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Optimization of melt treatment for in-house recycling of Al alloy scrap

Ki-Bae Kim*, Hyun-Kwang Seok, Yeung-Seok Kim, Jong-Chul Yoon, Dock-Young Lee, Chang-Ryul Chung[a] and Do-Suk Han[a]

Division of Materials, Korea Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul 130-650, Korea
[a]Advanced Technology Center, R&D Division for Hyundai Motor Co. & Kia Motors Corp., #772-1, Jangduk-dong, Hwasung-si, Gyunggi-do 445-706, Korea

The production of premium quality castings for structurally safe components for aerospace and automotive applications requires that porosity and inclusions be minimized or eliminated to negate their harmful influence on the mechanical properties. Also in order to achieve a competitive advantage in the automotive industry it has become necessary to use Al alloy scrap to keep the cost-down of the material. A riser and runner part of a cylinder head from the gasoline engine of an automobile was used as the Al alloy scrap. For in-house recycling of Al alloy scrap the variations of the content of alloying elements, microstructures, mechanical properties, and volume of inclusions were examined with respect to the frequency of scrap use and the variations of various inclusions were measured according to different melt treatments. The contents of Mg, Si, Ca, and Sr decreased, but Fe increased with the frequency of scrap use. The tensile strength and yield strength of Al alloy scrap were slightly decreased but not significantly changed, but the fracture toughness and elongation to failure almost halved due to the increase of total volume of inclusions according to the frequency of scrap use. The majority of oxide film and inclusions in Al alloy scrap was removed by a fluxing treatment, but the fluxing treatment followed by a treatment in a Gas Bubbling Filtration (GBF) resulted in a significant increase in the volume of oxide film. The fluxing treatment was the most effective in removing the oxides and inclusions from the Al scrap melt.

Key words: melt treatment, recycling, Al alloy scrap, inclusion, cylinder head.

Introduction

Recycling of aluminum has been undertaken virtually since the metal started to be used in the late 19th century, because of an energy saving benefit of 94% and an environmental benefit in the large scale reduction of CO_2 gas emission when manufacturing the metal from scrap instead of bauxite [1]. Also Al recycling operations help to rid the environment of unnecessary waste. Recycled Al has been able to compete economically with primary Al alloy. If the alloy does not degrade during the recycling process the recycled Al alloy can be utilized like the primary alloy and the price of a cast part can be reduced and the casting company can make a bigger profit.

Recently, the production of premium quality castings for the structurally safe components for aerospace and automotive applications requires that porosity and inclusions be minimized or eliminated to negate their harmful influence on the mechanical properties [2, 3]. Also in order to achieve a competitive advantage in the automotive industry it has become necessary to use Al alloy scrap to keep the cost-down of the material [4]. However the Al alloy recycling process requires a wide range of control techniques to meet tight criteria on quality [5].

The porous disc filtration apparatus (PoDFA) technique was introduced as a method of assessing metal cleanliness by Alcan [6]. Using this method, the factors controlling the precipitation and sedimentation of non-metallic inclusions could be evaluated. The present study was undertaken to determine the optimized melt treatments such as modification, degassing, and fluxing, for the in-house recycling of Al alloy (A356.2) scrap.

Experimental Procedures

A riser and runner part of a cylinder head of a gasoline engine of an automobile which is supplied by Daerim Enterprise Co. to be the first Vender Company of Hyundai Motor for cylinder heads was used as the first scrap alloy in this study. The first scrap alloy was produced using a commercial A356.2 (Al-7 wt%Si-0.35 wt%Mg) alloy. The first scrap was remelted and poured into a metallic mold to produce a sample having a thickness of 25 mm, the cooling rate of which is almost same as that of the cylinder head. The sample was termed the second scrap alloy. In the remelting process, just a degassing process using a Gas Bubbling Filtration (GBF) was included and a flux and modifi-

*Corresponding author:
Tel : +82-2-958-5454
Fax: +82-2-958-5449
E-mail: kibaekim@kist.re.kr

cation by Sr were not included to examine the compositional variation of the scrap. The second scrap alloy was remelted to produce a third scrap alloy and subsequently remelted to produce a 4^{th} scrap alloy.

