Processing Molten Aluminum—Part 2:

Cleaning Up Your Metal

The key to improving the mechanical properties of aluminum castings is the ability to produce "clean" metal. Techniques such as filtration, degassing and other fluxing practices can help in achieving this goal.

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The ultimate mechanical properties of Al-Si alloy castings will, in large part, be determined by the condition of the metal while it is still molten. It has been long understood by the producers of high quality castings that molten metal cleanliness is the key in manufacturing mechanically sound aluminum castings.

Whereas, Part 1 of this two-part series on "Processing Molten Aluminum" (see *modern casting*, January 1990, pp 24-27) discussed the beneficial effects of silicon modification on aluminum casting properties, it is equally well known that the treatment's advantages can be negated by metal contaminated with solid inclusions, oxides and gas.

Methods are available and in use that can help "clean" the liquid metal and ensure its overall quality. Among the most common of these are filtering for inclusion removal; degassing techniques to reduce or eliminate hydrogen porosity; and fluxing for the removal of trace elements and to prevent gassing of the metal. Like silicon modification, these processing tools were covered during the 2nd AFS International Conference on Molten Aluminum Processing held Nov 6-7, 1989.

Clean Metal

Increasingly, foundries of all types are finding that the cleanliness of their molten metal is important in producing predictable mechanical properties in the final casting. This is especially true in the case of aluminum due to its extreme reactivity in its molten state.

Some of the general benefits of clean aluminum include the following.[1]

- By eliminating or minimizing solid or dross-related inclusions, which can result in "hard spots," problems in subsequent machining operations can be reduced or avoided.
- While filtration cannot improve the mechanical properties developed in already clean metal, it can help eliminate some of the reasons for isolated low test values caused by inclusions.
- It has been documented that by eliminating oxides from the melt the fluidity of the molten alloy has been significantly enhanced and the shrinkage characteristics altered in a manner that will frequently benefit the casting being produced. The benefit achieved is proportional to the amount of oxides removed.

Metal quality is described by D. Apelian and S. Shivkumar, Aluminum Casting Research Laboratory, Drexel University, as "a composite of three interrelated components: the control of alkali trace elements, hydrogen reduction and inclusion removal. Operations utilized for the removal of trace elements and hydrogen are generally referred to as fluxing, and commonly employ inert-reactive gas sparging in batch devices or flow-through reactors. The removal of nonmetallic and intermetallic particulate suspensions presents the most significant challenge in molten metal treatment systems . . . Today, the feasibility and contribution of filtering metal prior to casting is well accepted and, in fact, a majority of the primary aluminum that is cast is now filtered."[2]

In the case of aluminum, "clean" metal may be generally differentiated from "dirty" metal by the amount of inclusions (both solid and liquid) as well as the level of hydrogen gas contained in the molten bath. According to the Drexel researchers, inclusions are usually "nonmetallic and intermetallic particulate suspensions [which] may be introduced into the melt through the charge material or during various processing operations." Some common sources for solid inclusions in molten aluminum are the refractory lining of the melting furnace and transfer devices, the use of grain refiners, and aluminum oxide films.

Hydrogen, on the other hand, results from molten aluminum's propensity to absorb the gas from the air around the furnace, during melting, pouring, transfer and other processing operations.

According to F. Painchaud, Bomem, Inc, and J. P. Martin, Alcan International, Ltd, Quebec, Canada,[3] "Hydrogen is the only gas capable of dissolving to a significant extent in molten aluminum (Fig. 1). It is formed upon exposure of the molten metal to water vapor which is found in large quantities in the combustion products of fossil fuels. Its solubility in molten metal is much larger than in the solidified form which leads to outgassing when the metal is cast."

In other words, molten aluminum readily takes in hydrogen from its local environment and will hold it in solution as long as it remains molten. But as it solidifies and cools after pouring, it is unable to hold the hydrogen, and attempts to rid itself of the gas. In doing so, it leaves voids, called pores, in the solidified metal.

The size and amount of porosity of the cast part is usually the result of the gas level in the molten aluminum and the cooling rate of the part. Figure 2 illustrates a standard rating system used by many aluminum foundries to show the level of gas in their metal.

