ARCHIVES
of
FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 11
Special Issue
1/2011

5 – 10

1/1

Hydrogen analysis and effect of filtration on final quality of castings from aluminium alloy AlSi7Mg0,3

M. Brůna*, A. Sládek
Department of Technological Engineering, Žilina University from Žilina , Univerzitná 1825/1 010 26 Žilina, Slovakia
*Corresponding author. E-mail address: Brunam@fstroj.uniza.sk

Received 21.02.2011; accepted in revised form 25.02.2011

Abstract

The usage of aluminium and its alloys have increased in many applications and industries over the decades. The automotive industry is the largest market for aluminium castings and cast products. Aluminium is widely used in other applications such as aerospace, marine engines and structures. Parts of small appliances, hand tools and other machinery also use thousands of different aluminium castings. The applications grow as industry seeks new ways to save weight and improve performance and recycling of metals has become an essential part of a sustainable industrial society. The process of recycling has therefore grown to be of great importance, also another aspect has become of critical importance: the achievement of quality and reliability of the products and so is very important to understand the mechanisms of the formation of defects in aluminium melts, and also to have a reliable and simple means of detection.

Keywords: Castings defects; Quality management; Aluminium; Filtration; Remelting

1. Introduction

In the case of recycling aluminium and its alloys, scrap components such as used beverage cans, car cylinder heads, window frames from demolished buildings and old electrical conductors are recycled by secondary aluminium refiners or remelters. One of the most important factors in recycling aluminium is that remelting saves up to 95% of the energy needed to produce the primary product. Another important factor is that the majority of used aluminium can be recycled, which makes it highly valuable. Today recycled aluminium accounts for one-third of global aluminium consumption world-wide. The quality standard of the recycled material, usually cast into bars or ingots for subsequent re-melting by the casting industry, has to be of a standard sufficient to make adequate castings. It is well known by casters that the remelting industry turns out ingot of differing quality from plant to plant, and, unfortunately, quality can also vary from a single plant on a melt to melt basis.

In a final product, the properties and quality are influenced by melt treatment, casting technique, solidification mode and microstructure. Solidification is the stage at which the microstructure is formed. Segregation and hot tearing are among the kind of defects that can occur during solidification. However, there are many defects that are formed at the melting, remelting stage and during the handling of the melts in a casting process. All these processes occur before the stage of solidification. Undoubtedly, any defect present or created at the melting stage could be carried to the final microstructure effectively adding to any solidification defects, and will, of course, affect the component’s life. Therefore it is apparent that the control of the quality of the product begins with the control of the quality of the melt. At present, there is no single quality test that is capable of identifying and classifying the most serious defects that can exist in aluminium alloy melts. These defects, which have been held responsible for potential failure mechanisms, are dissolved hydrogen and the entrained aluminium oxide.

2. The Dissolution of Hydrogen

The majority of light metals and alloys in their molten condition are inclined to considerable adsorption of gases. The gases absorbed by the surface of the metal are capable of diffusing into the metal in the atomic state. Oxygen, nitrogen and other gases form chemical compounds on the surface of the liquid metal, however hydrogen appears as the principal gas that can be taken into solution in the bulk liquid.

Hydrogen, on account of the small volume of its atom, diffuses more rapidly than other gases in liquid metals. Diffusion through an alumina film is accomplished in the following stages:

1. Dissociation of the molecular hydrogen
2. Development of activated adsorption on the oxide surface
3. Release of hydrogen from the adsorbed layer and its passage into true solution
4. Movement of the dissolved hydrogen through the crystal lattice
5. Passage of hydrogen into the absorbed layer on the opposite side of the film
6. Desorption of atoms of hydrogen
7. Transport by advection of the bulk liquid.

The main source for hydrogen results from the dissociation of water vapour. Fluxes, crucibles, refractories and charge materials all usually contain some moisture which will add hydrogen to the melt. Water vapour may be readily found in the atmosphere, especially on hot and humid days. It is important to understand that amount of hydrogen contained in melt can rapidly influence quality of casted metal.

