



Influence of aging treatments and alloying additives on the hardness of Al–11Si–2.5Cu–Mg alloys

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ABSTRACT

This study investigated the effects of cooling rate, heat treatment as well as additions of Mn and Sr on hardness and hardening characteristics in Al–11Si–2.5Cu–Mg alloys. The results of scanning electron microscopy reveal that the age-hardening behaviour is related to the precipitation sequence of alloy. An energy dispersive spectroscopy analysis was used to identify the precipitated phases. The results also show that the hardness of the solution heat-treated samples is higher in air-cooled alloys than in furnace-cooled ones. Furthermore, the hardness observed in solution heat-treated samples is higher than in as-cast samples for air-cooled alloys, with the highest hardness level in the non-modified alloys. The highest hardness levels among the artificially aged samples were observed in the non-modified, air-cooled alloys. These levels occur after aging for longer times at lower temperatures (e.g. 30 h at 155 °C). The alloys studied did not display any softening after 44 h at 155 °C, whereas at 180 °C, softening was noted to occur after 10–15 h. At short aging times of 5–10 h, high hardness values may be obtained by aging at 180 °C. At aging temperatures of 200 °C, 220 °C and 240 °C, softening began after 2 h had elapsed. The cooling rate during solidification does not appear to have any significant effect on the precipitation characteristics and hardness of the Sr-modified alloys at certain aging temperatures. On the other hand, the effects of cooling rate may be clearly observed in the non-modified alloys. Manganese has a minimal effect on the hardness of the aged samples as it diminishes the potential action of age-hardening, while strontium lessens the hardness of the artificially aged samples. The effect of strontium, however, is more pronounced in the air-cooled alloys than in the furnace-cooled alloys. Strontium also has a noticeable effect on the reduction of hardness in aged Mg-containing Al–Si–Cu alloys, in that it affects the precipitates containing Cu and Mg.

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1. Introduction

Aluminum–silicon alloys are extensively used in the automotive industry to reduce vehicle weight as well as to improve fuel economy. The commercial importance of these alloys is based on their high fluidity and low shrinkage properties in casting, brazing and welding applications. Furthermore, a high specific strength and good corrosion resistance renders these alloys suitable for manufacturing purposes; the hardness of Si particles imparts wear resistance to these alloys.

The eutectic Al–Si group of alloys is ideally suited to manufacturing pistons and other major vehicle parts because of their capacity for exceptional castability, wear resistance and low expansion. Thus, the structure and mechanical properties of Al–Si

alloys and, ultimately, their service performance, are primarily dependent upon composition, manufacturing process and heat treatment.

The mechanical properties of heat-treatable alloys are determined by the temperature and duration of both the solution heat treatment and aging processes [1]. The solutionizing of the casting produces a number of different effects in that it dissolves age-hardening particles such as Mg₂Si and Al₂Cu, homogenizes the casting and changes the morphology of the eutectic Si. It was formally concluded that the proper duration of time required for obtaining optimum response to the aging treatment should be about 8 h [3,4]. Age-hardening characteristics in Al alloys depend on the precipitates involved; these include CuAl₂, CuMgAl₂, Mg₂Si or Cu₂Mg₈Si₆Al₅ [1–7]. Most alloys contain more than one type of precipitate, where a greater the number of precipitates results in a more complex aging behaviour. Impurities and minor alloying additions may also have an effect.

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The present alloys contain Cu and Mg, and therefore, a combination of precipitates should be present in the microstructure. The ratios of Cu-to-Mg in these alloys are greater than 6.6:1 and less than 8:1. According to Mondolfo [1], if the ratio of Cu-to-Mg is 8:1, then Al_2Cu is the main hardening agent, whereas if the ratio of Cu-to-Mg lies between 4:1 and 8:1, then the aging agents are Al_2Cu and Al_2CuMg . Thus, in this study, Al_2Cu and Al_2CuMg aging agents are expected to be found acting together.

Reif et al. [8] reported the hardening observed in a Al–9Si–3.5Cu alloy was mainly due to the precipitation of the θ' (Al_2Cu) phase. The Mg_2Si phase found in the as-cast structure was no longer observed after solution heat treatment or beyond the aging treatment [9,10]. This is in agreement with Makhlof et al. [11], whose work showed that Cu most significantly affects the tensile strength and hardness of the 380-type alloys. It was also reported that individual additions of Cu and Mg in proportions of about 2.6% and 0.4% to the eutectic Al–Si alloys, lead to 45% and 50% increases in hardness in the T6 condition [4]. Additions of Mn improve the elevated temperature properties of Al–Si alloys [12] as well as increase strength and lower ductility values in Al–Cu–Mg cast alloys [2].

The purpose of the present research was to investigate the effects of Sr modification, Mn additions, cooling rate during solidification and aging treatments on the hardness and precipitation during the heat treatment of Al–11Si–2.5Cu–Mg alloys. The authors reported on the changes in the microstructure due to these variables. Optical microscopy was used to produce a complete assessment of the microstructural changes and intermetallic phase precipitation which occur during solidification. Image analysis was used for quantification purposes. The results showed that the volume fractions of intermetallic phases are generally much lower in the furnace-cooled samples than in the air-cooled ones due to the dissolution of the β -AlFeSi and Al_2Cu phases during slow cooling at critical dissolution temperatures. Sludge particles were also observed in nearly all of the air-cooled alloys with sludge factors of between 1.4 and 1.9. These particles, however, were not observed in the furnace-cooled alloys with similar sludge factors [13].

