Cleanliness Measurement Benchmarks of Aluminum Alloys
Obtained Directly At-Line Using the Prefil-Footprinter Instrument

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Abstract
Benchmarking is an important aspect of today's Total Quality Management (TQM) and is a requirement for world-class corporations. Quality measurement is also required by standardization programs such as ISO9000 and QS9000. As liquid metal quality is an essential aspect of the quality of final products from casting foundries and casthouses, it is important that world-class operations accurately benchmark metal quality. For decades, and still today, metal cleanliness has been widely monitored using the metallographic analysis of solidified samples. These samples may or may not be filtered. With filtering, the required techniques are time consuming and resource-intensive -- analysis results of grab samples are obtained off-line only after significant delays. If no filtering is used, the results suffer from low sensitivity and human interpretation.

The following paper proposes a new way of expressing cleanliness measurements of liquid aluminum, and provides benchmark references for popular A356 castings. The paper also provides the measurement conditions and the validity of these benchmarks, and gives a description of the instrument used to generate cleanliness measurements directly at-line.

Introduction
Casting defects that are related to molten metal cleanliness results from three main categories:
1. General inclusion level and oxide films present in the bulk liquid.
2. Local clusters of inclusions and oxide films caused by poor metal treatment.
3. Formation of oxide films during mould filling itself.

Experience with automotive casting shows that categories 1 and 2 are responsible for most of the inconsistent production and batches of rejected castings [1]. Since production consistency is often more important than maximum quality, it is essential that foundry engineers quantitatively monitor molten metal cleanliness at each stage of the manufacturing process.

High quality inclusion-critical products, such as thin gauge sheet for can body stock, or foil and plates, have triggered the need to monitor and minimize the presence of non-metallic inclusions in the early 80’s [2]. Techniques based on pre-concentration/filtration step, followed by metallographic analysis, have been developed: such are the PoDFA from
Introduction – cont’d

Alcan [3] and the LAIS from Union Carbide [4, 5]. However, with these techniques it usually takes several days before obtaining results, which is very time-consuming. These off-line procedures require an experienced metallurgical technician to carry out the analyses and while the results can be extremely useful, the technique is relatively expensive.

In order to simplify the process and provide useful information to the foundryman ‘at-line’, the way in which inclusions build up to filter during the pressure filtration test itself has been investigated. Several attempts to achieve this goal failed or were abandoned in the early 80’s for various reasons [6, 7, 8].

The principle mechanism operating during the filtration of a fluid containing solid inclusions through a fine filter is ‘cake’ filtration. The build up of a ‘cake’ and its subsequent permeability is a dynamic process that is critically dependent on the type, size, shape and mixture of inclusions present in relation to the filter itself. In the case of liquid metals, temperature, viscosity and surface tension of the fluid also influence the characteristic behavior of the system.

The net result of these influences, under highly controlled standard conditions, is a characteristic called ‘filtration behavior curve’ or ‘Footprint’, which can be used to define or benchmark the quality of a given metal supply.

Prefil®-Footprinter Operating Principle

The Prefil operating principle is illustrated in Figure 1. A ready-to-use crucible, equipped with a porous filter disc at the bottom, is first pre-heated and installed in the pressure chamber. The operator then takes a sample of metal with a ladle, pours it into the crucible, closes the pressure chamber and starts the test. The system applies pressure in the chamber when the metal temperature reaches the specified value for the test, forcing the liquid metal to flow through the porous filter disc.

Two filtration rate curves selected from previous results for clean and less clean but acceptable metal are displayed on the computer screen. These curves are a reference for the process and the alloy. As the metal falls in a weigh ladle, the filtration rate of the current test is measured and the curve is graphed on top of the other two.

If the new curve lies between the two reference curves, the metal cleanliness is acceptable. If the new curve lies below the Low reference curve, the metal is less clean and consideration should be given to employing a cleaning technique.

Building a database makes it possible to determine extremes of metal cleanliness found at a specific location. The database is used as a point of comparison or reference thus providing a footprint of a process. The results of a given alloy, obtained at a given temperature and location, can be judged against the footprint database and used for shop floor quality control.