3. Metal quality

One of the challenges faced by the foundry technologist and researchers is to obtain a consistent quality. Therefore extensive efforts have been made to produce quality products from various alloy systems meeting the demanding mechanical behaviour. There are three important features that define metal quality: control of trace elements, reduction of dissolved gas, and removal of non-metallic inclusions. Inclusions in the aluminium alloy act as stress-raisers, and can cause premature failure of a component. Oxide particles and films are often the most common inclusions observed within aluminium melts. The oxides arrive in the melt right from the start of melting. They arrive as oxide skins on the surface of the material to be melted. When remelted in a crucible furnace, or other type of bath of molten metal, as each piece of solid charge is submerged and melts, its surface oxide floats free and becomes suspended in the melt. Such films are finally found as complete, massive, film-like or dross-like inclusions in finished castings. The presence of these defects, as well as gas or shrinkage porosity formed during solidification, can make properties unpredictable and significantly affect the mechanical properties of aluminium castings, especially the ductility and fatigue properties. Since the significant expression in the definition of casting is the use of liquid metal to give the shape of the object directly, the primary quality factor begins with the control of the melt. As indicated above, the liquid metal may gain a significant amount of oxide from the melting and remelting process. However, even more may be added if the melt is handled poorly, particularly if it is violently stirred or is poured.

During melting, important interactions that occur between an aluminium melt and its environment include the absorption of hydrogen and the formation of oxide films. Hydrogen dissolves readily in liquid aluminium but is much less soluble in the solid state and may therefore form porosity if it is rejected from solution during solidification. The free energy of formation of alumina is such that it is impossible to prevent its formation at exposed liquid aluminium surfaces. In fact, the alumina film is an important part of the melting process, simply because it protects the metal underneath from further oxidation, or even, as in the case of molten magnesium, combustion. However, the problem begins when an oxide film is pushed into, or otherwise entrained, in the melt. These entrainment events are surface folding actions in which two non-wetting surface films will come into contact with gas trapped between them. This constitutes a defect that will act exactly like a crack in the liquid and is known as a ‘double oxide film’ defect or a ‘bifilm’. As a result, the potential for introducing defects into aluminium castings begins at the melting and also remelting stage where hydrogen gas and oxide films become incorporated into the melt.

4. Secondary Remelting – Recycling

Secondary aluminium refiners convert most of their materials into foundry ingot, generally based on the aluminium-silicon alloy system with additions of other metals such as copper and magnesium. These ingots, formulated according to recognised national or international specifications, go into the manufacture of aluminium cast components. A significant share of the secondary aluminium refiners’ output is also delivered in a molten form by road tanker to large foundry users thus eliminating the need for further melting operations. One of the most important factors in recycling aluminium is that remelting saves up to 95% of the energy needed to produce the primary product. Another important factor is that the majority of used aluminium can be recycled, which makes it highly valuable. Today recycled aluminium accounts for one-third of aluminium consumption world-wide. Naturally, the recycling process does not consist simply of gathering scrap and remelting it, usually into bars or ingots for subsequent re-melting by the casting industry. The quality of the recycled material has to be of a sufficient standard to make adequate castings. With a view to attempting to understand the factors that are of major importance in the control of quality, a typical secondary remelting process includes:

1. Sorting of scrap into alloy types
2. Centrifuging and drying to reduce contaminants such as oil and water.
3. Magnetic separation of iron.
4. Melting.

5. Fluxing and degassing to remove inclusions, oxides and dissolved gases.
6. Pouring into a holding furnace
7. Chemical analysis and adjustment of analysis if necessary.
8. Transferring to casting unit via a launder (a refractory lined open channel)
9. Casting into bars or ingots on an automated casting machine.

5. Devices for melt quality control

5.1. Reduced pressure test

The reduced pressure test is a foundry floor tool which allows the operator to qualitatively assess the cleanliness of a batch of molten aluminum, allowing corrective action to be followed. The main principle of this technique is based on the formation of gas porosity when liquid aluminum is cooled under the reduced pressure. The size of the porosity formed is magnified by the effect of the reduced pressure, resulting in a visibly porous sample as shown in Fig. 1. The samples solidified under these conditions are evaluated either by visual observation for bubble formation during solidification, or by determining the density of the solidified sample. Visual evaluation of the sectioned sample is often done by comparing the result to a standard chart.

