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Influence of additives on the microstructure and tensile properties of near-eutectic Al–10.8%Si cast alloy

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ABSTRACT

The continuing quest for aluminum castings with enhanced mechanical properties for applications in the automotive industries has intensified the interest in aluminum–silicon alloys. In Al–Si alloys, the properties are influenced by the shape and distribution of the eutectic silicon particles in the matrix, as also by the iron intermetallics and copper phases that occur upon solidification. The detailed microstructure and tensile properties of as-cast and heat-treated new experimental alloy belonging to cast Al–Si near-eutectic alloys have been investigated as a function of Fe, Mn, Cu, and Mg content. Microstructural examination was carried out using optical microscopy, image analysis, and electron probe microanalysis (EPMA), wavelength dispersive spectroscopic (WDS) analysis facilities. Tensile properties upon artificial aging in the temperature range of 155–240 °C for 5 h were also investigated. The results show that the volume fraction of Fe-intermetallics increases as the iron or manganese contents increase. Compact polygonal or star-like particles form when the sludge factor is greater than 2.1. The Al_2Cu phase was observed to dissolve almost completely during solution heat treatment of all the alloys studied, especially those containing high levels of Mg and Fe, while $Al_5Cu_2Mg_8Si_6$, sludge, and α-Fe phases were found to persist after solution heat treatment. The β-Al_5(Fe,Mn)Si phase dissolved partially in Sr-modified alloys, and its dissolution became more pronounced after solution heat treatment. At 0.5% Mn, the β-Fe phase forms when the Fe content is above 0.75%, causing the tensile properties to decrease drastically. The same results are obtained when the levels of both Fe and Mn are increased beyond 0.75%, because of sludge formation. On the other hand, the tensile properties of the Cu-containing alloys are affected slightly at high levels of Mg as a result of the formation of $Al_5Cu_2Mg_8Si_6$ which decreases the amount of free Mg available to form the Al_2CuMg phase. The results also show that, for the heat-treated alloys, peak aging is achieved at 180 °C, although the highest quality index corresponds to 155 °C aging temperature, for all the alloys investigated. Accordingly, 155 °C may be considered as the optimal aging treatment. It is also consistent with this observation that quality index is more sensitive to variations in tensile ductility than in tensile strength.

1. Introduction

Eutectic and near-eutectic Al–Si alloys are used extensively in the casting industry, because of excellent abrasion and corrosion resistance, low coefficient of thermal expansion, and high strength-to-weight ratio [1–5]. These properties led to the application of Al–Si alloys in the automobile industry, especially for cylinder blocks, cylinder heads, pistons and valve lifters [6]. With an increase in Si content, however, the mechanical properties of Al–Si alloys, elongation in particular, are reduced noticeably. Thus the low expansion group of Al–Si eutectic or near-eutectic alloys, referred to as 'piston alloys', need to be modified. A number of technical articles have been published in the literature about the microstructure and tensile properties of near-eutectic Al–Si alloys with and without eutectic modification and grain refinement [2,7–12].

Mechanical properties of near-eutectic and eutectic Al–Si cast alloys depend not only on the chemical composition but, more importantly, on microstructural features such as the morphology of dendritic α-Al, and other intermetallics which are present in the microstructure. The morphology and size of eutectic Si, as well as the precipitation hardening phases during heat treatment, also exert an important influence on the mechanical properties. The combined effects of such structures are somewhat complicated.

Iron is always present in commercial Al–Si alloys and has consistently emerged as the main impurity element which is perhaps the most detrimental to the mechanical properties of these alloys.

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According to Bäckerud et al. [13], the two main types of Fe–Si bearing intermetallic phases occurring in this alloy are the β-Al_5FeSi and the α-$Al_{15}(Mn,Fe)_3Si_2$ phases. The first phase, with its acicular or platelet-like form, is considered detrimental to the ductility of alloys due to its stress-raising potential and poor binding strength with the matrix [14]. The second phase, however, is considered less harmful to the mechanical properties than the β-Fe phase. There are several studies concerning the influence of Fe on the mechanical properties, for instance Kumari et al. [15] which has examined the effects of varying Fe content in small amounts of from 0.17% to 0.6% in Al–7%Si–0.3%Mg alloys. It was found that the variation of iron within this range does not have any significant effect on the tensile strength. However, the increase of Fe reduces the elongation of the samples to a marked extent, due to the presence of the needle β-Fe phase, which provides brittle behavior to the alloy. A similar investigation was carried out by Niu et al. [16] but with regard to higher Fe levels and Al–Si–Cu alloys. Increasing the iron content from 1% to 1.8% successively resulted in a significant reduction of the tensile strength and also the elongation. Komiyama et al. [17] observed that in the Al–9.2%Si–4%Cu–0.5%Mg alloy, hardness increases, whereas tensile strength and elongation decrease with an increase in the iron content; the tensile strength decreases markedly when the iron content exceeds 0.5%. Manganese is the most commonly used and the least expensive element for Fe neutralization in Al–Si alloys [18]. On the other hand, the higher amounts of Mn required for Fe neutralization lead to sludge formation ultimately affecting machinability [1,19–22].