The Al alloy scrap was remelted at a melt temperature of 730 °C and then degassed using Ar gas in a GBF under optimized conditions, which were a pressure of 5 kgf/cm^2, a flux of 5 *l*/minute, and a rotor speed of 200 rpm. After holding for 20 minutes the degassed melt was poured through a porous disc filtration apparatus (PoDFA) into the preheated metallic mold at 80 °C to examine the volume of different inclusions and mechanical properties, respectively. A cleaning flux (20NaCl-30KCl-20$NaSiF_2$-25$NaSO_3$-5$MgCO_3$) was pulled down and stirred into the remelted scrap using a melting tool, inside which the flux was put in a wrapped state using Al foil.

The scrap and ingot were heat-treated for 5 h at a solution treatment temperature of 535 °C and then for 4h at an aging temperature of 180 °C. The microstructures were observed without etching just after final polishing and a tensile test specimen was machined from the heat-treated scrap and ingot. Gas and inclusions in the melt of the Al alloy scrap were analyzed using an Aluminum Scanning (ALSCAN^{TM}) system, the concept of which has been developed and validated by Alcan International's R&D Center, and porous disc filtration apparatus (PoDFA) technique in accordance with the frequency of scrap use. The total volume of inclusions was obtained using the analysis of Bomem Co. through the cake on the filter from the test using PoDFA apparatus. Also, the compositional variation was checked by spectroscopic analysis.

Results and Discussion

Effect of the frequency of scrap use

The chemical composition in terms of the main alloying elements of the Al scrap according to the frequency of scrap use was measured and is shown in Table 1. There were many compositional variations of alloying elements according to the frequency of scrap use. In particular Mg was much decreased, but Fe was increased. Also Si, Ca, and Sr were decreased.

It is known that Mg reacts readily with oxygen to form an oxide. Accordingly, increasing the number of melting operations and the time of melting allows Mg to come into contact with oxygen more readily. Therefore it was considered that the Mg content could be decreased by increasing the frequency of scrap use. However, it should be noted that the Mg content did not vary until the second scrap melt and decreased around 20% at just the third scrap melt.

Table 1. Chemical composition of main alloying elements of the Al scrap according to the frequency of scrap use (wt%)

	Si	Fe	Mn	Mg	Ti	Ca	Sr
1st scrap	7.14	0.121	0.067	0.361	0.106	0.0012	0.0065
2nd scrap	6.83	0.165	0.067	0.361	0.108	0.0014	0.0053
3rd scrap	6.68	0.157	0.066	0.294	0.105	<0.0001	0.0005

It is known that Fe easily dissolves when it contacts with Al melts. This phenomenon occurs rapidly when the Fe content of the Al melt is small. Fe in the Al melt reacts easily with Al to form a brittle intermetallic compound, which degrades the mechanical properties of Al castings and deteriorates their quality. It is common to use a high purity Al alloy containing a low Fe content to produce premium quality castings. However, when using an Al alloy containing a low Fe content, a die soldering of the melt occurs frequently and so the die mold life is reduced [7]. The content of Fe could increase with the frequency of casting operations due to die soldering.

A variant of the melting tool made from iron or steel has been utilized during the melting operations. Usually the melting tool is coated with alumina to prevent the reaction with the Al melt. However the alumina coatings could be removed easily during frequent melting operations. Accordingly, the content of Fe would be increased with the frequency of melting operations and the melting time due to the reaction of the Al melt with the melting tool.

The concentration of Si was reduced continuously in accordance with the frequency of scrap use, but this phenomenon is very unusual. Si as a major alloying element is very important in controlling both the melting temperature and the fluidity of melt. Accordingly, Si should be added in the melt, to make up for any reduction in Si content. Also the contents of Ca and Sr were reduced because of their ready reaction with oxygen similar to Mg. These elements can react with oxygen at the surface of the melt and within melt during melting and holding.