Fig. 1. Test samples (A) solidified under atmospheric pressure and (B) solidified under vacuum

The sampling procedure is very simple. A small amount, about 200 g., of aluminum melt is poured into two thin wall steel crucibles. One crucible is leaved to solidify under atmospheric pressure while other is seated in the chamber, where the pressure is reduced to 80 mbar and remains constant until the melt is fully solidified. After solidification, the samples are removed from the molds and evaluated either by density measurement or by sectioning to observe the porosity. The entire process requires roughly several minutes for completion. The popularity of the RPT as currently widely used in the industry lies in the relative simplicity and inexpensive nature of the test. One major disadvantage is, however, that it is not quantitative. Nevertheless, it becomes possible to identify the size, shape, type and distribution of non-metallic inclusions in the final product which can be seen on a polished cross section of the reduced pressure test. These can be used by the cast shop as the ‘fingerprints’ of the melt. Thus even in its simplest qualitative form, the test is useful.

5.2. Tatur test

Tatur test has been developed by A. Tatur in order to measure affinity of alloys to build up macro and micro porosity during solidification. Unfortunately, this test has been rarely used in aluminum casting plants as a routine quality control tool. The main reason for that could be an extra work necessary for full evaluation of the melt cleanliness.

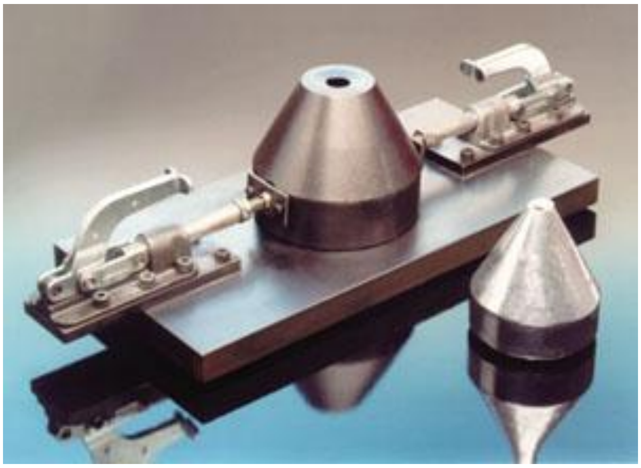

Fig. 2. Tatur test

Fig. 2 presents the form of Tatur test, which has been designed to promote the formation of shrinkage porosity. The Tatur test utilizes a permanent mold of fixed geometry containing two parts. The upper part is conic with orifice. During experiment the melt is poured through the preheated mold orifice and allowed to solidify without extra addition of the melt. Due to contraction during liquid-solid transformation, conic design of upper part and absence of riser, the formation of micro and macro porosity will be enhanced. By using simple techniques such as the density measurement and water displacement, it is possible to quantify the volume of micro and macro shrinkage and contraction. In order to draw reliable conclusions, it is necessary to perform a large number (about 20) of tests and to evaluate them statistically. The low reproducibility of the measurements is additional reason why this technique has not been widely used at foundry floor as a quality control tool. Fig. 3 shows some typical micro and macro porosity forms achieved using Tatur test.

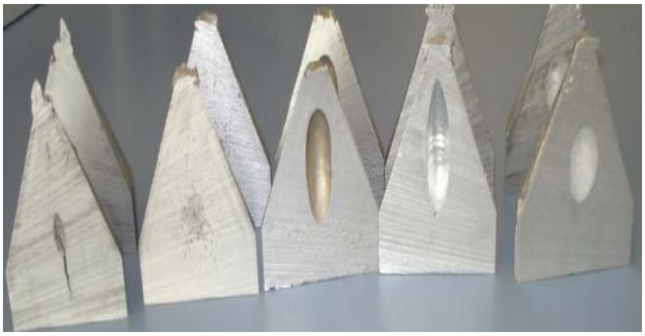

Fig. 3. Typical shrinkage porosity obtained using Tatur test

5.3. K–mold

K - mold device is a fracture test invented by Sanji Kitaoka in Japan in 1973, at Nippon Light Metal Ltd company. More than forty years this device has been used as a simple shop floor equipment. The purpose of this equipment is to evaluate the macro cleanliness of molten aluminum melt at production conditions. The main advantages of his equipments are: (1) quick evaluation (approximately 10 min), (2) easy handling, (3) easy sampling and melt cleanliness assessment; (4) portable, (5) sensitive to the inclusions and oxide film, (6) costly friendly, and (7) appropriately accurate.

