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Influence of Sc content on the microstructure and mechanical properties of cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy

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ABSTRACT

In this work, the influence of Sc content on the microstructure and mechanical properties of cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy was investigated. It was found that the grain size of As-cast alloy was significantly reduced in steps with the increase of Sc addition, accompanied by the arising and increasing of cubic primary Al_3(Sc, Zr) phases. No evidence for the presence of the ternary W ($Al_{8-x}Cu_{4+x}Sc$) phase was obtained. The volume fraction of nanoscale Al_3(Sc, Zr) dispersoids was improved with the increase of Sc content, and the presence of Sc was observed to refine the S′ (Al_2CuMg) morphology during ageing. The addition of Sc lowered the growth rates of δ′ (Al_3Li) particles and δ′-Precipitate-free zones (δ′-PFZs) of the base alloy. The tensile property results showed that, with the increasing Sc content and ageing times, the yield strength (YS) and ultimate tensile strength (UTS) were continuously increased, and the highest elongation of 6.0% was obtained in the 0.2Sc-containing alloy aged for 32 h at 175 °C. The results indicated that the optimal Sc addition in cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy was 0.2 wt%.

1. Introduction

Al-Li alloys are attractive for aerospace and aircraft applications because they can offer lower density and higher modulus than conventional aluminum alloys. [1–3]. Each 1 wt% of lithium added to the aluminum alloy (all compositions are in wt% hereafter unless noted otherwise) can lower its density by 3% and simultaneously increase the elastic modulus by approximately 6% (for Li additions up to 4%) [4]. Replacements of conventional aluminum alloys currently used with low-density high-stiffness Al-Li based alloys are therefore of considerable commercial interest to both airframe manufacturers and aluminum producers. Successful development and commercialization of the wrought Al-Li alloys have been obtained such as the AA2099 and AA2195 over the past few decades [2,3]. However, there exist few investigations focused on the development of cast Al-Li alloys. In the light of the promising potential of weight reduction and stiffness enhancement achieved by replacing the conventional cast Al alloys with cast Al-Li alloys, novel low-density high-stiffness cast Al-Li alloys could meet the increasing requirements for the specially lightweight-critical and stiffness-critical structures in aircraft, aerospace and military industries. Hence, it is urgent to develop specifically designed cast Al-Li alloys with low density, high strength and elastic modulus.

In our earlier work, the microstructural evolution and mechanical properties of cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy were studied [5]. It was proved that this alloy possessed an excellent combination of strength and ductility in the field of cast Al-Li alloys after subjected to optimized heat treatments. Present work aims to further improve its strength and/or ductility while maintaining the benefit of low density and high stiffness. The existing literatures indicate that the strong age hardening response observed in wrought Al-Li-X alloys heavily relies on the thermo-mechanical treatment (TMT). The pre-age stretch plays a significant role in enhancing precipitation kinetics of fine T_1 (Al_2CuLi) plates at the expense of δ′ (Al_3Li) and/or θ′ (Al_2Cu) phases through the introduction of greatly increased heterogeneous nucleation sites [6,7]. In practice, however, the cast Al-Li alloys do not lend themselves readily to the use of T8 temper (a pre-age stretch prior to subsequent artificial ageing). Microalloying might be the alternative, applicable approach to enhance the performance of cast Al-Li alloys.

In general, microalloying effects could be interpreted as two types: one promotes the precipitation of strengthening phases by lowering the solubility of the precipitate components in the matrix or by reducing its interfacial energy via segregating to the precipitate-matrix interface

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(e.g., element Ag, Mg, and/or Zn) [8–10], and the other forms new strengthening precipitates. Scandium was selected for investigation in this work primarily based on the second effect and the detailed considerations will be given as follows.

Element Sc attracted our attention primarily because minor addition of it will produce a considerable strengthening effect and remarkable grain refinement on some aluminum alloys. However, making a Sc addition to Cu-containing Al-Li alloys needs careful investigations based on the existing literatures [11–16].

There exist controversial reports in the literatures regarding influences (positive or negative) of Sc content on the microstructures and mechanical properties of Al-Cu-X alloys [11,14]. Minor Sc addition to some Al-Cu alloys would result in significant grain refinement, accompanied by remarkable strengthening effects associated with the formation of numerous Al_3Sc particles [17–20]. However, Sc might react with Cu and ternary W phase would form consequently, which has been suggested to be of $Al_{8-x}Cu_{4+x}Sc$ [13], $Al_{5-8}Cu_{7-4}Sc$ [21] or $Al_{5.4-8}Cu_{6.6-4}Sc$ [22] compound. The formation of coarse W phase instead of Al_3Sc would diminish the positive effects of Sc [13,15,16]. In making a Sc addition to Al-Cu-Li alloys, it is necessary to take these circumstances into account and experimental trials are essential. The formation of W phase in Al-Cu-X-Sc alloys is far from clear, and there exists no certain knowledge on the microstructural evolution and mechanical properties of cast Al-Cu-Li alloys with reference to different Sc addition. Present work aims to study on the microstructural influences associated with different Sc additions in cast Al-Li-Cu alloys to fill this gap and contribute to a more comprehensive understanding of the formation of W phase.

The ageing precipitation behavior and mechanical properties of cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy were investigated in our previous work [5]. The primary aim of this work is to investigate the influences of Sc addition (x = 0%, 0.1%, 0.2% and 0.3%) on the microstructures and mechanical properties of cast Al-2Li-2Cu-0.5Mg-0.2Zr alloy. The existence form of Sc, the feasibility of Sc addition to improve the alloy strength and/or ductility and the optimal Sc addition are discussed in detail.

