



Improving aging and creep resistance in a dilute Al–Sc alloy by microalloying with Si, Zr and Er

N.Q. Vo^{a,c,*}, D.C. Dunand^{a,c}, D.N. Seidman^{a,b,c}

^a Department of Materials Science and Engineering, Northwestern University, Evanston, IL 60208, USA

^b Northwestern University Center for Atom-Probe Tomography, Northwestern University, Evanston, IL 60208, USA

^c NanoAl LLC, Skokie, IL 60077, USA

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Abstract

Nanosized precipitates in an Al–0.06Sc at.% alloy containing various microalloying additions were studied, with the goal of developing cost-effective aluminum alloys for high-temperature applications, using micro-hardness, electrical conductivity and atom-probe tomography measurements. Substituting 0.005 at.% Er for the more expensive Sc maintains high ambient-temperature strength, and dramatically improves the high-temperature creep resistance, as anticipated from the increase in lattice parameter mismatch between the α -Al(fcc) matrix and the coherent $L1_2$ -ordered $Al_3(Sc,Zr,Er)$ precipitates. A concentration of the slow-diffuser Zr as low as 0.02 at.% is sufficient to provide coarsening resistance at 400 °C (an homologous temperature of 0.72) for up to 66 days by forming a Zr-enriched outer shell encapsulating the precipitates. Finally, adding 0.05 at.% Si enhances ambient-temperature strength by increasing the number density of precipitates, while decreasing the homogenization and peak-aging heat-treatment times, which is caused by the Si atoms accelerating the Er and Sc diffusion kinetics. Si-containing alloys are also cost effective, owing to the existence of Si in commercial purity Al. But addition of Si reduces the precipitate coarsening resistance: the magnitude of this effect is, however, determined by the Si concentration.

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1. Introduction

The strong demand for low-density components in transport systems necessitates the design and fabrication of lightweight Al alloys for high-temperature applications (e.g., in and near engines and brakes), which do not lose their strength as a result of aging for long exposure times at elevated temperatures. In coarse-grained Al alloys, micro-alloying additions of Sc (<0.3 at.%) results in significant improvements in creep and coarsening resistance up

to 300 °C, due to the formation of nanoscale, elastically hard and coherent $Al_3Sc(L1_2)$ structure) precipitates [1–10].

Many studies have identified elements that can substitute for Sc in Al–Sc-based alloys to: (i) decrease the use of the expensive Sc; (ii) increase ambient strength; (iii) increase service temperature, while maintaining high strength; and (iv) increase high-temperature creep strength. Substitutional elements for Sc are the rare-earth (RE) [11–23] and transition metals (TM) [24–36].

RE elements can substitute for Sc in $L1_2$ -ordered $Al_3(-Sc_{1-x}RE_x)$ precipitates, where x increases with the RE atomic mass and x is as large as 0.4 and can reach unity [14] for Er, Tm, Yb and Lu [15,37]. Diffusivities of RE elements in α -Al are essentially unknown, with the exception of Er and Yb. Their diffusivities at 300 °C were determined by measuring the kinetics of precipitation, and are

* Corresponding author at: Department of Materials Science and Engineering, Northwestern University, Evanston, IL 60208, USA. Tel.: +1 847 491 3575; fax: +1 847 491 7820.

E-mail address: voquynhon@gmail.com (N.Q. Vo).

four- and tenfold greater than Sc in α -Al, respectively [14]. Thereby, in dilute Al–Sc–Er and Al–Sc–Yb ternary alloys, the precipitate cores are enriched in Er and Yb, while their shells are enriched in Sc [13,19]. Similar observations were found for other RE elements (Sm, Gd, Tb, Dy, Ho, Tm and Lu) in Al–Sc–RE ternary alloys, where core–shell $\text{Al}_3(\text{Sc}_{1-x}\text{RE}_x)$ precipitates are found to be enriched in RE elements in their cores after aging at 300 °C [11,15,19]. As a result, RE substitution reduces the use of Sc, while maintaining the high number density of precipitates and thus the high ambient strength of an alloy. The high-temperature creep resistance of Al–Sc–RE ternary alloys is also improved compared with Al–Sc binary alloys [19,38–40], which is due to a larger lattice parameter mismatch between α -Al and $\text{Al}_3(\text{Sc}_{1-x}\text{RE}_x)$ [37], which increases the elastic interaction between precipitates and dislocations. Since RE elements appear to have larger diffusivities compared with Sc in α -Al, they do not improve precipitate coarsening resistance at higher service temperatures or longer exposure times.