The effects of uncontrolled gas in aluminum can be devastating on the usefulness of the final casting. While this is largely dependent upon type of alloy being cast and cooling rate, in general, "under appropriate local cooling conditions, [hydrogen] can generate poros-

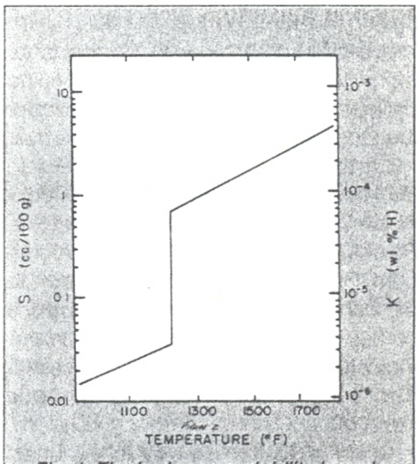

Fig. 1. The hydrogen solubility in molten aluminum is demonstrated in this graph.

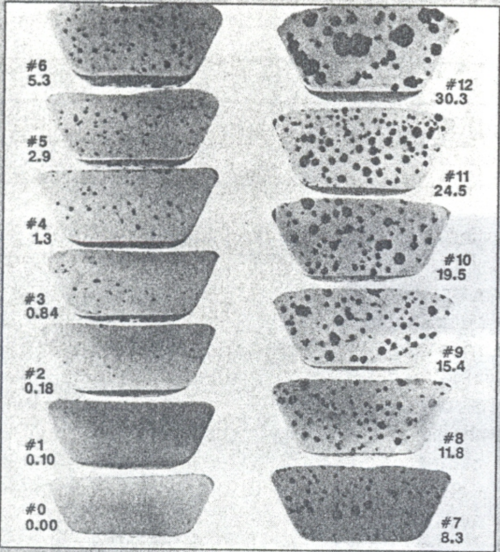

Fig. 2. This Aluminum Comparative Standard shows gas percent surface area porosity at 100 mm of pressure. It was developed by the Stahl Specialty Co.

ity and/or surface blisters resulting in reduced mechanical properties and resistance to corrosion and crack propagation, as well as the generation of surface defects."[3]

The problems caused by inclusions and hydrogen entrapment in aluminum castings are not new to the aluminum foundry. But ongoing research is providing a better understanding of the nature of these contaminants and their effects on the casting properties. Going hand in hand with this research is the development of new tools aimed at controlling the detrimental effects of impurities and assuring higher, more predictable properties in the final casting.

Filtering Aluminum

Fueled by the growing demands for higher quality and more uniform casting properties, some foundries are using or are studying the potential of filtering their metal to achieve these goals. H. Devaux, D. Hiebel, M. Richard, Centre Technique des Industries de la Fonderie, Sevres, France, and S. Jacob, Aluminum Pechiney, in their presentation to the conference, described the purpose of filtration as a process to "remove inclusions from melts in the most efficient way, very easily and at a moderate cost."[4]

While inclusion removal is the basic aim of filtration, it is important to note, according to the French researchers, that the size, amount and type of inclusion that are effectively filtered may not be detrimental to the casting. "Intuitively it may be concluded that the larger the inclusion volume, the more detrimental the effect. In fact, we cannot predetermine the effect of an inclusion on mechanical properties from a simple estimation of its dimensions," they reported.

In terms of filtration systems, the authors described three types, each of which exhibit both advantages and disadvantages for the foundry.

- Grids—These are either metallic or resin bonded glass and are set in the mold as close as possible to the mold cavity. While these are the easiest to use and relatively inexpensive, their efficiency is directly dependent upon the size of mesh.
- Filter Bed—This type of filtration system is comprised of a bed made up of either *inert* or *active* aggregrates. Inert grains, like charcoal or pure alumina, do not react with liquid aluminum. Active aggregates, on the other hand, refer to grains of fluxes or alumina balls coated in fluxes. Reportedly, active bed filters are more efficient in removing inclusions and help to degas the metal at the same time. Efficiency of filter beds depends upon grain fineness, bed thickness and metallic flow velocity. Because filter beds are difficult to use, they are generally reserved for laboratory work.
- Ceramic Filters—A more recent development is the ceramic filter. These are available as cellular foam or as fine-celled extruded or compressed types (Fig. 3). "They offer an intermediate efficiency between volumic filters and grids." Considered a little more costly, their ease of use is very good when the mold is properly designed.