Figure 1 shows microstructures of Al alloy scrap samples with respect to the frequency of scrap use. All the microstructures were dendritic with a similar size of secondary dendrite arm spacing, which is closely related to the cooling rate. Therefore it was considered that the cooling conditions were almost the same in pouring the melts of different scraps into molds. However, in the case of the 3^{rd} scrap an elongated Si phase in the interdendritic regions was observed instead of a globular Si phase in the case of the 1^{st} and 2^{nd} scrap. This elongated Si phase mostly appeared in unmodified castings. This matches well with the chemical compositions in that Sr was almost absent in the 3^{rd} scrap.

Figure 2 shows the mechanical properties of heat-treated Al alloy scrap with respect to the frequency of use. The tensile strength of Al alloy scrap slightly decreased from 300 MPa for the 1^{st} scrap to 280 MPa by the 3rd scrap and the yield strength did not change significantly according to the frequency of scrap use.

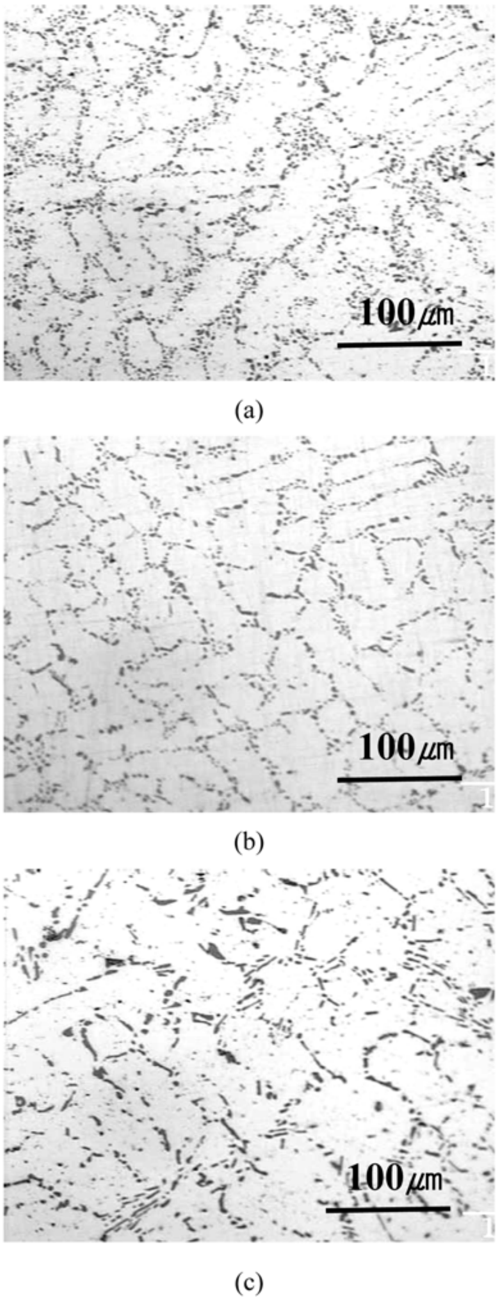

Fig. 1. Microstructures of Al alloy scrap with respect to the frequency of use; (a) 1st scrap, (b) 2nd scrap, (c) 3rd scrap.

However, the elongation to failure almost decreased by a half from around 10% for the 1st scrap to 5% for the 3rd scrap. Generally it is known that the elongation to failure is largely dependent on the volume fraction of inclusions, but the tensile and yield strength are not dependent on the volume fraction of inclusions. Sometimes the tensile and yield strength may be increased with an increase in the volume fraction of inclusions when the inclusions act as a dispersoid-strengthener. Therefore it was considered that the volume fraction of inclusions was increased with the frequency of scrap use.