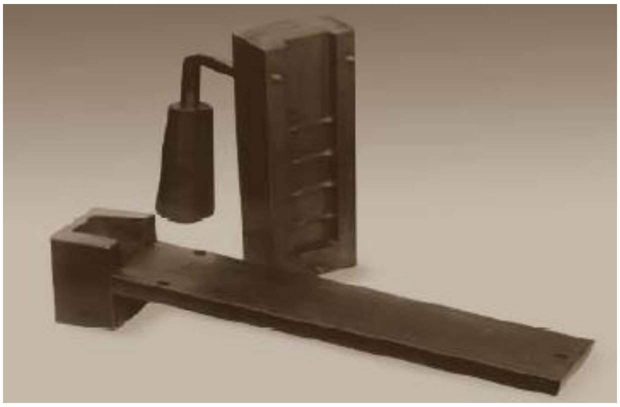

Fig. 4. K-mold

Experimental procedure is very simple. Around 400 g of the melt is poured into the preheated mold and after a few seconds test samples like flat bars (240x36x6mm) are obtained. The test samples need to be broken into several pieces and put together as shown in Fig. 5. The fracture surfaces have been analyzed either visually or under a low magnification. Rapid solidification of the sample produces very fine matrix, and thus inclusions are clearly detected on the fracture surface.

Fig. 5. Fractured pieces of K-mold test sample

The cleanliness of the melt is expressed through K-mold value. This value is based on the visual inspection of the surface of the test pieces and count of the number of the inclusions on the surface for the evaluation of the cleanliness of the melt.

5.4. New devices for melt quality control (Foseco)

To be suitable for foundry applications, a device for measuring the hydrogen content in liquid aluminum has to meet a number of particular requirements such as: (1) short response time, (2) reliable values, (3) reproducible results, (4) long life in foundry environment and (5) simple handling. Recently developed device by Foseco Company, named ALSPEK H hydrogen analyzer (fig. 6) fulfils all these requirements and enables foundrymen to control the hydrogen content before, during and after the degassing process.

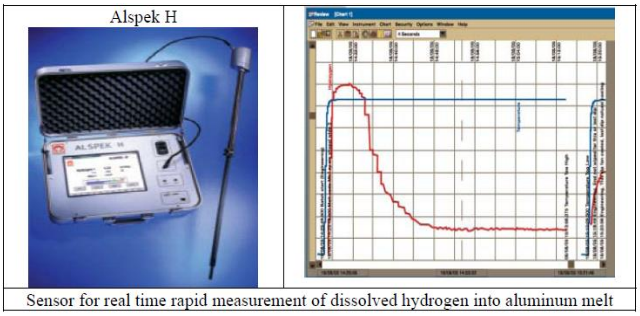

Fig. 6. FOSECO devices recently developed for assessment melt quality control

Melt Quality Index, MQI	Comments
MQI 7 – 9	Extremely dirty
MQI 4 – 6	dirty
MQI 1 – 3	clean

Rapid test for monitoring the cleanliness of aluminum melt

Fig. 7. Rapid test for monitoring the cleanliness of Al melt

The ease of use of ALSPEK H means that it can readily be used to measure melt quality in different locations around the foundry. Fast and accurate spot measurements of hydrogen concentrations can be performed in ladles and furnaces, or the probe can be left immersed in one location to provide continuous real time measurement of hydrogen levels. It is also possible to carry out a real time hydrogen measurements during a degassing treatment. All measured values are automatically logged and can be downloaded later to provide important data for quality control and certification purposes. So far there is not such equipment on the market that can on line measure the variation of the hydrogen solubility in aluminum melt.