In order to improve the mechanical properties of near-eutectic Al–Si alloys, it is necessarily to make a modification in composition by adding alloying elements such as Cu, Mg, and Ni to these alloys. Common precipitation hardening phases such as Al_2Cu, Mg_2Si and Al_2CuMg are formed by Cu and Mg with Al [23–25]. The aging time and temperature are normally chosen to optimize alloy strength. The increase in strength which occurs with increasing Mg content becomes more evident after heat treatment, while the improvement in strength properties is accompanied by a corresponding reduction in ductility. Dunn and Dickert [26] compared the effect of increasing Mg up to 0.55% on the tensile properties and hardness of A380 and 383 alloys. The presence of Mg was seen to increase the tensile strength, yield strength, and hardness at all temperatures. Elongation was observed to be reduced by the presence of Mg; the minimum value appeared to be acceptable, however, provided the Mg content did not exceed 0.35%. The effect of varying Mg content on the mechanical properties of a 380 Al diecasting alloy as a function of aging time at 180 °C was studied by Jonsson [27]. He concluded that the tensile and yield strengths increased substantially with increasing Mg content when the alloys were subjected to artificial aging.

This study is part of a larger research project which was conducted to provide a better understanding of the effects that melt treatment and the addition of alloying elements would have on the microstructure and tensile properties of cast Al–Si near-eutectic alloys. The study was confined to a new experimental alloy belonging to this family, and which contains about 10.8%Si. The primary purpose of this article is to report on the microstructural changes resulting from the effects of adding alloying elements, namely, Fe (0.5–1%), Mn (0.5–1%), Cu (2.25–3.25%), and Mg (0.3–0.5%), with the relevant heat treatment parameters of solution treatment and aging conditions applied to this alloy. Qualitative and quantitative approaches were taken for this purpose. The influence of these additions on the tensile properties values was also measured.

2. Experimental procedures

The as-received Al–10.8%Si ingots were cut into smaller pieces, cleaned, dried and melted in charges of 34 kg each to prepare the required alloys. Using this base alloy, three main groups of alloys were prepared, corresponding to additions of Sr and Ti, Fe and Mn, and Cu and Mg; they were coded R, RF, and RC, respectively. The melting process was carried out in a SiC crucible of 40-kg capacity, using an electrical resistance furnace under argon gas atmosphere. The melting temperature was maintained at 750 ± 5 °C. All alloys were grain-refined by adding 0.2%Ti as Al–5%Ti–1%B in rod form and modified by adding 150 ppm Sr in the form of an Al–10%Sr master alloy, using a perforated graphite bell. Taking the modified grain-refined RGM alloy as a reference, additions of Fe, Mn, Cu, and Mg were then made to it in order to study the effects of these alloying elements on tensile properties of the alloy. Iron and Mn were added in the form of Al–25%Fe and Al–25%Mn master alloys, respectively, whereas Cu and Mg were added in the form of the pure metal. These alloying elements were added in amounts calculated to obtain the desired compositions. Table 1 lists the chemical analyses of the various alloys studied and their respective codes, as obtained from samplings for chemical analysis taken from the corresponding melts. The chemical analysis was carried out using arc spark spectroscopy at the GM facilities in Milford, NH.

All melts were degassed using pure, dry argon injected into the melt for ~15 min by means of a rotating graphite degassing impeller, at 125 rpm rotation, to ensure homogeneous mixing of the additives, and a melt hydrogen level of 0.1 mL/100 g. The degassed melt was carefully poured into preheated (450 °C) L-shaped rectangular graphite-coated metallic molds for preparing samples for metallographic observation.

From each of the castings prepared for metallographic observations, two samples measuring 25 × 25 mm were sectioned off to represent each alloy condition. One sample was used in the as-cast condition, while the second sample was solution heat-treated at 495 °C for 8 h in order to avoid incipient melting of the copper-rich phase and lowering the mechanical properties of the casting. The time at the nominal solution treatment temperature must be long enough to homogenize the alloy and to ensure a satisfactory degree of precipitate solution. Microstructures of the polished sample surfaces were examined using an Olympus PMG3 optical microscope. The characteristics of eutectic silicon particles, including area, length, aspect ratio, roundness, and density, were measured and quantified using a Leco 2001 image analyzer system in conjunction with the optical microscope. For each sample, 50 fields at a magnification of 500× were examined, so as to cover the entire sample surface in a regular and systematic manner. In addition, porosity measurements were carried out at a magnification of 50× over 30 fields per sample. The porosity parameters measured were percentage porosity, pore area, and pore length. Phase identification was carried out using electron probe microanalysis (EPMA) in conjunction with wavelength dispersive spectroscopic analyses (WDS), using a JEOL JXA-8900 l WD/ED combined microanalyzer operating at 20 kV and 30 nA, where the size of the electron beam was ~2 μm.

Tensile test bars were produced by pouring the degassed molten metal into a preheated steel permanent mold (type ASTM B-108) at 450 °C. Thirty-five bars were prepared for each alloy composition. The test bars were divided into seven sets: one set was kept in the as-cast condition, while the other six sets were solution heat-treated at 495 °C for 8 h, then quenched in warm water at 65 °C, followed by artificial aging at 155 °C, 180 °C, 200 °C, 220 °C, and 240 °C for 5 h (*i.e.* T6 and T7 tempered). The solution and aging heat treatments were carried out in a forced-air Blue M Electric Furnace equipped with a programmable temperature controller (±2 °C). The aging delay was less than 10 s.

The as-cast and heat-treated test bars were pulled to fracture at room temperature at a strain rate of 4×10^{-4}/s using a Servohydraulic MTS Mechanical Testing machine. A strain gauge exten-