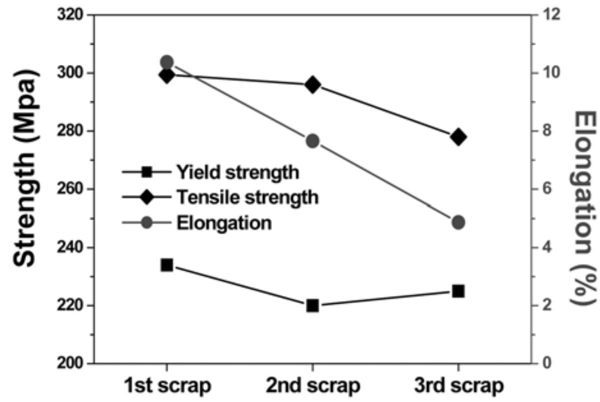

Fig. 2. Mechanical properties of heat-treated Al alloy scrap with respect to the frequency of use.

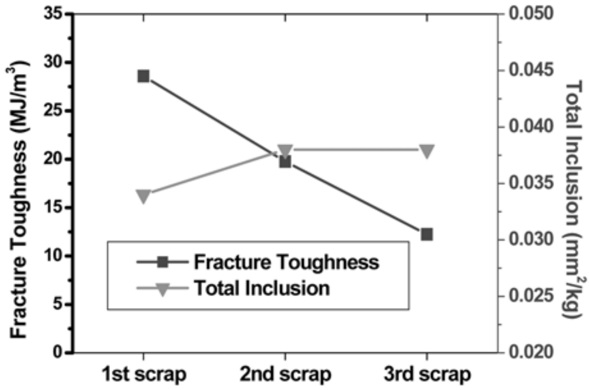

Fig. 3. The fracture toughness and the total volume of inclusions of the Al alloy scrap with respect to the frequency of scrap use.

The dynamic properties such as fatigue characteristics and fracture toughness have been evaluated as an increasingly important group of properties for Al alloy castings in structurally safe components for automobiles. In this study, considered the concept of fracture energy the fracture toughness was approximated using the strength and elongation to failure obtained in tensile tests using the following Eq. (1).

$$T\ (MJ/m^3) \approx (\sigma_y + \sigma_T)/2 \times \varepsilon \quad (1)$$

, where T is the fracture toughness, σ_y is the yield strength, σ_T is the tensile strength, and ε is the elongation to failure. Figure 3 shows the fracture toughness calculated from Eq. (1) and the total volume of inclusions of heat treated Al alloy scrap with respect to the frequency of scrap use. The total volume of inclusions was obtained from the analysis of Bomem Co. from the cake on the filter from a test using the PoDFA apparatus. The fracture toughness of around 28 MJ/m^3 for the 1st scrap was significantly reduced to around 13 MJ/m^3 for the 3rd scrap. Also the total volume of inclusions increased by around 15% from around 0.033 mm^2/kg to around 0.038 mm^2/kg. Therefore it was considered that the decrease of fracture toughness and elongation to failure resulted from the increase of the total volume of inclusions.

However, the decrease of the fracture toughness and elongation to failure was considered to be too great considering the increase in the total volume of inclusions. Recall that the Mg and Sr contents were substantially reduced with the frequency of scrap use. Mg and Sr would enhance the mechanical properties through precipitation strengthening and modification of the Si phase, respectively. Consequently, it was considered that the variation in composition of the alloying elements as well as the total volume of inclusions acted to give the decrease of the fracture toughness and elongation to failure with the frequency of scrap use.

Effect of Melt Treatment

Figure 4 shows the total volume of inclusions and oxide film measured from the analysis of the cake on the filter from the PoDFA test by Bomem Co. that is professional company specializing in evaluating inclusions in Al alloys. Al scrap melt containing substantial amounts of oxide film and inclusions was significantly purified by a fluxing treatment. The majority of the oxide film and inclusions were removed by the fluxing treatment. However, the fluxing treatment followed by a GBF resulted in an increase of the volume of inclusions and oxide film. In particular, the volume of the oxide film was greatly increased to almost the same content as before the fluxing treatment. The scrap melt in the melting or holding furnace was agitated due to the turbulent flow, which could also occur during the GBF treatment. The agitation of the scrap melt resulted in the break up of protective oxide layer on the surface of the melt and then the contact with air caused the increase in the oxide film content. Therefore, the fluxing treatment was the most effective way to remove the oxides and inclusions from the Al scrap melt.

