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On-line prediction of the melt hydrogen and casting porosity level in 319 aluminum alloy using thermal analysis

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Abstract

One of the major problems associated with aluminum castings is the porosity. Porosity is attributed to the shrinkage process and a lack of interdendritic feeding, which result in a reduction of the mechanical properties, loss of pressure tightness and poor surface integrity in castings.

In this research was developed a methodology for on-line prediction of the hydrogen and porosity levels in 319 melts and castings, respectively. The main tools used for this research were thermal analysis and image analysis. Thermal analysis revealed that the nucleation temperature for the Al–Si–Cu eutectic changed in up to 12.3 °C for a range of dissolved hydrogen from 0.06 to 25 mL H_2/100 g Al. The hydrogen–porosity threshold determined for the 319 alloy was ∼0.15 mL H_2/100 g Al in the low pressure conditions (6 kPa). A statistical analysis demonstrated that this technology is highly accurate ($R^2 = 0.91$) to predict the amount of hydrogen and the porosity.

Keywords: Hydrogen level; Al–Si alloys; Porosity; Thermal analysis; Image analysis; Hydrogen threshold

1. Introduction

A comprehensive understanding of melt quality, including the porosity level, is very important for the control and prediction of casting characteristics. If one can assess these characteristics on-line during the manufacturing process, one can make proactive decisions pertaining to melt and casting quality control. This can substantially reduce cost downtime and scrap levels.

Hydrogen is the only gas soluble in liquid aluminum, and it is one of the main factors involved in the formation of porosity in aluminum castings. Quantification of the amount of dissolved hydrogen in aluminum melt has been for a long time a subject of high attention by several authors [1–10]. Among many developed techniques for the assessment of the amount of dissolved hydrogen into aluminum melt the Reduce Pressure Test (RPT) or Straube–Pfeiffer technique has been widely accepted at the aluminum foundry. The RPT utilizes a liquid aluminum sample that is poured into a pressure tight chamber. The sample is left there to solidify under low pressure. Under this condition, the growth of porosity is virtually unrestricted and the amount of porosity that is created by a given amount of hydrogen gas is much larger than one would expect under actual casting conditions. This makes it easy to qualitatively estimate the hydrogen content in the melt.

In the early stage of its development the RPT was only used as a quality control tool for molten alloy. Now conventional RPT is a semi-quantitative method for measuring hydrogen content and is widely used in the aluminum industry. It is simple, inexpensive and versatile method. Because it has various ways to show the existence and quantity of hydrogen, it has served a variety of purposes in production and research, such as quantity control and hydrogen detection and measurement. It has a workable accuracy for many applications. However, its accuracy is generally lower than that of some other methods, such as the sub-fusion and the fusion methods and Telegas.

The long time has been recognized a necessity of making the RPT truly quantitative measurement technique. In 1955 Rosen-

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tal and Lipson [1] attempted to quantify the amount of dissolved hydrogen in aluminum melt by measuring the volume percent of porosity of the RPT samples. In experiments it was assumed that all of the pores formed in test sample under vacuum were filled with hydrogen gas at the applied pressure and solidification temperature. Sulinski and Lipson [5] have shown that assumption was not correct as some hydrogen was retained in solid solution while some was removed from the test samples during the test under a low pressure. During 1973 Hess [6] unsuccessfully tried to quantify the RPT by calibrating the test sample density against the amount of dissolved hydrogen.

Gruzleski and co-workers [7] showed that reduced pressure sample density could be related in a clear and reproducible way to the amount of hydrogen dissolved in aluminum melt and measured by one of the recirculation gas techniques. In that work Gruzleski and co-workers tried to develop a calibrated curve for a given alloy (413, 356, 357 and 319) and a specific sample mold geometry of the solidified test sample to the actual amount of dissolved hydrogen in liquid alloy. The following parameters have been analyzed in these experiments: sample pouring temperature, mold temperature, chamber temperature and pressure and melt cleanliness. The amounts of dissolved hydrogen were varied over the range 0.07–0.35 mL H_2/100 g Al melts by using various degassing and re-gassing procedures. In all cases a linear relationship was obtained to best fit the density–hydrogen and weight–hydrogen relationships. The correlation coefficient (R^2) for all experiments with various alloys falls in the range from 0.7 to 0.8. The scatter of the data according to authors can be related to the various parameters above mentioned. Among these variables the most important were variation in the melt cleanliness and imprecision in chamber pressure control. According to authors, the scattering of the data increases as the amount of dissolved hydrogen increases. For the entire hydrogen range used in their experiments the amount of 0.15 mL H_2/100 g Al melt has been recognized as a threshold value. This value represents the amount of dissolved hydrogen below which it is not reasonable to detect any gas pores in as cast solidified structure using conventional metallographic techniques by visual observation.