In addition to the filter systems described above, in some cases in-furnace filtration also has proved to be a viable method for removing inclusions from molten aluminum. These types of systems are used in reverberatory and crucible melters.

Depending upon the furnace type and design, a filter is placed in the refractory wall or furnace bottom allowing the metal to flow through, thus providing a ready pool of clean metal. Reportedly, in some foundry operations using in-furnace filtration, the filters are changed at intervals ranging from two to four weeks.

"While offering a low-cost method of making clean metal available at the top of the pouring sprue, in-furnace filter systems cannot solve metal cleanliness

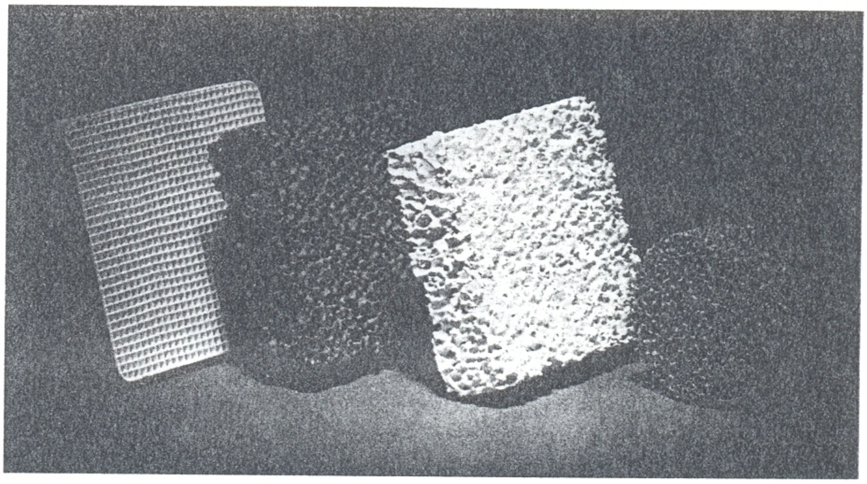

Fig. 3. A variety of ceramic filters has been developed to aid in the removal of inclusions in aluminum melts. Shown here are examples of a fine-celled extruded filter along with three different cellular filters.

problems generated in faulty gating systems," according to D. E. Groteke, Alreco Metals, Inc. "Having clean metal available to pour will not solve all of the metal-related defects in production castings."[1]

Measuring Gas Content

Like inclusions, the entrapment of hydrogen gas in aluminum castings can result in significant deterioration of casting properties. Again, this occurs because "the solubility of hydrogen in aluminum decreases exponentially with temperature and hydrogen is rejected during solidification."[5] The result is an aluminum casting with internal voids and highly diminished mechanical properties. Figure 4 shows the loss in ultimate tensile strength (psi) as a function of dissolved hydrogen in an aluminum alloy.

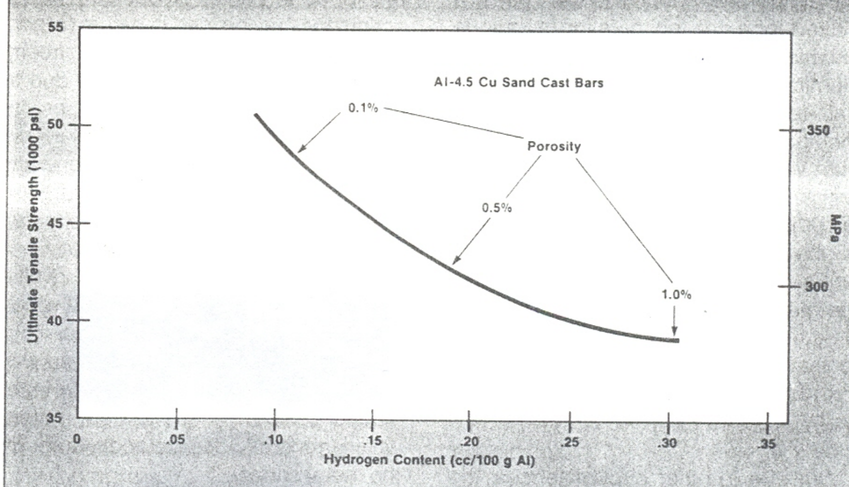

Fig. 4. The influence of hydrogen on the mechanical properties of an aluminum alloy casting can be dramatic, as shown in this graph.