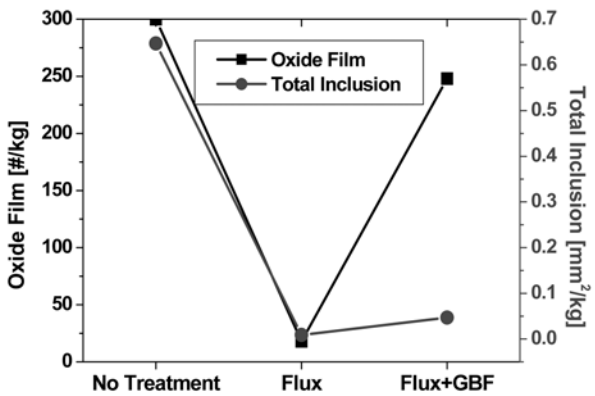

Fig. 4. Total volume of inclusions and oxide film measured from the analysis of the cake on the filter from the PoDFA test by Bomem Co. according to different melt treatments.

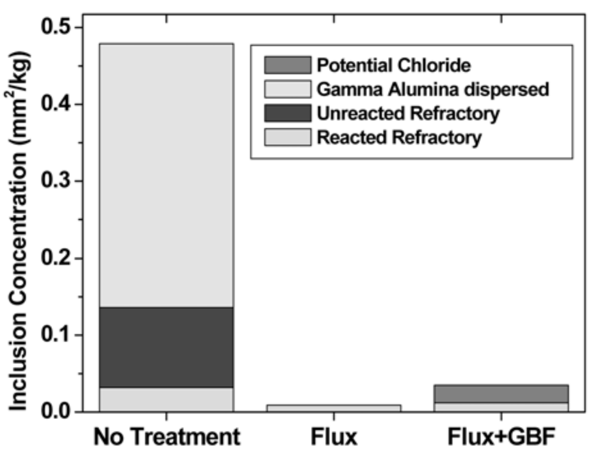

Fig. 5. The concentrations of various detrimental inclusions with respect to different melt treatments.

Figure 5 shows the concentrations of various detrimental inclusions measured from the analysis of the cakes on the filters from the PoDFA tests with respect to different melt treatments. The majority of the detrimental inclusions such as alumina, unreacted refractory, and reacted refractory were removed by the fluxing treatment. A small amount of reacted refractory, which is a spinel-like inclusion created from the reaction of the melt with the crucible, remained and was not removed. However, this small volume of inclusions did not affect on the mechanical properties of Al castings. However, the fluxing treatment followed by a GBF resulted in a slight increase of the reacted refractory and the creation of a different chloride inclusion. The chloride arose due to the reaction of the chlorine dissolved in the melt. Accordingly, because of the agitation of the scrap melt during the GBF treatment the reaction rate with the chlorine dissolved in the melt increased and so the chloride inclusions could be created. However, it was considered that the increased inclusion concentration due to the GBF treatment was too small to affect the mechanical properties of Al castings.

Conclusions

For in-house recycling of Al alloy scrap the variations of contents of alloying elements, microstructures, mechanical properties, and volume of inclusions with respect to the frequency of scrap use were examined and the variations of various inclusion were measured according to different melt treatments. The contents of Mg, Si, Ca, and Sr decreased, but Fe increased with the frequency of scrap use. The tensile strength and yield strength of Al alloy scrap was slightly decreased and not changed, respectively, but the fracture toughness and elongation to failure were almost halved due to the increase of the total volume of inclusions with the frequency of scrap use. The majority of the oxide film and inclusions in the Al alloy scrap was removed by a fluxing treatment, but the fluxing treatment followed by a GBF resulted in a significant increase of the volume of oxide film. The fluxing treatment was the most effective in order to remove the oxides and inclusions from the Al scrap melt.

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