Transition metals, such as Zr, Hf and Ti, can also substitute for Sc in L_{12} -ordered $\text{Al}_3(\text{Sc}_{1-x}\text{TM}_x)$ precipitates [24]. In the case of Zr, $\text{Al}_3(\text{Sc}_{1-x}\text{Zr}_x)$ precipitates exhibit significantly higher coarsening resistance compared with Al_3Sc precipitates in Al–Sc binary alloys, owing to the sluggish diffusivity of Zr in α -Al. A Zr-enriched precipitate shell is formed during aging and serves as a diffusion barrier for Sc, which is enriched in the precipitate core [31,28,29,41]. A recent study demonstrated that Al–0.06 Sc–0.06 Zr alloy maintains high strength at an aging temperature of 400 °C, with the average precipitate radius $\langle R(t) \rangle$ remaining nearly unchanged during aging for up to 64 days [41]. Titanium and Hf also improve the coarsening resistance of $\text{Al}_3(\text{Sc}_{1-x}\text{Ti/Hf}_x)$ precipitates by the same mechanism, but are less effective than Zr [27,30,42].

A combined approach to using the benefits of both RE and TM elements, where they substitute for Sc, has been achieved by designing new Al–Sc–Er–Zr alloys [41,43]. Alloy compositions and heat-treatment conditions were chosen, following the principal design requirements: affordability, high-temperature strength and coarsening resistance, maintaining precipitate coherence and minimizing grain refinement to eliminate diffusional creep. In Al–Sc–Zr alloys, research demonstrates that a total solute concentration below ~ 0.15 at.% results in larger grains in the as-cast condition by forming single α -Al phase alloys [29,31,32]. Thus, Sc and Zr concentrations of 0.06 at.% each were chosen to provide significant precipitation strengthening and sufficient coarsening resistance. With a solubility of 0.046 at.% Er in an Al–Er binary alloy at 640 °C [14], an Er concentration of < 0.02 at.% was chosen to reduce the occurrence of primary precipitates. As a result, coherent, spheroidal and L_{12} -ordered precipitates were formed, consisting of an Er-enriched core enveloped by a Sc-enriched inner shell and a Zr-enriched outer shell. The formation of nanostructured core/double-shell precipitate is a consequence of sequential precipitation according

to their intrinsic diffusivities ($D_{\text{Er}} > D_{\text{Sc}} > D_{\text{Zr}}$). The nanostructured precipitates are coarsening resistant for at least 64 days at 400 °C [41]. Moreover, substituting 0.01 at.% Er for Sc in the Al–0.06Sc–0.06Zr–0.04Si (at.%) alloy provides a significant improvement in the creep threshold stress, owing to an increase in the lattice mismatch between the $\text{Al}_3(\text{Sc,Zr,Er})$ precipitates and the α -Al matrix, compared with Er-free alloys [43].

The previous design and results for an Al–0.06Sc–0.06Zr at.% with 0.01 or 0.02 at.% Er substituting for Sc have several problems. The maximum solubilities of Er and Zr in the α -Al matrix are only ~ 50 and ~ 200 –300 at.ppm at 640 °C, respectively, as measured by atom-probe tomography (APT), owing to the formation of primary $\text{Al}_3\text{Er}(\text{L}_{12})$ and $\text{Al}_3\text{Zr}(\text{L}_{12})$ precipitates during solidification and subsequent cooling, and incomplete dissolution of the Al–Zr master alloy [41]. As a consequence, the Er-containing alloy had finer grains than the Er-free alloy, resulting in undesirable diffusional creep in the low-stress regime during creep experiments at 400 °C [43]. Substitution of 0.01 or 0.02 at.% Er for Sc resulted in a ~ 20 –30% decrease in microhardness, as a result of a smaller total Sc plus Er supersaturation [41]. Also, the heat treatment of the alloys was time consuming: 72 h for solutionizing/homogenizing at 640 °C and 24 h for peak-aging at 300 °C [43]. This article presents a further optimization of this advanced Al–Sc–Er–Zr alloy by decreasing the Er and Zr concentrations to 50 and 200 at.ppm, respectively, which are the experimentally measured maximum solubility values. A Sc concentration of 550 at.ppm was chosen, so that the total Sc + Er concentration is 0.06 at.% to regain the high ambient peak strength, and the total Sc + Er + Zr concentration is 0.08 at.% to prevent primary precipitation during solidification, and to maintain a coarse-grained structure that does not exhibit measurable diffusional creep at small stresses. Decreasing the concentrations of the relatively expensive Er and Zr also results in less expensive alloys. Furthermore, 0.05 at.% Si was added to obtain three important advantages: (i) increasing precipitate number density by stimulating heterogeneous nucleation [44]; (ii) accelerating the Er and Sc precipitation kinetics to decrease the aging time [44]; and (iii) decreasing the cost of the alloy because of the presence of Si impurities in commercial-purity aluminum [45].

2. Experimental procedures

The alloy with a nominal composition of Al–0.055Sc–0.005Er–0.02Zr–0.05Si (at.%) (which is used hereafter unless noted otherwise), referred to as the improved alloy, was melted in air in a resistively heated furnace using 99.999 at.% pure Al, Al–12Si, Al–5.0Zr, Al–1.3Sc and Al–1.2Er, in alumina crucibles. The master alloys were preheated to 640 °C to accelerate solute dissolution upon addition to the melt. The melt was held for 30 min at 800 °C, stirred vigorously and then cast into a graphite mold, which was preheated to 200 °C. The mold was placed on

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