Simply put, the process of removing or minimizing the gas content, particularly hydrogen, in the bath prior to pouring is called degassing. To achieve nearly any level of casting quality, degassing is essential. And while a variety of degassing techniques are available to effectively and efficiently degas molten aluminum, the ability to measure gas content is essential in order to determine the most effective method.

T. E. Acklin, Willard Industries, and N. J. Davidson, Robert Mitchell, Inc, point out that while various tests have been used to determine gas levels in molten aluminum, the reduced pressure test is probably the most widely used in foundries today.[5]

This test is relatively simple and can be performed on the foundry floor. The components of the system include a mechanical or venturi vacuum pump, a bell jar which is evacuated and a gage for measuring the reduction in pressure under the jar. A small copper cup is used for procuring melt samples.

In operation, they explain, "A sample of molten aluminum alloy is removed from the bath via the sample cup. This is placed under the bell jar and the vacuum pump is energized. The measuring gage should reach about 26-27 in. during the course of solidification.

"The product of this procedure is a cup shaped specimen which permits the gas level to be reviewed in at least three distinct ways. The first is merely to view the top of the sample. If it resembles a cabbage or is, at least somewhat puffed up, it may be concluded that a rather heavy gas concentration exists in the melt. On the other hand, if the top surface is smooth, or possibly concave, one may decide that the melt is low enough in gas and castings will be poured from this metal.

"The second approach to analyzing the gas content of the melt is accomplished by cutting the sample in half on the transverse plane and examining the cut surfaces for porosity." (See Fig. 2.)

"A third approach, a more refined version of the second, involves polishing the sample halves in order to better delineate the porosity developed during solidification. This approach does help to more effectively note the presence of fine porosity. Fine pores can often be masked by the saw marks developed in the cutting process."[6]

Another viable technique for measuring the level of hydrogen gas in molten aluminum, according to Acklin and Davidson, is the *initial bubble test*. Used more extensively in Europe than in the U.S., this testing technique operates as follows:

"Utilizing a reduced pressure environment, a molten sample is placed in a small furnace that constitutes part of the system and is equilibrated to a specific temperature. This is usually within the range of the metal temperature of the alloy bath. The furnace unit is then sealed under a vacuum. The vacuum level at which the first bubble of hydrogen is released from the surface of the melt is noted. This reduced pressure level is then indexed on a scale against the temperature of the sample holding furnace and hydrogen level in cc/100 grams is read from the nomograph."[5]

Another reduced pressure test system, called the Severn unit, also was described by Acklin and Davidson. Developed in the United Kingdom, the unit reportedly offers a more quantitative measure of hydrogen in molten aluminum. In operation, "a constant weight of molten aluminum, 100 grams, is placed in a vacuum chamber and the pressure is reduced to a predetermined level by means of the associated vacuum equipment. The sample chamber is then isolated from the rest of the environment and allowed to solidify. In the course of solidification, the hydrogen that is released develops a partial pressure. This partial pressure is measured by means of a calibrated Pirani gage. The information obtained is then translated to a digital readout system."

Generally, the reduced pressure tests described here are considered *batch testers* in that they provide hydrogen measurements for single baths of molten metal. On-line systems, which provide continuous measurements of hydrogen in molten aluminum, also have found use in metalcasting operations, but to a much lesser degree than batch measurement methods.

According to Acklin and Davidson, the Telegas system, marketed by Alcoa, is one example of an on-line hydrogen measurement system. Due to the unit's high initial and operating costs, it has been used most effectively by primary metals producers.

More recently, an on-line hydrogen measuring system has been introduced by Alcan International, Ltd, Quebec. This system has been designed for use in foundry operations by reducing the higher operating costs of other on-line systems. According to F. Painchaud, Bomem, Inc, Quebec, and J. P. Martin, Alcan International, this system uses "a closed-loop gas recirculation technique in which a probe is inserted in molten aluminum and a small volume of carrier gas is brought into contact with the metal and recirculated until an equilibrium level is achieved between the hydrogen gas content in the carrier gas and the monoatomic hydrogen content of the metal. . .The time required to achieve this equilibrium depends upon the mass transfer rate of dissolved hydrogen from the bulk of the liquid metal to the probe/metal interface and then into the carrier gas. This process normally requires approximately five minutes."[3]

But due to other circumstances, the authors recommend that to ensure reproducible results, a ten minute analysis should be undertaken.

