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Ambient- and high-temperature mechanical properties of isochronally aged Al–0.06Sc, Al–0.06Zr and Al–0.06Sc–0.06Zr (at.%) alloys

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Abstract

Ambient- and high-temperature precipitation strengthening are investigated in Al–0.06Sc, Al–0.06Zr and Al–0.06Sc–0.06Zr (at.%) alloys. Following solidification, Sc is concentrated at the dendrite peripheries while Zr is segregated at the dendrite cores. During isochronal aging, precipitation of Al_3Sc ($L1_2$) commences between 250 and 300 °C for Al–0.06Sc, and reaches a 429 MPa peak microhardness at 325 °C. For Al–0.06Zr, precipitation of Al_3Zr ($L1_2$) first occurs between 400 and 425 °C and reaches a 295 MPa peak microhardness at 475 °C. A pronounced synergistic effect is observed when both Sc and Zr are present. Above 325 °C, Zr additions provide a secondary strength increase that is attributed to precipitation of Zr-enriched outer shells onto the Al_3Sc precipitates, leading to a peak microhardness of 618 MPa at 400 °C for Al–0.06Sc–0.06Zr. Upon compressive creep deformation at 300–400 °C, Al–0.06Sc–0.06Zr exhibits threshold stresses of 7–12 MPa; these values may be further improved by optimal heat-treatments.
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1. Introduction

The Al–Zr system shows particular promise for developing creep-resistant, thermally stable Al-based alloys at elevated temperatures [1,2]. During post-solidification aging, decomposition of supersaturated Al–Zr solid solutions occurs initially by the formation of nanometer-scale Al_3Zr precipitates with a metastable cubic $L1_2$ structure, which transform to the equilibrium $D0_{23}$ phase after prolonged aging at elevated temperatures (>450 °C) [3–11]. The stability of the $L1_2$ metastable phase at high homologous temperatures is attributed to the slow diffusion kinetics of Zr in α-Al and a small lattice parameter mismatch of Al_3Zr ($L1_2$) with α-Al [1].

In previous studies by the authors, the microstructures and ambient-temperature mechanical properties of conventionally solidified Al–Zr alloys were studied during isothermal aging at 375, 400, 425 °C [12] and 500 °C [13] or during isochronal aging up to 600 °C [13]. Precipitation of spheroidal, nanometer-scale Al_3Zr ($L1_2$) precipitates results in a pronounced hardening response at all aging temperatures investigated. There is no appreciable overaging effect despite extended aging times (3200 h) at 425 °C ($0.75T_m$, where T_m is the absolute melting temperature of Al) [12], and only at or above ~475 °C do the metastable $L1_2$ trialuminide precipitates transform to their equilibrium $D0_{23}$ structures [13].

The Al_3Zr precipitates are, however, heterogeneously distributed (Fig. 1), reflecting the dendritic microsegregation

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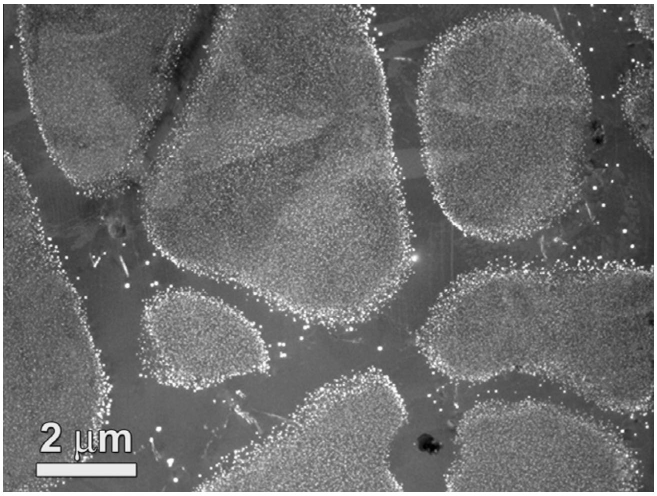

Fig. 1. Centered dark-field transmission electron micrograph of an Al–0.1Zr–0.1Ti (at.%) alloy aged at 375 °C for 1600 h, exhibiting an inhomogeneous dendritic distribution of 3–5-nm-radius $Al_3(Zr_{1-x}Ti_x)$ ($L1_2$) precipitates [12].

of Zr solute atoms during solidification [12]. Because Zr forms a terminal peritectic with Al, the liquidus and solidus boundaries of the α-Al solid solution plus liquid two-phase region have positive slopes and k_0, the equilibrium partition coefficient for solidification, is greater than unity. The first solid to form during solidification is therefore richer in Zr compared to the bulk alloy composition, resulting in solute-rich dendritic cells surrounded by solute-depleted interdendritic channels. Upon aging, only the enriched dendritic cells are sufficiently supersaturated to cause precipitation of Al_3Zr. The precipitate-free interdendritic channels have a deleterious effect on the mechanical properties, both at ambient temperature [1,3,15–19] and during creep experiments performed at 300, 350 or 400 °C [14]. Precipitation strengthening in these alloys occurs on multiple length scales: (i) on the nanometer-scale scale by a shearing or Orowan precipitation strengthening mechanism; and (ii) on the micrometer-scale related to the volume fraction of the precipitate-rich dendrites [13].

