Materials Science & Engineering A 601 (2014) 70–77

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effects of substituting ytterbium for scandium on the microstructure and age-hardening behaviour of Al–Sc alloy

N.Q. Tuan [a,*], A.M.P. Pinto [a], H. Puga [a], L.A. Rocha [a,b], J. Barbosa [a]

[a] *CT2M – Centre for Mechanical and Materials Technologies, University of Minho, Azurém, 4800-058 Guimarães, Portugal*
[b] *Universidade Estadual Paulista (Unesp), Faculdade de Ciências de Bauru, SP 17033-360, Brazil*

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form
12 February 2014
Accepted 14 February 2014
Available online 20 February 2014

Keywords:
Aluminium–scandium alloys
Ytterbium
Age-hardening
Precipitate coarsening
TEM
High-resolution TEM

ABSTRACT

In order to reduce the cost of Al–Sc alloys and maintain their mechanical properties, the microstructure and mechanical properties of Al–0.24 wt% Sc–0.07 wt% Yb in comparison with Al–0.28 wt% Sc alloys were studied. The aging behaviour, precipitate morphologies, precipitate coarsening and precipitation hardening of both alloys were investigated. The average diameter and the size distribution of nanoscale Al_3Sc and $Al_3(Sc,Yb)$ precipitates at various aging conditions were measured. Transmission electron microscopy (TEM) and high-resolution TEM were used to deeply understand the precipitate evolution. A maximum hardness around 73 (HV_{30}) was obtained with a precipitate diameter from 4.3 to 5.6 nm for both alloys.

1. Introduction

Al–Sc alloys have excellent mechanical properties at ambient and elevated temperatures due to the presence of a high number density (as high as $10^{22}\,m^{-3}$) of elastically-hard Al_3Sc ($L1_2$ structure) precipitates [1–4]. The Al_3Sc precipitates remain fully coherent with the α-Al matrix at elevated temperatures [1,5]. Among alloying elements of Al alloys, Sc has one of the greatest strengthening effects on a per-atom basis [6]. The Al_3Sc precipitates are very stable with respect to coarsening, even for long aging times at 350 °C [1], while in commercial age-hardening 2xxx and 6xxx series alloys containing Cu, Mg and Si, the precipitates coarsen rapidly at temperatures above 250 °C [6]. At ambient temperature the lattice parameters of Al and Al_3Sc are 0.40496 and 0.4105 nm, respectively, showing a small lattice parameter mismatch of Al_3Sc precipitates with the α-Al matrix [7–9]. A good interfacial strength between the Al_3Sc precipitates and the α-Al matrix will hinder dislocation motion and prevent grain growth [10]. In addition, the high thermal stability of the Al_3Sc precipitates will improve the strength of these alloys at high temperature [11,12]. Therefore Al–Sc alloys are widely used in the fabrication of sports equipment, aerospace components and in a range of structural applications.

Although Al–Sc alloys are very attractive, their use is limited by the cost and availability of Sc. A possible solution for this problem could be replacing part of the Sc content by other alloying elements similar in nature in order to reduce the Sc content without decreasing properties. Among them, rare-earth metals (REMs) are attractive ternary additions to substitute Sc, showing some interesting characteristics/benefits: (i) many REMs substitute Sc in the Al_3Sc precipitates forming $Al_3(Sc_{1-x}REM_x)$ ($L1_2$ structure) with high solubility [13,14]; (ii) the light REMs have a smaller diffusivity in Al than Sc [15], improving the coarsening resistance of the precipitates; (iii) REMs increase the lattice parameter mismatch between α-Al and $Al_3(Sc_{1-x}REM_x)$ [13,14], which could increase the creep resistance of the alloy [16]; (iv) most of the REMs have electronegativity values very similar to Sc suggesting that these metals should strongly resemble Sc in their interaction with α-Al. The metallic radii of all REMs are significantly larger than Sc leading to an increasing of the lattice parameter mismatch between α-Al and $Al_3(Sc_{1-x}REM_x)$. Karnesky et al. [17] showed that the Vickers hardness of Al–0.06 at% Sc–0.02 at% REM alloys (REM = Dy, Er, Gd, Sm, Y, or Yb) aging at 300 °C are generally similar to that of Al–0.08 at% Sc alloy. The Al–0.06 at% Sc alloys microalloyed with Yb or Gd have much improved creep resistance when compared to binary Al–Sc or ternary Al–Sc–Zr alloys with the same composition and precipitate radius [18]. According to Sawtell and Morris [19,20], addition of 0.3 at% Er, Gd, Ho, or Y improves the tensile strength of Al–0.3 at% Sc alloys at room temperature.

---

[*] Corresponding author. Tel.: +351 253510220; fax: +351 253516007.
E-mail address: quoctuan1884@gmail.com (N.Q. Tuan).

http://dx.doi.org/10.1016/j.msea.2014.02.042
0921-5093

In this study, we investigate dilute Al–0.24 wt% Sc alloys with microalloying addition of 0.07 wt%Yb to compare with Al–0.28 wt %Sc alloy. The effects of substituting Yb for Sc on the microstructure and the mechanical properties of Al–Sc alloy are investigated by using SEM, TEM, high-resolution TEM and Vickers hardness.

2. Experimental procedure

Al–0.28 wt% Sc and Al–0.24 wt% Sc–0.07 wt% Yb alloys were cast by using commercially pure Al (99.83 wt% purity), Al–2 wt% Sc master alloy and pure Yb (99.99 wt% purity). The alloys were melted in a graphite crucible using a high frequency induction furnace. For each alloy, pure Al was firstly melted at 720 °C ± 5. Then the Al–2 wt% Sc master alloy and pure Yb were added into the melt. The melt was kept at this temperature for 30 min and stirred with an alumina rod to ensure homogeneity. The molten alloys were poured into cylindrical copper moulds with 16 mm in diameter and 80 mm in length and water cooled. The composition of the as-cast alloy was measured by X-ray Fluorescence Spectrometry (Bruker S8 Tiger). The chemical composition of the as-cast alloys is given in Table 1.