ALSPEK MQ (fig. 7.) is another product developed at Foseco Company aimed at offering the foundry a practical, simple, rapid and meaningful method of measuring and bench marking melt cleanliness. The principle behind ALSPEK MQ is the ability of a fine foam filter to trap non-metallic inclusions. Foam filters are multi-dimensional where the metal must follow a tortuous path in order to pass through. Larger particles are trapped on the face of the filter thereby restricting the flow of the subsequently flowing metal. The internal random structure of the filter encourages changes in metal flow direction and metal velocity causing smaller inclusions to become trapped in the internal structure. The principle of the ALSPEK MQ device is that as the number of particles and inclusions in the melt increases so the flow through the filter will becomes more restricted. This apparatus is still under foundry trials before start to be widely used in daily quality control.

6. Filtration

In 1935 a procedure was proposed for the filtration of light metal melts by DEGUSSA, which was transferred to Aluminium melts very soon. The bed filtration (BF) was developed using bulk petrol coke and/or ceramic particles by ALCAN in the 1940´s. The development of ceramic foam filters (CFF) started in the beginning of the 1970´s by SELEE. First rigid media filters (RMF), which are called also bonded particle tube filters (BPF), appeared on the market in the 1980ies, but were initially not accepted by the Aluminium industry. In the 1990ies two stage filter systems were developed having much better particle removal efficiency. The latest advances in filtration technology are the development of surface active filter systems starting in the mid 1990s. By the formation of active surfaces inside the filter itself the effectiveness for the separation of small inclusions was significantly improved. For the filtration of molten metals the same laws apply as for aqueous suspensions.

Two different kinds of filtration have to be distinguished: cake and bed filtration. Usually both filtration types occur combined and happen successively. In the case of cake filtration the filtration process itself happens at least at the beginning by sieve effects. First inclusions larger in size as the pore diameter of the filter settle on the filter surface form a thin layer. The thickness of the cake increases as more melt flows through and more inclusions are separated. For Aluminium melt treatment cake filtration is rather unusual and limited to melts with high inclusions contents (> 200 ppm) and larger inclusions. Bed filtration is the common mechanism used for Aluminium melts. In this case the separation of inclusions from the melt is rather complex. It happens mainly by direct collision or adhesion of particles to/at the filter surface, sedimentation by gravity as well as by inertia forces, collision of particles by Brown's movement or/and fluid dynamic effects. Up to now no closed theory exist of the filtration of Aluminium melts. So a mathematical modelling, which would allow calculating filtration efficiencies, filtration times, filter sizes etc. is not yet possible. The filter materials are generally refractory material, preferentially Al2O3.

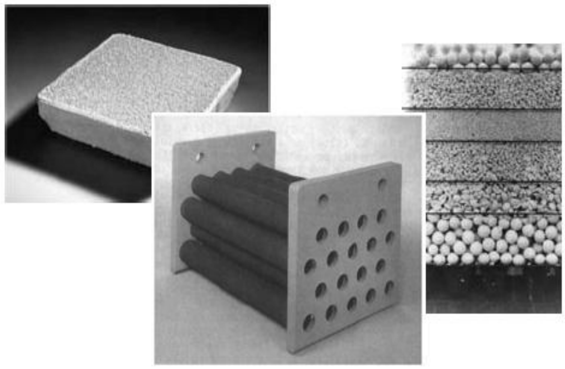

Fig. 8. Filter devices for Aluminium melt filtration
(from left to right: CFF, RMTF, BF)