When the test is completed, the pressure is automatically released from the pressure chamber and the lid unlocked. The operator saves the test data, empties the weigh ladle, removes the crucible and prepares for the next test. Optionally, the metal residue above the filter can be saved. Indeed, a thorough off-line metallographic examination of the material trapped by the filter can confirm the results and extend the interpretation.

![Figure 1: Prefil®-Footprinter Operating Principle](image-url)
**Description of the Prefil Instrument**

The PREFIL® Footprinter system is built into a two-part wheeled cabinet illustrated in Figure 2. The upper part of the cabinet houses the user interface console, the crucible pre-heater, the pressure chamber and the scale tray.

The user interface is located at the top of the cart. It integrates control buttons, a computer and its peripherals.

A crucible pre-heater is integrated in the unit. For the safety of the personnel, it is hidden under a protective cover. The pressure chamber sits next to the crucible pre-heater above the weigh ladle and scale tray.

**Application Example, Metal Source (Figure 3)**

As more and more aluminum is recycled, remelt facilities are presented with a dilemma, e.g. cost versus quality. Information on liquid aluminum cleanliness of various types of scrap allows to rapidly qualify metal before directing it to specific products. The Prefil-Footprinter also shows optimum location for various types of scrap to be remelted in order to reduce potential inclusion contamination in the system. Reduction in production costs, gains in productivity and quality is obtained in these cases.

**Application Example, Filtration**

In-line metal treatment is commonly employed in the production of castings throughout the automotive casting industry. Performance evaluation and stability of a CFF (Ceramic Foam Filter) can be accomplished using the Prefil-Footprinter. Filter characterization versus pore size ppi), specific loading (kg/m²/sec), refractory composition, filter thickness and manufacturing technique can be qualified and compared. In Figure 4, fresh metal was first melted and two samples drawn. A sample was then taken following a 10 ppi CFF. Finally, metal residue of the first three tests was used again for a forth test (recycled).
**Application Example, Degassing**

It is generally accepted [9, 10, 11] that in-line rotary degasser acts as a cleaning element as well as a degassing element for molten aluminum. However, in-plant experience shows that the contrary is often encountered as production time constraints have priority over good metal handling practices. In Figure 5, two tests were taken before the degasser and two tests after the degasser. From the graph, it can be seen that the results from the tests taken before the degasser were better, exactly opposite of what was expected.

**Application Example, Settling and Tap Transfer**

Another well accepted phenomenon in the industry is the fact that settling is good for molten metal cleanliness. Conversely, disturbing the melt is detrimental [11, 12]. In Figure 6, a Prefil sample was first taken at the pump well of a 30 ton reverb. The furnace was charged with secondary A356 ingots and 40% recycled scrap. Then a second sample was taken from the transfer ladle (~400kg) just after the metal transfer from the furnace. The graph clearly shows a much lower filtration rate indicating higher concentration of inclusions and oxide films likely created when tapping from the furnace. A third sample was finally taken from the transfer ladle 40 minutes after tapping, thus allowing inclusions and oxide films to float up and settle down.

**Results**

**Prefil Filtration Curves vs Metallographic Analysis**

To verify the reproducibility and sensitivity of the Prefil system and to determine whether or not a good correlation existed between the Prefil and PoDFA methods, a comparative evaluation of Prefil-Footprinter and PoDFA Metal Cleanliness Results has been done for Foundry Alloy A356.

Three average Prefil curves are shown in Figure 7. Each curve is the average of three tests. Three pairs of PoDFA samples were also taken at the same time. The average total inclusion contents, as determined by metallographic analyses, for the PoDFA and Prefil testing are indicated beside each of the three curves and are also presented in Table I.

The curves show the excellent reproducibility of the Prefil method for clean metal. As expected, it was more difficult to observe good reproducibility for dirtier metal since cleanliness is much more variable and simply harder to control. The
The reproducibility margin of the curves is well within $\pm 10\%$ for fresh A356.2 fluxed and settled.

The sensitivity and reproducibility of the Prefil-Footprinter can be seen when examining the three metal cleanliness levels. Prefil was sensitive to the increase in oxide film levels seen for the fresh A356.2 after it was mixed. The Prefil curves agree well with the metallographic analysis presented in Table I: The higher the slope of the Prefil curve, the lower the total inclusion count.