2. Experimental procedures

The Al–11Si–2.5Cu–Mg alloys were melted in a 7-kg capacity Si–C crucible using an electrical resistance furnace with the melting temperature maintained at 720 ± 5 °C. Various Sr and Mn additions were made using Al–10 wt.% Sr and Al–25 wt.% Mn master alloys, respectively. Samples for chemical analysis (spectroanalysis) were taken from each melt condition. Table 1 lists the alloy codes used as well as the chemical composition of these alloys. Alloy melts were rotary degassed using pure dry argon at a flow rate of 5–10 ft³/h for 15–20 min, then poured at 720 °C into rectangular cross section metallic molds preheated to 450 °C. Subsequently, these molds were left to solidify either in the furnace or in ambient

air. In the latter case, the samples were poured into the mold inside a furnace having an initial temperature of 680 °C. The furnace was then turned off and allowed to cool. The resulting dendrite arm spacings are 40 μm for air-cooled alloys and 120 μm for furnace-cooled alloys, with the cooling rates in the range of 10 and 10^{-2} °C/s, respectively.

Specimens (1 in. \times 1 in. \times 3 in.) for heat treatment were cut from the castings. The solution heat treatments were carried out for 8 h at 490 °C, as was recommended earlier [4], using a Blue M electric furnace equipped with a programmable temperature controller (accurate to ± 2 °C). The solution heat-treated samples were quenched in warm water (~ 60 °C) and then aged at 155 °C, 180 °C, 200 °C, 220 °C and 240 °C for up to 44 h. Hardness measurements were carried out using a Brinell hardness tester with a 10-mm diameter ball and a 50-kg applied load. Each data point reported in this paper represents the average of eight indentation readings taken from two perpendicular sections of the sample.

A field emission gun scanning electron microscope (Hitachi S-4700 FEG-SEM) was used with a mixed detection system using lower and upper detectors. The upper detector was used for its high resolution and high signal to noise ratio ability for secondary electron imaging. The system can be adjusted, with the voltage bias, to give images consisting of pure secondary electrons to pure backscattered electrons, and anywhere in between. This provides a great flexibility in overcoming charging and in optimizing imaging contrast. Samples for analysis by FEG-SEM were sectioned off of each mold casting and mounted. Subsequently, these samples were ground and polished using standard procedures. An X-ray microanalysis using energy dispersive spectroscopy (EDS), allows the FEG-SEM to qualitatively analyze the elements present in a selected area of backscattered electron image.

3. Results and discussion

The following sections and subsections will present and discuss the hardness values of the Al–11Si–2.5Cu–Mg alloys, as affected by cooling rate during solidification, alloying additions, solution heat treatment, aging time and temperature. The features of alloy microstructure, including the type and surface fraction of the intermetallic phases as well as Si particle characteristics, have all been published elsewhere [3,4,13].

3.1. Effects of cooling rate during solidification and solution treatment

Fig. 1 shows the Brinell hardness values (BHN) of the as-cast and solution heat-treated alloys. It will be observed that the effects of the cooling rate during solidification, *i.e.* whether the castings are air-cooled or furnace-cooled, appear to have no noticeable effect on the hardness of the as-cast samples. The marginal effect of cooling rate during solidification on the alloy hardness of the as-cast samples (Fig. 1) is in agreement with the results obtained by Paul and Exner [14]. These authors found that the influence of cooling rate on hardness and yield strength during solidification was negligible and suggested that the loss of hardness with increasing distance between Si particles was a result of lower Si particle density. The hardness values of solution heat-treated samples, however, are higher when air-cooled than when furnace-cooled. Furthermore, in the air-cooled 'E' alloys, the solution heat-treated samples display higher hardness levels than the as-cast samples (Fig. 1). The highest hardness levels of 108–109 BHN were measured in the non-modified solution heat-treated alloys, *i.e.* alloys E1 and E4.

In the case of furnace-cooled alloys, known as the 'H' alloys, the hardness behaviour cannot be described by one simple trend (Fig. 1). The non-modified H1 and H4 alloys exhibit higher hard-

Table 1
Chemical composition (wt.%) of the alloys used.

Alloy	Si	Cu	Mg	Fe	Mn	Cr	Sr	Zn	Al
E1	10.8	2.7	0.38	0.43	0.46	0.029	0.0001	0.13	Bal.
E2	10.8	2.6	0.38	0.41	0.46	0.028	0.0167	0.13	Bal.
E3	10.8	2.6	0.38	0.40	0.46	0.028	0.0272	0.13	Bal.
E4	11.1	2.7	0.37	0.46	0.68	0.029	0.0004	0.13	Bal.
E5	10.9	2.6	0.38	0.42	0.69	0.029	0.0163	0.13	Bal.
E6	11.7	2.7	0.41	0.52	0.63	0.040	0.0301	0.12	Bal.
H1	10.8	2.3	0.31	0.45	0.41	0.039	0.0004	0.11	Bal.
H2	11.1	2.5	0.37	0.46	0.47	0.039	0.0152	0.11	Bal.
H3	12.1	2.5	0.35	0.54	0.49	0.043	0.0407	0.11	Bal.
H4	11.0	2.5	0.33	0.44	0.70	0.040	0.0009	0.11	Bal.
H5	11.0	2.5	0.36	0.42	0.65	0.036	0.0132	0.11	Bal.
H6	10.7	2.5	0.36	0.36	0.63	0.030	0.0300	0.12	Bal.

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