Cooling curve analysis has been used for many years to define binary phase diagrams and for fundamental metallurgical studies [8–12]. The cooling curve method is used in commercial applications for characterization of the melt, for instance, the level of silicon modification, the low melting points of secondary eutectic(s), fraction solid and other characteristic temperatures such as liquidus, Al–Si eutectic, Al–Si–Cu eutectic and solidus temperature. Thermal analysis was also used to determine and predict casting properties including grain size, dendrite arm spacing (DAS) and dendrite coherency point. In addition thermal analysis is a simple, inexpensive and a consistent technique with high level of accuracy and repeatability.

Recently, it has been proved that thermal analysis (TA) can be used to assess the level of dissolved hydrogen in aluminum melt [13]. It was found that an increase in the hydrogen levels from 0.083 to 0.280 mL H_2/100 g Al decreases the $T_{\mathrm{E,NUC}}^{\mathrm{AlSiCu}}$ temperature of the 319 aluminum alloys by 8 °C. Statistically high correlation coefficient ($R^2 = 0.82$) between $T_{\mathrm{E,NUC}}^{\mathrm{AlSiCu}}$ and the hydrogen dissolved in the aluminum melt suggests that dissolved hydrogen depresses the nucleation temperature of the copper rich eutectic phases. This difference is large enough to be used as a parameter for predicting the level of dissolved hydrogen in the liquid aluminum melt. The result is expected since the literature suggests that copper decreases the hydrogen activity in liquid aluminum alloys [4,5]. Therefore, it is plausible to note that an increase in the concentration of hydrogen increases copper's ability to react with Al, Si and Mg which results in the formation of copper rich eutectic phases at lower temperatures.

Unfortunately, there are no data in the literature showing that thermal analysis can predict the amount of porosity in cast aluminum alloys. Therefore, the main purpose of this work is to find out if thermal analysis in combination with RPT technique can be used for on-line prediction of the amount of porosity in aluminum cast components. The present work was partly inspired by the earlier attempts of the authors to develop a quantitative technique for assessment of the amount of porosity and dissolved amount of hydrogen in 3XX series of aluminum alloys using RPT apparatus.

2. Experimental procedures

2.1. Materials

Secondary W319 aluminum ingots from the Nemak-Windsor Aluminum Plant production line were used in all experiments. The chemical composition as obtained from the optical emission spectroscopy for the alloy used in the present research is provided in Table 1.

2.2. Melting and degassing procedures

The secondary W319 aluminum ingots were cut and loads of 12 kg were charged into the crucible of a resistance furnace. In order to eliminate the moisture, the ingots were preheated in the resistance furnace at 400 °C for few hours. Finally, the alloy was heated up to 760 °C. The melt temperature was chosen to be constant parameter during all experiments. The temperature of the melt was controlled with a thermocouple inserted into the liquid metal, while the chamber temperature of the furnace was controlled with the thermocouple attached to the inner wall of the furnace. The top of the furnace was covered with high temperature resistant bricks in order to eliminate any temperature gradient in the molten alloy.

A degassing unit (FOSECO) was used to reduce the level of hydrogen in the melt on the lowest feasible level. Following the removal of the dross, the graphite propeller was introduced into the melt and the top of the furnace was again protected. Propeller rotated 100 cycles/min blowing argon at a rate of

Table 1
Chemical composition (wt%) for the W319 alloy used in the Enviro-AlTAP experiments

Si	Cu	Fe	Mg	Mn	Zn	Ti	Ni	Sn	Pb
7.77	3.48	0.42	0.17	0.25	0.18	0.12	0.04	0.04	0.008