Bed filters (BF) are bulks built of Al2O3-balls or chips with a size of 2 – 8 mm. Bulks of carbon or coke are not used anymore. BF´s are separate in-line units, which need rather much space. They are built in externally heated boxes and are suited for the throughput of large amounts of melts up to 1000 t. Particle form and size, layer thickness, and the sequence of different layers are varied to improve the filtration effectiveness. BP filters are suited for the separation of small inclusions < 20 μm from melts with low inclusion concentrations. Ceramic foam filters (CFF) consist of a labyrintic structured ceramic material in which a very effective cleaning of the Aluminium melt happens by deep bed filtration effects. They are produced by the infiltration of a ceramic sludge into porous polyurethane foam. During firing the plastics decomposes and the porous ceramic remains. CFF are also built in separate boxes, which must not be heated externally. Filter plates are commercial available in different sizes, thicknesses (normally 50 mm) and pore sizes between 10 ppi to 80 ppi (pores per inch). They are one-way products and rather cheep so that the operational costs are low. This filter type is used most often in Aluminium metallurgy. Rigid media filters (RMF) consist of porous ceramic tubes, which are built in like BF´s in external heated boxes in form of pipe bundles. The melt flows from the outside to the inside of the pipes. The filtration processes are very similar to the CFF´s. Because they have a smaller pore size there is a greater pressure drop and they have a shorter lifetime. RMF´s are rather expensive in respect to investment and operation cost, therefore their application is limited to special applications. State of the art is the application of deep bed filtration in foundries, where large amounts of the same alloy have to be cleaned. For general purposes CFF´s are used. Only for special applications RMF´s are in operation because they are most efficient for the removal of very small particles. In normal filter systems single CFF plates or combination of CFF´s with different pore sizes are built in in separate boxes which must not be heated externally. They are positioned in-line directly before the DC unit. The melt is allowed to run through the filter plate, mostly downwards. CFF´s are used in combination with BF´s and with degassing units, too. Additional ceramic filter clothes may be used at the DC casting unit to retain coarse impurities which can enter the melt after filtration. Targets for the filter development in the future are filters that can remove even finer particles with high efficiency at a reasonable pressure drop and with minimized metal losses.

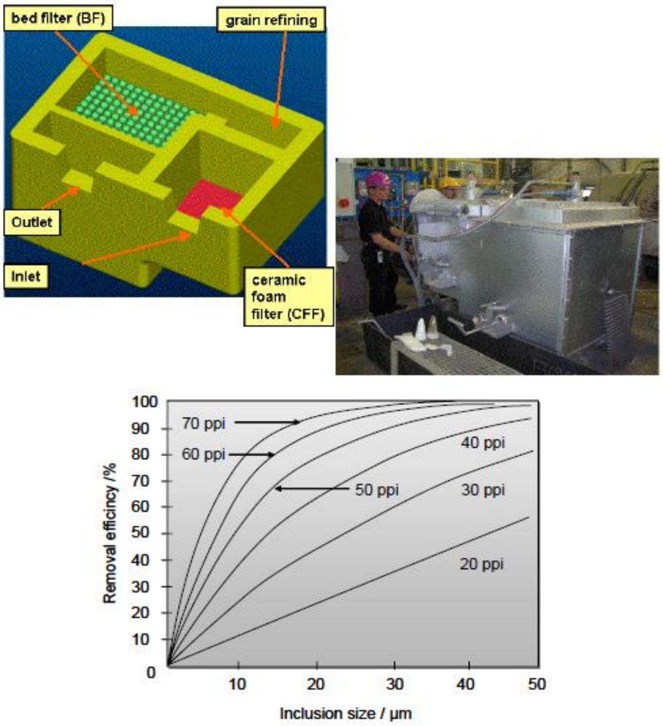

Fig. 9. In line Aluminium melt treatment: Hydro (VAW)-Filter (left), removal efficiency of for different particles sizes in different filters (right)

7. Conclusions

The quality of cast products in aluminum casting plants directly depends on the quality of molten metal from which the products are cast. Comprehensive understanding of the melt quality is of the vital importance for the control and prediction of actual casting characteristics. This paper represents a review of the most common tools used in aluminum casting plants in melt quality control such as: (1) reduced pressure test, (2) K-mold (3), Tatur test and two new equipments recently developed by Foseco. This paper is also focused on today melt treatment techniques for Aluminium castings. Emphasis was laid on filtration because this technique is widely spread in aluminium castings industries.

Acknowledgements

The authors wish to thank European Regional Development Fund for received financial support to create present paper within execution of the project "Equipment for the production of prototype parts by casting on a computer-controlled base" with ITMS code 26220220047.

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