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The effect of Sc additions on the microstructure and age hardening behaviour of as cast Al–Sc alloys

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ABSTRACT

The grain refinement effect and the ageing behaviour of Al–0.5 wt.% Sc, Al–0.7 wt.% Sc, and Al–1 wt.% Sc alloys are studied on the basis of optic microscopy (OM), scanning electron microscopy (SEM), X-ray diffraction (XRD) observations and hardness measurements. In Al–Sc alloys the higher grain refinement is observed for Sc contents greater than 0.5 wt.% accompanied by a notorious morphology modification, from coarse columnar grains to a fine perfect equiaxed structure. The as cast structures are characterized by a rich supersaturated solid solution in Sc, that promotes a great age hardening response at 250 °C and 300 °C. The age hardening curves also demonstrate a low overageing kinetics for all the alloys. Although the higher Sc content in solid solution for the alloys with 0.7 and 1 wt.% Sc, the age hardening response of all the Al–Sc alloys remains similar. The direct age hardening response of the as cast Al–0.5 wt.% Sc is shown to be greater than the solutionised and age hardened alloy.

1. Introduction

Aluminium alloys are widely used in industrial applications, with particular emphasis to transportation industries, owing to the particular combination of low density, high corrosion resistance and high strength to weight ratio. The strength of aluminium alloys is mainly due to age hardening mechanisms. However, in order to fulfil the new requirements of service structural aircraft and automobile components, alloys with higher resistance at high temperatures are needed. One of the most promising approaches to improve the mechanical properties of aluminium alloys is based on the addition of alloying elements either with low solubility or totally insoluble in aluminium. Among the range of possible elements, Scandium is the most effective precipitation hardener element in Al alloys [1–4]. Heat treatments in the range of 250–350 °C, reported to promote considerably precipitation hardening in Al(Sc) alloys with Sc content up to 1 wt.% [5,6]. The high response to hardening mechanisms is a consequence of the fine homogeneous dispersion of Al_3Sc particles, formed during decomposition of the αAl supersaturated solid solution, which nucleates in aluminium matrix and grain boundaries, thus blocking the dislocations motion [2,7–10]. It has also been reported on a per atom basis, Sc has higher strength effect than Zr [11]. Thus far, small scandium additions (up to 0.8 wt.%) have been reported to greatly improve aluminium alloys properties, including mechanical strength [12–14]. Scandium additions up to 2 wt.%, has been described to promote an increase in strength of 50 MPa in aluminium in the as cast state and 80 MPa in homogenised state [15]. For wrought aluminium alloys, namely Al–Mg, low Sc additions (up to 0.35 wt.%) is reported to increase strength in 100–200 MPa [16]. Concerning to the casting needs, hypereutectic additions of Sc (0.55 wt.%) to aluminium alloys induce the formation of fine equiaxed structures (25–50 μm), acting like a stronger inoculant when compared to the traditional Al–Ti, Al–Ti–B and Al–Ti–C master alloys, which produces coarser grain structures (150–250 μm) and have high tendency to induce fading phenomena [15,17–19]. Due the scarcity on the study of the combined effect of Sc addition and optimised heat treatments on aluminium alloys, the main aim of this work is to study the effect of Sc addition on the microstructure of as cast Al–Sc alloys and the ageing hardening response of as cast alloys with and without solution heat treatment.

2. Material and experimental procedure

Aluminium alloys containing 0.5, 0.7 and 1 wt.% Sc were produced using Al–2 wt.% Sc master alloy and commercially pure Al. The alloys were melted in a graphite crucible using a high frequency induction furnace and poured into a copper mould to obtain 16 mm internal diameter and 86 mm long cast samples. The compositions of the studied alloys are given in Table 1. A thermocouple was positioned in the centre of the mould cavity to measure the cooling rate. For the alloys production the Al melt was heated up to 720 °C ± 5 and the Al–2Sc addition was done. Temperature was kept constant for 30 min for melt homogenization, which was assumed by the stirring effect caused by the induction coil.

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Table 1
Composition the experimental alloys (wt.%).

Alloy	Al	Sc	Si	Fe	Cu	Other
Al–0.5Sc	99.18	0.52	0.10	0.09	0.02	0.09
Al–0.7Sc	99.02	0.72	0.14	0.08	0.02	0.02
Al–1Sc	98.31	1.20	0.33	0.06	0.03	0.07

In order to prevent solid state reactions, the castings, once solidified, were water quenched.

To evaluate the influence of the cooling rate, a portion of the Al–0.7Sc alloy was poured directly into water.

In order to study the effect of solution heat treatments, two age-hardening treatments were preformed: in one, the Al–0.5Sc alloy was solution treated at 600 °C for 24 h, water quenched to room temperature and aged, in air, at different temperatures, between 250 and 400 °C with holding times in the range 0–8192 min. Age hardening treatments of the as cast alloys (Al–0.5Sc, Al–0.7Sc and Al–1Sc), were also carried out at 300 °C, without previous solution treatment.