Finally, by comparing the Overall Melt Cleanliness results, shown in Table I, both the “Inclusion Content” and “Oxide Film Content” fields from the Prefil and PoDFA samples correlate.

<table>
<thead>
<tr>
<th>Metal conditions</th>
<th>Fresh, Fluxed &amp; Settled</th>
<th>Fresh &amp; Mixed</th>
<th>Remelted &amp; Settled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample type</td>
<td>PoDFA 1</td>
<td>Prefil 1</td>
<td>PoDFA 2</td>
</tr>
<tr>
<td>Inclusion Content [mm$^2$/kg]</td>
<td>0.019</td>
<td>0.013</td>
<td>0.010</td>
</tr>
<tr>
<td>Oxide Film Content [No/kg]</td>
<td>7</td>
<td>8</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Average Inclusion Content [mm$^2$/kg]</td>
<td>0.016</td>
<td>0.013</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Avg. Oxide Film Content [No/kg]</td>
<td>7.5</td>
<td>8</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Δ Avg. Inclusion Content [%]</td>
<td>37.5%</td>
<td>40%</td>
<td>8.9%</td>
</tr>
<tr>
<td>Δ Average Oxide Film Content [%]</td>
<td>13.3%</td>
<td>N/A</td>
<td>31.6%</td>
</tr>
</tbody>
</table>

Note on metallographic analysis repeatability:
The repeatability of metallographic analysis is $\pm 16\%$ for an inclusion content over 1.25 mm$^2$/kg. The precision of the metallographic analysis decreases with an increase of the metal cleanliness. When the inclusion content is less than 0.07 mm$^2$/kg, repeatability is $\pm 40\%$ [3].

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**Background for Benchmarking**

A benchmark is a good model as long as the applied criteria are significant to the application. A benchmark must be based on realistic data that precisely represents a specific application in the industry. For example, we could define a benchmark for A356.2, for a given temperature, process, and stage in the process. However, a general benchmark on “casting alloy” would be useless.

Establishing a benchmark is equivalent to taking a state-of-the-art snap shot of a given moment in time for a particular application. As we gain more experience with the Prefil-Footprinter, benchmarks will continue to be refined.

To establish a benchmark, we calculate the average of all tests in similar conditions plus and minus the standard deviation. The average plus one standard deviation becomes a high benchmark for this particular condition. The average minus one standard deviation becomes the low benchmark.

Assuming the conditions are relevant and a normal distribution for results is obtained from sampling at different plants, then 66.6% of Prefil measurements encountered in the industry for a specific condition fall in-between the high and low benchmarks. 16.7% should be higher and 16.7% should be lower. If a Prefil result is close to the high benchmark, 16.7% of aluminum plants in the world do better than that most of the time (Figure 8).

The benchmarks presented in Figures 9 and 10 are based on information gathered over a period of two years in several plants around the world. They are made-up of several samples. The minimum number of tests that we have considered for a benchmark is 30. All these curves were taken in similar conditions.
Conclusion

This paper shows the potential of the Prefil-Footprinter as a new way of measuring the cleanliness of aluminum alloys in the 21st century. For the past two decades, previous publications on aluminum cleanliness measurement using pressure filtration flow rates clearly demonstrated the rationale of this method and the desire of the scientific community to achieve it in a reliable form. Correlation between the Prefil method and the PoDFA method was demonstrated through controlled experimentation. Several application examples were provided to demonstrate the sensitivity and reproducibility of the instrument. Two benchmarks for the popular A356 were also presented as a comparative level of liquid aluminum cleanliness. Of course, the confidence one may have in these benchmarks in being realistic depends on how well it fits their situation. Validity of the benchmark is directly proportional to the number of tests compiled and plants surveyed. However, the two benchmark examples presented in this paper show the potential of how the Prefil-Footprinter can gather data. Therefore, in our view, the new Prefil-Footprinter is a powerful tool for any world-class aluminum casting organization in providing comparative cleanliness information, or benchmark, on a foundry process.

Bibliography