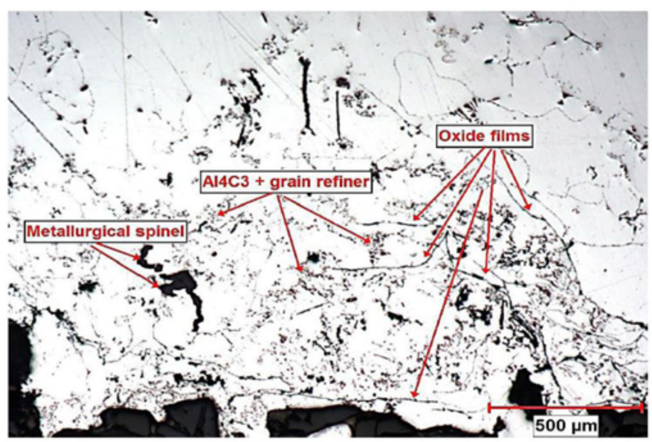

Figure 9. 50x Micrograph, before degasing

[3] Short = less than 250 micron, thin = less than 1 micron, (ABB specification)

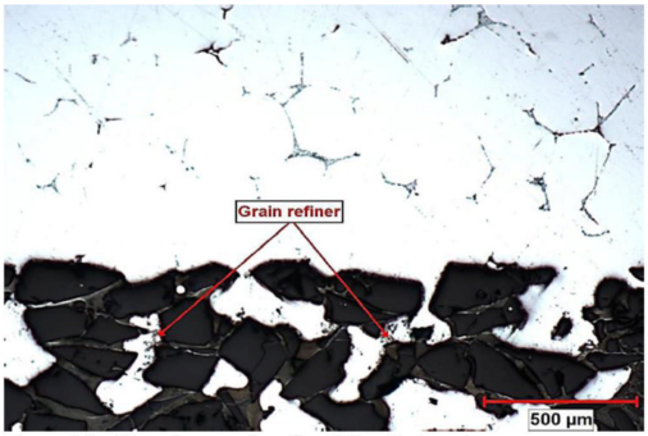

Figure 10. 50x micrograph, after Ultra-D degasing process

Alkali Removal

As previously reported, the Ultra-D degasing process is able to remove alkali metals without the use of corrosive chemicals. The mechanism of this removal is outside the scope of this paper. Table 6 shows the data obtained over a multitude of experiments. The standard deviation for the Na before degasing was .1 PPM. There was no statistically relevant data for Li, therefore it is not reported. Most of the Li values were undetectable by the spectrum analyzers. Each data point reported below corresponds to the same production run as the hydrogen data reported above.

Table 6. Na removal by Ultra-D degasing process

Date	Na Before (PPM)	Na After (PPM)
8/28/2013	3	0
10/1/2013	5	0
10/22/2013	3	0
2/24/2014	6	0
3/24/2014	3	0
Average	4.00	0
Std Dev	1.26	0

For Na levels up to at least 6 PPM the Ultra-D degasing process is able to remove Na to undetectable levels. Again it is important to note that especially for the Hi Mg 5xxx series of aluminum alloys even a few PPM of Na will cause significant casting and rolling problems.

Foundry: Sand and Die Casting

Similar to the continuous casting analysis, the foundry experiments were conducted by taking PoDFA samples after the metal was removed from the melting furnace and once again after the metal had been treated by the Ultra-D degasing process. The metal was held in a 1000 pound electrically heated pot and processed by a single head Ultra-D degasing system. For the 355 alloy discussed in the hydrogen removal section above; the inclusion removal data is presented in table 5.

Table 5. Inclusion removal for 355 alloy in sand foundry

Inclusion Type	Sample ID	
	Before Degaser	After Degaser
Small Carbide		
Large Carbide		
Mg O2		
Cuboid	0.079	0.037
Spinel	0.314	0.012
Others	0.031	0.012
Grain Refiner	1.147	.800
Total (mm^2/kg)	1.571	0.861
Total - GR (mm^2/kg)	0.424	0.061

As shown in the table above the Ultra-D degasing process is able to remove inclusions in the foundry alloys. In the 355 alloy above the removal efficiency for the inclusions was 85.6%. Figure 11 and 12 are the before and after micrographs, respectively.