Dendritically distributed Al_3Zr ($L1_2$) precipitates are also a significant problem in commercial wrought alloys, where Zr is added as a recrystallization inhibitor [1,3,15–19]. During solutionizing, which is typically performed at ~500 °C coherent Al_3Zr ($L1_2$) precipitates are formed, which inhibit subsequent recrystallization by pinning migrating grain boundaries, thus maintaining grain boundary strengthening. The alloys are prone to recrystallization, however, in the interdendritic regions, where the number density of Al_3Zr precipitates is small [20–23]. Several recent studies have aimed to minimize the extent of the precipitate-free interdendritic regions through multi-step annealing procedures [20,24,25] and other alloying additions, including Cu, Mg, Zn [21,26], Si, Fe, Mn [23,27] and Sc [22,27–33] in 7xxx and other commercial wrought alloys.

There is a particularly strong interest in adding Sc to improve the precipitate distribution, thereby improving recrystallization resistance of Al–Zr alloys [22,27–34]. Robson [31] and Forbord et al. [27] have demonstrated that by combining Sc, a solute forming a terminal eutectic with Al ($k_0 < 1$), with Zr, a peritectic solute ($k_0 > 1$), the precipitate-free regions associated with a Sc-free alloy may be eliminated. Their argument, supported by experimentally measured solute concentration profiles, is that during solidification Zr and Sc solute atoms segregate at the dendrite interiors and exteriors, respectively, effectively "filling in" the interdendritic regions with Sc, which forms Al_3Sc ($L1_2$) precipitates upon subsequent thermal aging. A similar effect has also been observed by Lieblich and Torralba [35,36] with Al–Li–Ti alloys, where Ti (a peritectic-forming solute) segregates to the dendrite interiors and Li (a eutectic-forming solute) segregates to the peripheries. A further advantage of combining Zr and Sc is the improved coarsening resistance of $Al_3(Sc_{1-x}Zr_x)$ ($L1_2$) precipitates compared with Al_3Sc ($L1_2$) [37–42]. Finally, first-principles calculations show that Sc should stabilize the $L1_2$ structure of Al_3Zr [43], which may delay their transformation to the equilibrium $D0_{23}$ structures.

We previously investigated precipitation strengthening in binary Al–0.1Sc, Al–0.1Zr and ternary Al–0.1Sc–0.1Zr (at.%) alloys aged isochronally from 200 to 600 °C [42]. Precipitate compositions, mean radii ($\langle R \rangle$) and volume fractions (ϕ) were measured in the Al–Sc–Zr alloy using atom-probe tomography (APT), and were used to identify and quantify the observed strengthening increments due to the resistance to shear of the $Al_3(Sc_{1-x}Zr_x)$ ($L1_2$) precipitates. The Al–Sc–Zr alloy, however, contained primary $Al_3(Sc_{1-x}Zr_x)$ precipitates formed during solidification, resulting in a fine-grained microstructure (~50 μm grain diameter), which is unsuitable for creep resistance. In this article, we investigate the as-cast solute microsegregation, ambient-temperature microhardness and high-temperature creep resistance in more dilute, coarse-grained Al–0.06Sc, Al–0.06Zr and Al–0.06Sc–0.06Zr (at.%) alloys.

2. Experimental procedures

2.1. Alloy compositions and preparation

Binary Al–0.06Sc and Al–0.06Zr alloys and a ternary Al–0.06Sc–0.06Zr alloy were investigated; alloy designations and exact compositions are summarized in Table 1 (all compositions are in at.% unless otherwise noted). Small

Table 1
Compositions of the Al–Sc, Al–Zr and Al–Sc–Zr alloys investigated (at.%).

Alloy	Nominal comp.		Verified comp.[a]	
	Sc	Zr	Sc	Zr
Al–0.06Sc	0.06	–	0.062	–
Al–0.06Zr	–	0.06	–	0.059
Al–0.06Sc–0.06Zr(a)	0.06	0.06	0.057	0.059
Al–0.06Sc–0.06Zr(b)	0.06	0.06	0.074	0.077

[a] As measured by direct-current plasma emission spectroscopy.