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The influence of impurity level and tin addition on the ageing heat treatment of the 356 class alloy

A.M. Kliauga, E.A. Vieira, M. Ferrante *

Department of Materials Engineering, Universidade Federal de São Carlos, 13565-905 São Carlos, SP, Brazil

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Abstract

The influence of the addition of 0.5 wt.% Sn to Al–7Si–0.3 Mg alloys (356 and A356) on their ageing behaviour and mechanical properties was evaluated. Adding Sn led to a reduction of the iron rich intermetallics volume fraction, and of hardness. During solution heat treatment, Mg went into the solid solution, and Sn particles grew by competitive growth, concentrating at phase boundaries and interfaces. During aging β'' and Si precipitated. In the alloys with Sn, the β'' precipitation was accelerated and its hardening effect was greater, whereas the Si precipitation did not changed significantly. The mechanical properties of the A356 alloy were compatible with the hardening achieved during the heat treatment and to the amount of defects (pores) present in the microstructure. The yield strength and elongation of the A356 + 0.5% Sn alloy decreased after solution heat treatment and with increasing ageing temperature. These detrimental effects were minimized by treating this alloy in the T5 condition at 150 °C.

Keywords: Al–7Si–0.3 Mg alloys; Sn addition; Aging heat treatment; Mechanical properties

1. Introduction

In aluminum, tin is usually used as an alloying element in bearing alloys in amounts of 10% or higher because of its good tribological properties [1,2]. Alternatively, it can be used as a trace element (~0.05%) to enhance precipitation hardening in Al–Cu or Al–Cu–Mg alloys, due to its strong interaction with vacancies [3]. Other applications have been suggested, for example, Sercombe and Schaffer studied the influence of various trace elements on the Al–Cu alloy sintering rate and concluded that among Pb, In, Bi, Sb, Ni, Zn, Sn and Si, the most effective sintering aid was Sn [4]; Røset et al. [5] added 0.28 and 1 wt.% Sn to a 6082 alloy with the intent of increasing its machinability without interfering in its extrudability; and Vieira et al. [6] found that in an A356 alloy for thixocasting, the addition of Sn increases the liquid wettability without interfering in the morphology and coarsening rate of the solid phase. In addition, it considerably reduced the viscosity and thixotropy of an Al–7Si–0.3 Mg alloy, leading to better flow behaviour of the semi-solid state.

The purpose of this article is to evaluate the influence of the addition of 0.5 wt.% Sn to Al–7Si–0.3 Mg alloys (356 and A356) on their ageing behaviour and mechanical properties. The 356 alloy class characteristics are well known and there is a large amount of literature with regards to its constitution and properties. It typically contains 6.5–7.5% Si and 0.2–0.45% Mg and its grade is determined by the amount of iron impurity present, which should be lower than 0.6%. Iron levels generally vary from 0.04% (best primary metal) to 0.5% (secondary metal) with typical primary levels in the 0.1–0.2% range.

The microstructure of these alloys in the as-cast state consists of primary grains of α-Al solid solution with interdendritic regions of Al–Si eutectic, in which various intermetallic phases are present: Mg_2Si, which is normally observed in small quantities as small precipitate colonies; β-Al_5FeSi needles; and $Al_{15}(Mn,Fe)_3Si_2$ or π-$Al_8Mg_3FeSi_6$ (both with a Chinese script form). Minor modification additives may alter the as cast structure. Beryllium favors the formation of an insoluble Fe-bearing phase containing Mg [7] and Sr may form a complex $Mg_2SrAl_4Si_3$ intermetallic compound prior to eutectic transformation [8].

A solution heat treatment (T4) is performed to dissolve Mg_2Si, homogenize the solid solution and to fragment and spherodise the eutectic silicon. When π-phase is present, it decomposes slowly to release Mg into the solution. This decomposition produces very fine Fe-rich precipitates, probably β phase [9,10].

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* Corresponding author. Tel.: +55 16 33518256; fax: +55 16 33615404.
E-mail address: ferrante@power.ufscar.br (M. Ferrante).

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Table 1
Alloys composition in wt.%

Alloy	Si	Mg	Fe	Cu	Mn	Zn	Ti	Sn	Pb	Cr	Ni	Al
M1	7.01	0.28	0.39	0.14	0.2	0.07	0.02	0.004	0.01	–	0.006	Rest
M1S	7.01	0.28	0.39	0.14	0.2	0.07	0.02	0.5	0.01	–	0.006	Rest
M2	7.13	0.4	0.12	0.01	0.007	0.007	0.006	0.009	0.007	0.002	0.002	Rest
M2S	7.13	0.4	0.12	0.01	0.007	0.007	0.006	0.5	0.007	0.002	0.002	Rest
356[a]	6.5–7.5	0.2–0.45	0.25	<0.6	0.35	0.35	0.25	–	–	–	–	Rest
A356[a]	6.5–7.5	0.25–0.45	0.2	<0.2	0.1	0.1	0.2	–	–	–	–	Rest

[a] Values obtained from ASM Handbook, vol. 2, Properties and Selection: Non Ferrous Alloys and Special—Purpose Materials.