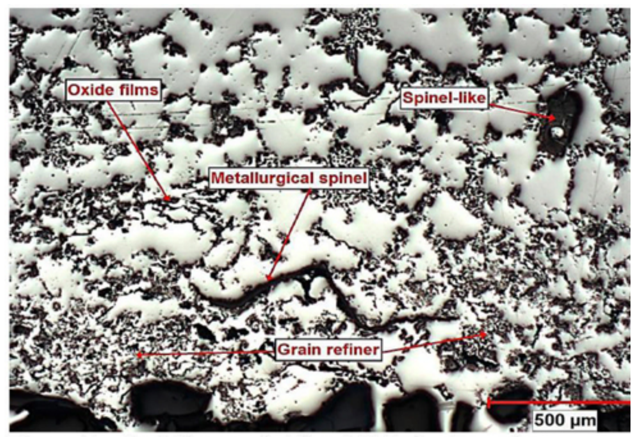

Figure 11. 50x Micrograph Alloy 355 Before Degasing

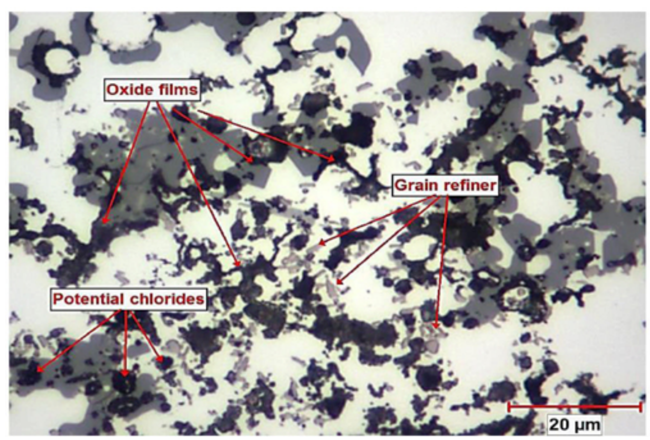

Figure 12. 1000x Micrograph Alloy 355 After degasing (increased magnification to show some inclusions)

Discussion on Corrosive Gasses such as Chlorine

When chlorine is added to the melt, either in salt form or with direct gas injection there is a potential to form chlorides in the melt (Totten & MacKenzie, 2003). These chlorides are inclusions and are harmful to the final product. During the trials at the Southwire alloy rod line some comparative tests were completed for customer acceptance. Specifically on 4047 a comparative analysis was done between conventional chlorine degasing and the new Ultra-D degaser. More data has to be accumulated therefore no definitive conclusions are being made but it is interesting to note from this one data point that while the Ultra-D degaser removed 55.68% of the inclusions, degasing using chlorine, may have added inclusions to the melt. These inclusions were in the form of large carbides and chlorides. Table 6 details the effects of the chlorine degaser to the inclusion content.

Table 6. Inclusion content for chlorine degaser on Southwire Alloy rod line

Inclusion Type	Sample ID		
	No Degasing	After Chlorine Degasing	After Filters
Small Carbide	0.053	0.073	
Large Carbide	0.132	0.438	
Mg O2			
Cuboid			
Spinel			
Chlorides	0.105	0.183	0.284
Grain Refiner	0.238	2.958	1.679
Total (mm^2/kg)	0.53	3.652	1.963
Total - GR (mm^2/kg)	0.29	0.694	0.284

The only source in the process to create the chlorides is the chlorine gas injected during degasing.. It is important to note that the CFFs do collect the carbide particles and that they do not pose a problem other than more frequent filter changes. More importantly though is that the chloride particles created in the degaser are small enough to pass through the filters and into the final product. This will cause decreases in properties in the final product.

CONCLUSIONS

After the paper presented in 2013 extensive optimization work was done on the Ultra-D degasing process. Consistent hydrogen values under .15 mL/100g in the continuous casting process can be obtained using no corrosive gasses or chemicals. Maintaining the casting temperature within the optimum efficiency zone of the Ultra-D degasing system results in degasing efficiency over 74% in the 5xxx alloys. In the foundry environment, hydrogen values can be obtained under .10 mL/100g depending on the metal temperature, but more importantly the density of the metal sample after an RPT is greater than 98% of theoretical.

Upon investigation of inclusion removal the efficiency of the Ultra-D degasing system in 5xxx alloys is over 97% and when coupled with CFFs virtually total inclusion removal were obtained. Complete removal of medium to large oxide films were obtained via the Ultra-D degasing process. Most importantly the process did not introduce any new inclusions into the metal via chlorine and chloride creation.

The Southwire Ultra-D degasing process is a viable and technically appropriate process for the degasing and cleaning of aluminum and its alloys. It is effective in the dynamic environment of the continuous casting launder as well as the static foundry crucible.

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