Available online at www.sciencedirect.com

SciVerse ScienceDirect

Acta Materialia 61 (2013) 1676–1690

Acta MATERIALIA

www.elsevier.com/locate/actamat

Effect of interfacial solute segregation on ductile fracture of Al–Cu–Sc alloys

B.A. Chen [a], G. Liu [a,*], R.H. Wang [b], J.Y. Zhang [a], L. Jiang [a], J.J. Song [a], J. Sun [a,*]

[a] *State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, China*
[b] *School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China*

Received 26 September 2012; received in revised form 21 November 2012; accepted 24 November 2012
Available online 12 December 2012

Abstract

Three-dimensional atom probe analysis is employed to characterize the Sc segregation at θ'/α-Al interfaces in Al–2.5 wt.% Cu–0.3 wt.% Sc alloys aged at 473, 523 and 573 K, respectively. The interfacial Sc concentration is quantitatively evaluated and the change in interfacial energy caused by Sc segregation is assessed, which is in turn correlated to yield strength and ductility of the alloys. The strongest interfacial Sc segregation is generated in the 523 K-aged alloy, resulting in an interfacial Sc concentration about 10 times greater than that in the matrix and a reduction of ~25% in interfacial energy. Experimental results show that the interfacial Sc segregation promotes θ' precipitation and enhances the strengthening response. A scaling relationship between the interfacial energy and precipitation strengthening increment is proposed to account for the most notable strengthening effect observed in the 523 K-aged alloy, which is ~2.5 times that in its Sc-free counterpart and ~1.5 times that in the 473 and 573 K-aged Al–Cu–Sc alloys. The interfacial Sc segregation, however, causes a sharp drop in the ductility when the precipitate radius is larger than ~200 nm in the 523 K-aged alloy, indicative of a transition in fracture mechanisms. The underlying fracture mechanism for the low ductility regime, revealed by in situ transmission electron microscopy tensile testing, is that interfacial decohesion occurs at the θ' precipitates ahead of crack tip and favorably aids the crack propagation. A micromechanical model is developed to rationalize the precipitate size-dependent transition in fracture mechanisms by taking into account the competition between interfacial voiding and matrix Al rupture that is tailored by interfacial Sc segregation.

Keywords: Aluminum alloys; Solute segregation; Fracture mechanism; Interfacial decohesion; Precipitate

1. Introduction

Aluminum alloys combine high strength and light weight and are thus of utmost importance as structural materials. In particular, heat-treatable Al alloys, which are strengthened by the formation of precipitates, are used extensively in the automotive and aviation industries [1]. The binary Al–Cu system is a well-studied precipitation strengthening system because it forms the basis for a wide range of age-hardening alloys. The precipitation sequence observed on aging these alloys, supersaturated solid solution (SSSS) → Guinier–Preston (GP) zones → θ'' → θ' → θ, is often used as a model system for describing the fundamentals of precipitation hardening [2].

Small additions of various alloying elements are of prime importance in modifying the precipitation/microstructure and improving the mechanical properties of Al alloys [3]. Such microalloying effects have also been applied to the Al–Cu alloys [3–11]. Trace element or microalloying additions of Sn, Cd or In are well known to suppress low-temperature aging and enhance both the rate and extent of age hardening at elevated temperature, by promoting the formation of θ' at the expense of GP zones and θ'' [4,5]. Two types of proposal have been offered to describe the

---

* Corresponding authors.
E-mail addresses: lgsammer@mail.xjtu.edu.cn (G. Liu), junsun@mail.xjtu.edu.cn (J. Sun).

1359-6454/$36.00 © 2012 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actamat.2012.11.043

mechanisms for this microalloying effect. One is that the Sn (Cd or In) atoms segregate to the precipitate/matrix interface and lower the interfacial energy somewhat [5–7]. This mechanism was first suggested [5] to account for the weak X-ray reflection observed during the early stages of aging, and subsequently received indirect experimental support separately from calorimetric measurements [6] and transmission electron microscopy (TEM) observations [7]. The other proposal is that the trace elements facilitate heterogeneous nucleation of θ', either directly at Sn (Cd or In)-rich particles [8] or indirectly at the dislocation loops present in the as-quenched microstructure [9]. In a later study using atom probe field ion microscopy [10], it was directly revealed that no Sn was segregated at the θ'/α-matrix interface in the Al–Cu alloys with trace Sn addition. Clusters of Sn atoms were detected in as-quenched samples, and the formation of Sn clusters was clearly found to precede the formation of θ'. These atom probe analyses indicated that heterogeneous nucleation of θ'; is the predominant microalloying mechanism in the Sn (Cd or In)-modified Al–Cu alloys. Similarly, the heterogeneous nucleation mechanism is also responsible for the recent findings [11,12] that minor additions of Si and Ge in Al–Cu increases hardness and produces a fast hardening rate when aged at elevated temperature, where the first formed Si–Ge precipitates provide preferential nucleation sites for metastable θ'' and then for θ' phases.