Samples were polished down to 0.025 µm with non-crystallized colloidal silica and anodized with Barker's reagent and observed under polarised light in order to reveal the microstructure. Samples casted into water, were only etched with Keller's reagent, due to their complex shape. The microstructure morphology and grain size were checked by OM, using a Leica DM 2500 M. The grain roundness was evaluated according Eq. (1), where A is the grain area and P is the grain perimeter. A value of 1 indicates a perfect circle and as the value approaches to 0 points out to an increasingly elongated polygon, like columnar grain structures.

$$R_n = \frac{4\pi A}{P^2} \qquad (1)$$

In order to get detailed information on the microstructure and chemical composition, the samples were characterized on Nano-SEM–FEI Nova 200 FEG/SEM scanning electron microscope equipped with energy dispersive spectrometer (EDS) EDAX–Pegasus X4 M operating at accelerated voltage of 15 kV. Phases analysis was carried out by XRD using a Bruker D8 DISCOVER diffractometer equipped with αCu Ka radiation source.

Vickers hardness measurements were performed on as cast and heat treated samples. Eight measurements were made for each condition, using 30 kgf load and 20 s dwell.

3. Results and discussion

3.1. Microstructure of as cast alloys

Fig. 1a shows the typical grain structure of high purity aluminium without any addition of grain refiner. As expected, this structure is characterized by large columnar grains, with a dendritic substructure. This type of structure has been described to reduce workability, yield strength and ductility of aluminium alloys [19]. As cast microstructures of Al–Sc alloys with 0.5, 0.7 and 1 wt.% Sc contents are presented in Fig. 1b–d, respectively. For the Al–0.5 wt.% Sc alloy shown in Fig. 1b, there is a slight modification of grain structure, resulting the coexisting of smaller columnar and equiaxed grains smaller than those of cpAl (Fig. 1a). In fact results presented on Fig. 2 shows a decrease on the grain size and suggest a trend partial equiaxed structure although Fig. 1b still reveals that a dendritic substructure allied to columnar grain still persists. These results suggest that, despite the slight morphology modification and grain refinement, Sc content is still not enough to produce a perfect equiaxed structure. These results are supported by the Al-rich phase diagram [19], that shows that for Sc contents less than 0.55 wt.%, the first forming phase is αAl, resulting in a coarse columnar structure. This phenomenon is more pronounced in this alloy due to the high solidification rate (measured $\sim$300 K/s), since the eutectic composition shifts to right, so the Sc content necessary for grain refinement gets higher.

When Sc content is increased to 0.7 wt.% there is no evidence of columnar grains, as seen in Fig. 1c. The same behaviour is observed in the Al–1 wt.% Sc alloy (Fig. 1d). In these cases the columnar structure is replaced by a fine equiaxed structure throughout the

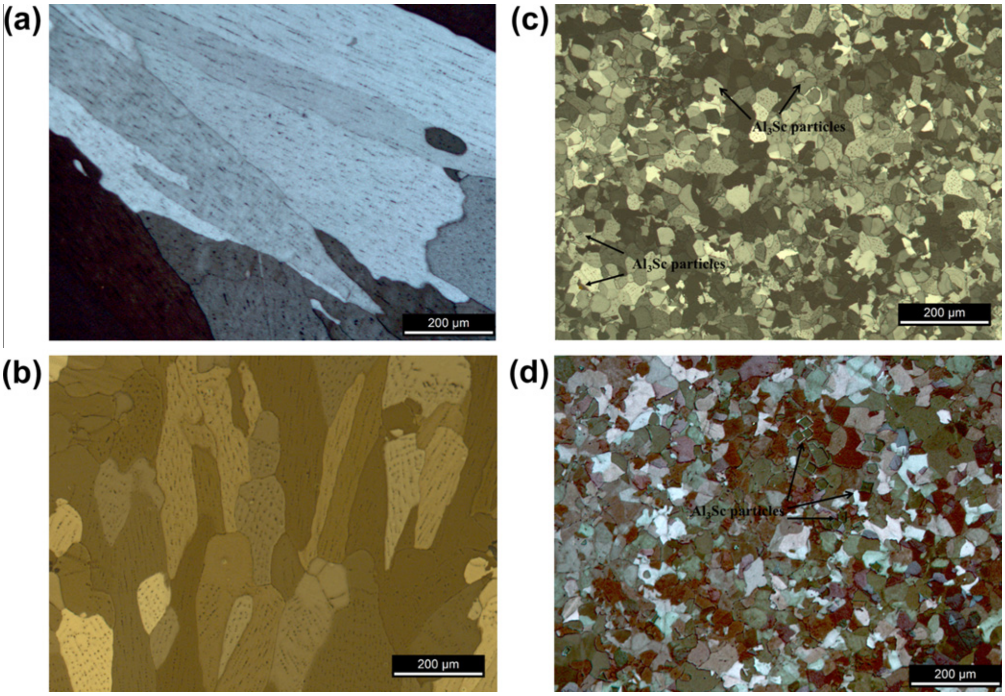

Fig. 1. Low magnification optical micrographs of as cast: (a) Al cp; (b) Al–0.5Sc; (c) Al–0.7Sc and (d) Al–1Sc.