2. Experimental Procedures

The cast Al-2Li-2Cu-0.5Mg-xSc-0.2Zr alloys (x = 0, 0.1, 0.2, and 0.3) used in this work were prepared in the same procedures illustrated in our previous work [5]. Al-10%Zr, Al-50%Cu, Al-2%Sc master alloys and pure Al, Mg, and Li were used in the preparation of the studied alloys. Table 1 lists the actual chemical compositions of the four alloys, determined by Inductively Couple Plasma-Atomic Emission Spectroscopy (ICP-AES). They are hereafter referred to as the base, 0.1Sc, 0.2Sc, and 0.3Sc alloy, respectively. A two-stage solution heat treatment was applied that consisting of a low-temperature stage at 460 °C for 32 h followed by a high-temperature stage at 520 °C for 24 h. After subjected to the solution treatment, the samples were immediately quenched into water (25 °C), and subsequently aged at 175 °C for times up to 1200 h in a silicon-oil bath controlled to ± 1 °C.

Samples of 10 mm × 10 mm × 10 mm in size taken from the same position of the As-cast and As-quenched ingots were subjected to optical (OM, LEICA MEF4M) and scanning electron microscopy (SEM, Phenom XL) observations after etched by the Keller's reagent for 20 s. Details of the sample preparation for metallographic and SEM observations have been described elsewhere [5]. Aged samples were mechanically ground to about 100 μm and 3 mm diameter disks were punched from these samples to prepare the thin foil specimens for the transmission electron microscopy (TEM) observations. TEM specimens were prepared using a double-jet electropolishing technique. A solution of 4% perchloric acid and 96% ethanol cooled to approximately −30 to −35 °C was used as the electrolyte. The disks were twin-jet electropolished using a Tenupol-5 twin-jet electropolisher operated at 30 V. The linear intercept method (ASTM E112–210) was utilized to evaluate the average grain size. Phase analysis was carried out by X-ray diffraction (XRD, Rigaku Ultima IV). The samples were scanned over the 2θ interval 10°–90° with an angular velocity of 4 deg./min. The As-quenched cylindrical samples of each alloy with dimensions of $\varphi 6 \times 60\ mm^3$ were subjected to elastic modulus measurements utilizing an ET-RT modulus tester (Nihon-tech, Japan), and the results were listed in Table 1. To determine the age hardening responses, macro Vickers hardness measurements were carried out on the polished samples water-quenched from 175 °C for different ageing times using a load of 5 kg and a dwell time of 15 s. For each ageing time and alloy, the average value is obtained by six hardness measurements. Tensile test of sheet specimens were tested at room temperature utilizing Zwick/Roell Z100 testing machine at a cross-head speed of 0.5 mm/min. Each tensile property value is the average of at least three parallel tests. Conventional TEM was performed on a JEOL2100 instrument, operated at 200 kV.

3. Results and Discussion

3.1. Effect of Sc Content on the As-Cast Microstructures

Fig. 1 shows the XRD patterns of As-cast Al-2Li-2Cu-0.5Mg-xSc-0.2Zr alloys. The results indicate that the base alloy consists of α-Al, δ′ (Al_3Li), Al_2CuLi, δ (AlLi), Al_2CuMg, and Al_2Cu phases, whereas additional diffraction peaks related to the Al_3Sc phase are well-defined in the Sc-containing alloys (Fig. 1b through d). The Al_2Cu and δ (AlLi) phases were not determined in our previous work [5] possibly ascribed to the relatively larger angular scanning velocity (10 deg./min) rather than the 4 deg./min used in this study. Moreover, none of these diffraction peaks were found to be consistent with the characteristic peaks related to the ternary Sc-containing W phase, which primarily evidenced the absence of W phase in the As-cast studied alloys. Previous study by Fridlyander and Rokhlin et al. [23] provided indications of the co-existence of T_1, Al_2Cu, AlLi, Al_2CuMg, Al_2MgLi, T_2 (Al_6CuLi_3) and T_B ($Al_{7.5}Cu_4Li$) phases with the α-Al solid solution in quaternary Al-Li-Cu-Mg system. However, no characteristic peaks originated from the Al_2MgLi, T_2 and T_B phases up to the detection limits could be identified in this work, possibly due to their small volume share.

Optical micrographs of the grain structures of the As-cast studied alloys are presented in Fig. 2. The grain refining effect introduced by Sc additions is obvious. The As-cast base alloy consists of dendritic or cellular dendritic α-Al grains with average grain size of about 95.3 μm. As is shown in Fig. 2a, a large number of coarse secondary phases are distributed in the vicinity of grain boundaries observed in the base alloy. The average grain size is reduced in steps with the increasing Sc

Table 1
Measured chemical compositions, elastic modulus and solution parameters of the cast Al-2Li-2Cu-0.5Mg-xSc-0.2Zr alloys in this work.

Alloys	Real compositions (wt%)						Elastic modulus/GPa	Solution parameters
	Li	Cu	Mg	Zr	Sc	Al		
Base	1.94	1.94	0.46	0.15	–	Bal.	78.83	460 °C × 32 h + 520 °C × 24 h
0.1Sc	1.96	2.07	0.45	0.18	0.11	Bal.	79.14	
0.2Sc	2.05	1.93	0.53	0.16	0.22	Bal.	79.08	
0.3Sc	1.92	2.03	0.47	0.17	0.31	Bal.	79.13	