The addition of a minor amount of Mg in Al–Cu alloys, however, was found [13] to promote low-temperature aging, i.e. increasing the response on natural aging. The mechanism was suggested [13] to be that Mg atoms preferentially trap quench-in excess vacancies to retard Cu cluster formation in the initial aging stage. In the following aging stage, complex Cu/Mg/vacancy clusters are formed and act as effective nucleation sites for GP zones. The formation of Cu/Mg/vacancy complex clusters greatly retards the cluster growth and increases the cluster number density, accounting for the enhancement in the natural aging response.

Most recently, segregations of Si and Mg atoms at θ'/matrix interfaces have been visibly revealed in Al–Cu alloys with minor Si and Mg additions [14,15], by using the advanced three-dimensional atom probe tomography (3DAP). The solute atom segregation will change the interfacial conditions (e.g. interface structure, chemistry composition and energies) and cause a series of evolutions in both precipitation behaviors and strengthening responses, including precipitate nucleation and concomitantly number density and driving force for precipitate coarsening [16]. Solute segregation at precipitate/matrix interfaces is an important microalloying method to tailor the precipitation and improve the hardening response.

Previous investigations of the microalloying effect are mainly focused on the underlying mechanisms and hardening response. Little attention has been paid to the influence of minor microalloying elements on ductile fracture of Al alloys. As a type of structural material for technological applications, the Al alloys should have not only high strength but also excellent ductility. The addition of microalloying elements will inevitably affect the deformation capability and ductility of the Al alloys through changing the size, number density, distribution and even interfacial conditions of precipitates. On the one hand, the more homogeneous distribution of finer precipitates caused by the microalloying effect can relieve local stress/strain concentration during deformation and therefore increase the ductility. On the other hand, the presence of microalloying elements may lead to the deterioration in the ductility of Al alloys, such as by forming coarse constituent and additional other second phase particles [17,18], and/or by changing the precipitate/matrix interfacial conditions when segregating at the interfaces. Competition between these opposite effects will determine the deformation behaviors of the microalloyed Al alloys, which needs to be understood in order to aid the further design of advanced Al alloy.

In this paper, systematical studies were performed to investigate the effect of minor Sc addition on microstructural evolution, hardening response and especially ductile fracture of Al–Cu mode alloys. Al–Cu–Sc was chosen for the study because (i) our primary experimental results have shown [19] that the addition of trace amounts of Sc in Al–Cu alloys remarkably promotes the homogeneous precipitation of θ' and greatly reduces the precipitate size, displaying a significant microalloying effect; (ii) highly coarsening-resistant Al_3Sc particles (e.g. coarse primary Al_3Sc, intermediate Al_3Sc dispersoids and fine Al_3Sc precipitates; see Fig. 1) will be formed additionally [20], which can improve the high temperature performance of Al–Cu-based alloys and extend their applications; (iii) the binary Al–Cu alloys are a typical type of plate-like precipitate-containing aluminum alloys, which have attracted extensive theoretical studies on precipitation thermodynamics, kinetics and strengthening. They are also ideal mode materials for investigating the microalloying effect on ductile fracture.

2. Experimental procedures

2.1. Material preparation and heat treatments

Alloys with a composition of Al–2.5 wt.% Cu alloys (abbreviated Al–Cu alloys), Al–2.5 wt.% Cu–0.3 wt.% Sc (Al–Cu–Sc) and Al–0.3 wt.% Sc (Al–Sc) were respectively melted and cast in a stream argon, by using 99.99 wt.% pure Al, 99.99 wt.% pure Cu and mast Al–2.0 wt.% Sc alloy. The cast ingots were homogenized at 793 K for 24 h and hot extruded at 723 K into plates 14 mm in thickness and 60 mm in width. All the plates were subjected to the same heat treatments, i.e. solutionized at 863 K for 3 h, followed by a cold water quench and subsequently aged at 473 K, 523 K and 573 K, for a series of times. The maximum error of all the temperature measurements in the present experiments was ±1 K.