Degassing Molten Aluminum

Most typically, degassing is carried out by introducing a sparging gas into the molten aluminum bath. As it bubbles up and through the bath, "Hydrogen is removed from the melt by diffusion into the sparging gas bubbles due to the difference in hydrogen partial pressures between melt and bubbles."[6]

The methods used to effectively degas aluminum, according to D. Saha, Air Products and Chemicals, Inc, and D. Fay, Uni-Cast, are generally differentiated based on two factors: type of sparge gas and the type of gas injecting device.

"A lance (wand), porous refractory (plug or tile) or rotary impellor is used to inject any of the following sparge gases [individually or in combination]: nitrogen, argon and chlorine. In addition, chlorine, dichlorodifluoromethane (freon 12), and more recently, sulfur hexafluoride, as a component gas blend with argon or nitrogen,"[6] have also been used in degassing operations.

To further explain, T. A. Zeliznak, Foseco, Inc,[7] describes the solution of hydrogen gas within a molten aluminum alloy as a reversible equilibrium process. "That is to say that the hydrogen concentration in one area will try to reach equilibrium with hydrogen volumes in an adjacent area. Simply reducing the metal temperature and limiting the amount of hydrogen to contact with the metal surface would cause natural degassing to occur, which is a time consuming process.

"To accelerate the rate of removal, a reaction gas is introduced below the metal surface through a graphite tube or lance. Hydrogen is removed from the melt by diffusion as a result of the difference in partial pressures. The reaction gas may be inert in nature (argon, nitrogen) or reactive (chlorine, freon). Reactive gases work effectively due to the chemical reaction which results when this type of gas is introduced into the metal. The gas bubbles generally introduced through a lance are large in size, and rise quickly through the metal, creating a turbulent metal surface.

"Other degassing methods involve the use of chlorine-based tablets which are held below the metal surface and allowed to react in much the same way as gaseous chlorine. All of these techniques generate a gas bubble pattern which generally rise vertically through the metal surface."[7]

A refinement of the degassing process has been the rotary impellor. Zeliznak explains that this technique introduces into the melt a large number of small gas bubbles which rise slowly permitting a longer reaction time. In addition, "the small gas bubbles provide a larger contact surface area to improve the removal of hydrogen gas. These smaller bubbles rise to the surface and do not generate the turbulent metal surface typically associated with lancing techniques."

Recent work has also shown that rotary impellor techniques provide other benefits beside metal degassing. According to L. C. B. Martins and G. K. Sigworth, Reading Foundry Products,[8] "When a rotary impellor is used in degassing of aluminum, copious small bubbles are produced which 'sweep through' and clean the aluminum melt. The ability of these small bubbles to degas has been well established technically and commercially. What is often just as important, however, but not so well known, is the fact that bubbles may also act to float out undesirable inclusions."

In further explaining this phenomena, Martins and Sigworth report that "The technical analysis suggests that flotation will occur with the use of inert gases (nitrogen or argon). Oxides readily wet the bubble, when they manage to collide with one, and are carried to the surface. Commercial experience suggests that the flotation of inclusions is increased by adding small amounts of chlorine, freon or sulfur hexafluoride to the inert purge gas.

"This effect cannot be explained readily by the scientific information available on flotation. It is proposed, however, that the halogen creates a flux at the surface, which more readily incorporates inclusions brought to the surface. Stirring the melt may also assist in inclusion removal."

Key to Quality

While much work remains to be done in understanding the nature of aluminum and how to better optimize its advantages as a high quality engineering material, much is also already known about controlling it in its molten state in order to meet increasingly stringent customer demands.

As has been discussed here and well documented in the literature, the key to improving the mechanical properties of aluminum castings is the the ability to produce "clean" metal: metal with little or no solid or liquid inclusions, as well as minimal or controlled amounts of hydrogen gas in the melt.

Techniques, such as filtration, degassing and other fluxing, have proved to help in producing clean metal. This, then, opens the door to other techniques, like silicon modification, which can further enhance the mechanical properties, and likewise, create new applications for high quality aluminum castings.

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