In order to study the effect of homogenization treatment and aging temperature on precipitation behaviour and age hardening response, two separate studies were conducted: in one, the as-cast alloys were treated at 640 °C for 72 h for homogenization and water quenched to room temperature. The samples were subsequently treated at various temperatures within the range 150–375 °C for 2 h, followed by water quenching to ambient room temperature; in the other, the same procedure without homogenization treatment was carried out.

In order to evaluate the aging kinetics, isothermal aging without homogenization treatment of the cast samples was carried out. The samples were aged at different temperatures between 300 and 350 °C for times ranging from 10 min to 7 days.

Vickers hardness was used to monitor the hardening behaviour. Vickers hardness measurements were performed at room temperature using 30 kg load and 20 s dwell time. Eight measurements were performed on each sample. Scanning electron microscopy (SEM) micrographs were obtained on a Nano-SEM-FEI Nova 200 FEG/SEM scanning electron microscope. Transmission electron microscopy (TEM) and high resolution electron microscope (HRTEM), were used to determine the structure and morphological characteristics of the precipitates. The specimens were examined by FEI TECNAI G20 operating at 200 kV. Thin foils for transmission electron microscope (TEM) and high resolution electron microscope (HRTEM) observations were sectioned from the alloys under different conditions. The foils were prepared by double-jet electropolishing in a solution of 25% nitric acid and 75% methanol solution. In order to determine the average diameter and evaluate the number of precipitates, the TEM micrographs were analysed by Image J software. For each condition, four TEM micrographs at various positions of sample with more than 200 precipitates were selected to measure the precipitate size.

3. Results and discussion

3.1. Age hardening behaviour of the as-cast alloys

3.1.1. Effect of homogenization treatment and aging temperatures on ageing behaviour

The Vickers hardness curves of Al–0.28 wt% Sc and Al–0.24 wt% Sc–0.07 wt% Yb alloys aged at various temperatures within the range 150–375 °C for 2 h with and without homogenization treatment are shown in Fig. 1. It is evident that the hardness values of the alloys aged in the as-cast condition are significantly higher than those of the alloys homogenized and aged. In the as-cast alloys, Sc and Yb exist in α-Al supersaturated solid solution due to the high cooling rate during solidification. The precipitation of intermetallic particles occurs during the homogenization treatment, reducing the supersaturation level of Sc and Yb in α-Al solid solution. As a consequence, homogenized alloys will have the lower hardening effect due to the lower fraction volume/density of precipitates. Fig. 2 shows SEM micrographs of as-cast and homogenized Al–0.24 wt% Sc–0.07 wt% Yb samples. In the homogenized samples, several large particles of intermetallic precipitates were formed and heterogeneously distributed in α-Al.

Also shown in Fig. 1 is the effect of substituting 0.07 wt% Yb for Sc of Al–0.28 wt% Sc alloy on aging behaviour at various temperatures. The onset of age hardening for both alloys occurs at 200 °C. The precipitates form most rapidly at the temperature range of 300–350 °C, for which the highest hardness values were obtained. In the aging process without homogenization treatment, the Vickers hardness value peaks of Al–0.28 wt% Sc and Al–0.24 wt% Sc–0.07 wt% Yb alloys are 72 HV at 325 °C and 68 HV at 350 °C, respectively. A decreasing in Vickers hardness is observed for both alloys for temperatures higher than 375 °C due to the precipitate

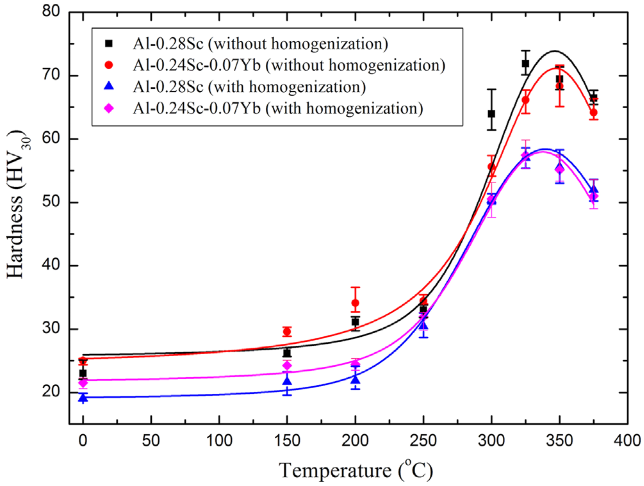

Fig. 1. Vickers hardness curves of Al–0.28 wt% Sc, Al–0.24 wt% Sc–0.07 wt% Yb alloys at various aging temperatures with and without previous homogenization treatment.

Table 1
Chemical composition of the as-cast alloys.

Alloy	Sc	Yb	Si	Fe	Ni	Cu	Ba	Mn	Ti	Al
Al–Sc										
wt%	0.283	–	0.383	0.130	0.010	0.007	0.060	0.010	0.009	Bal
at%	0.170		0.369	0.063	0.005	0.003	0.012	0.005	0.005	Bal
Al–Sc–Yb										
wt%	0.243	0.068	0.328	0.208	0.040	0.032	0.015	–	–	Bal
at%	0.146	0.011	0.316	0.101	0.018	0.014	0.003	–	–	Bal