Precipitation hardening after T4 occurs in a matrix saturated with Si and with all Mg in solid solution [9]. Heat treatment temperatures vary between 150 and 170 °C. In this temperature range, the precipitation sequence starts with the formation of Guinier–Preston (GP) zones, followed by coherent β'', semi-coherent β' and incoherent β (Mg_2Si) with the simultaneous precipitation of Si particles [11]. The tensile properties are governed by various factors, including the level of Mg retained in the matrix after the solution heat treatment and quenching, which is subsequently available for β'' precipitation during artificial ageing. This process, as well as the actual ageing parameters, control the alloy's yield strength and strain hardening characteristics. High matrix Mg results in higher yield strength and increased rates of strain hardening. However, the actual point of tensile fracture (expressed by ductility, and tensile strength) is controlled by the population of defects (porosities, oxides) [12] and second-phase particles (eutectic silicon, intermetallics) [13].

On the other hand, there is much less information about the effect of Sn on hardenability and on the mechanical properties of these alloys. It is known that its diffusion coefficient in the Al is very fast and it interacts with vacancies, slowing down the formation of GP zones of Al–Cu and Al–Zn alloys and enhancing the Mg_2Si hardening in Al–Cu–Mg–Si alloys [3,14]. It has been observed by Song et al. in an Al–4Mg alloy [15] and by Erb and Aust in pure Al [16], that Sn segregates to the grain boundaries and dislocations. In an Al–7Si–0.35Mg alloy, Bian et al. [17] have studied Sn additions until 0.2 wt.% and obtained an improvement of the mechanical properties in the aged condition of this alloy at 0.15% Sn, because of a modification in the Si particles shape. In another piece of work from the same group [18], it was reported that adding Sn to a Al–11Si–0.35Mg alloy slowed down the Mg_2Si precipitation, but increased the amount of precipitates because Sn precipitation at dislocations acted as nucleation sites. Røset et al. [5] have studied Sn additions of 0.28 and 1 wt.% Sn on a 6082 alloy and observed a decrease in hot deformation resistance and in the critical temperature for tearing; it was also noted that Sn had a strong effect on the age hardening response and 0.28 wt.% Sn improved the strength, while 1 wt.% Sn reduced it.

2. Experimental

The alloys used in this work are listed in Table 1. Alloys M1 and M2 are commercial 356 and A356 alloys with Mg and Fe content varying within their standard composition range. Alloys M1S and M2S were produced adding 0.5% Sn to alloys M1 and M2. The alloys were modified with TiB and Sr and degassed before casting into permanent moulds.

The amount of iron containing intermetallic phases (β-Al_5FeSi, $Al_{15}(Mn,Fe)_3Si_2$, and π-$Al_8Mg_3FeSi_6$) was measured by metallography before and after the solution heat treatment. These phases were identified by using the backscatter contrast in a Philips XL30 scanning electron microscope.

The as cast alloys were solution heat treated at 540 °C for 24 h (T4), quenched in water and immediately aged at 150, 160, 170, 190, 210 and 250 °C for times varying from 5 min to 88 h. A set of samples was naturally aged for some weeks. After ageing, the Brinell hardness value was measured in a Hecket macrohardness test machine, by applying a load of 31.25 kg for 30 s, using a 2.5 mm diameter hardened steel ball. Precipitation hardening maps were drawn noting down the time for maximum hardening at each temperature.

DSC thermograms from room temperature to 500 °C were acquired using a heating rate of 10 °C/min on T4 heat treated samples. This heat treatment consisted of a solution treatment at 540 °C for 24 h followed by quenching them in water at room temperature. Quenched samples were either transferred directly to the DSC equipment or, if this was not possible, they were immediately placed in a freezer at a temperature of approximately −10 °C. The total time in the freezer did not exceed 2 h. The analysis was carried out using NETZSCH equipment. Calibration was done using high purity Al and Zn samples at heating rates varying between 5 and 40 $°C\,min^{-1}$, and the resulting temperature accuracy and assured error were ±2 °C. The reference pan was run empty.

Using the hardness data, a set of ageing heat treatments was chosen for tensile test experiments for alloys M2 and M2S only (see Table 2). The same time conditions were used for T5 and T6 heat treatments.

T5 requires rapid cooling during the solidification process, so that enough hardening elements remain in the solid solution. To achieve this requirement, a new casting was prepared, and

Table 2
Ageing time and temperature conditions used

	Temperature (°C)		
	150	170	190
Time (h), alloy M2	11	4	2
Time (h), alloy M2S	11	2	0.27