Materials Science & Engineering A 709 (2018) 134–138

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Short communication

Secondary creep stage behavior of copper-clad aluminum thin wires submitted to a moderate temperature level

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ARTICLE INFO

Keywords:
Creep
Copper-clad aluminum wire
Intermetallics
Mechanical properties

ABSTRACT

This work focuses on the role of the microstructure on the creep behavior of thin copper-clad aluminum (CCA) wires. Creep tests were performed at 150 °C on hard drawn and annealed CCA and on pure metals. It is shown that the Cu-Al interface of CCA ensures a mechanical resistance leading to lower creep velocities than for metals. Creep mechanisms are driven by aluminum at lower stresses and copper for higher stresses, independently of the physical nature of the interface.

1. Introduction

Bimetallic composites based on the copper/aluminum couple are used for electrical devices and high frequency current equipment [1]. Composite products as Al-Cu laminates [2–5], bonded interconnections in electronics [6–8], stir welding joint [9,10] or copper-clad aluminum (CCA) wires [11] are currently manufactured.

CCA wires are an interesting alternative to copper cables in automotive industry because they typically present a weight reduction by an half for the same order of electrical conductivity, compared to traditional copper wires [12]. However, wires are subjected to thermo-mechanical ageing up to 150 °C under stress levels around the engine that may alter their electrical and mechanical properties [13]. The creep behavior observed in pure metals Al and Cu cannot be directly transposed in a bimetallic structure as CCA, and corresponding physical mechanisms remain largely not understood. The aim of this work is to bring new experimental results for CCA thin wires in creep conditions at moderate temperature levels. Short time creep experiments were performed on raw and annealed CCA wires and experimental results were analyzed with the help of in-situ X-Ray diffraction (XRD) analysis and Scanning electron microscopy. These results were compared to creep behavior of pure Cu and Al metals and discussed taking into account the bonding of the interface and the effective role played by intermetallic compounds for two distinct metallurgical states.

2. Materials and methods

CCA wires were produced by plating a 0.5 mm thick strip of copper (99.9%) around a 20 mm diameter aluminum (99.5%) rod. This bar was then drawn down to a diameter of 300 µm. The thickness of the copper ring is of the order of 12 µm and the volume ratio between aluminum and copper remains roughly constant (around a value of 85/15) through the successive dies. Virgin (RD samples) and post-treated annealed (AD samples) wires were tested and compared to raw drawn copper (99.99%) and aluminum (99.99%) wires.

Creep tests were performed at 150 °C on CCA, Cu and Al samples of 500 mm in length using a 50 kN load frame equipped with a 2 kN load cell at a strain rate of loading equal to $6.6 \times 10^{-5}\ s^{-1}$. Applied stresses were ranging from 0.3 σ_y to σ_y (the yield stress σ_y was evaluated by monotonous tensile tests at 150 °C). Between three and five tests per stress value were performed and a good reproducibility was observed for each condition. The maximum standard deviation for creep strain measurements is $\pm\ 20 \times 10^{-5}$. Creep time was stopped after five days, when the second stage – characteristic of creep mechanisms - was clearly defined.

Hardness and elastic coefficients on the intermetallic compounds which develop through the interface between Al and Cu were captured by nanoindentation tests using a Berkovitch indenter down to a constant depth of 1000 nm. This method was evidenced by previous work on hard metallic layer [14].

In-situ XRD analysis was performed at 150 °C in RD and AD wires to correlate the microstructural changes due to temperature with the creep mechanisms. Diffractograms were recorded for five days to follow the interfacial evolution. Raw CCA wires were also studied at 400 °C to increase the growth velocity of the intermetallic compounds through the interface. To the end, multiple wires were mounted in a copper tube and the system was cut to a 800 µm thickness sample in order to depict the presence of IMC. X-ray diffraction patterns were collected on a two

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http://dx.doi.org/10.1016/j.msea.2017.10.044
Received 3 July 2017; Received in revised form 10 October 2017; Accepted 13 October 2017
Available online 16 October 2017

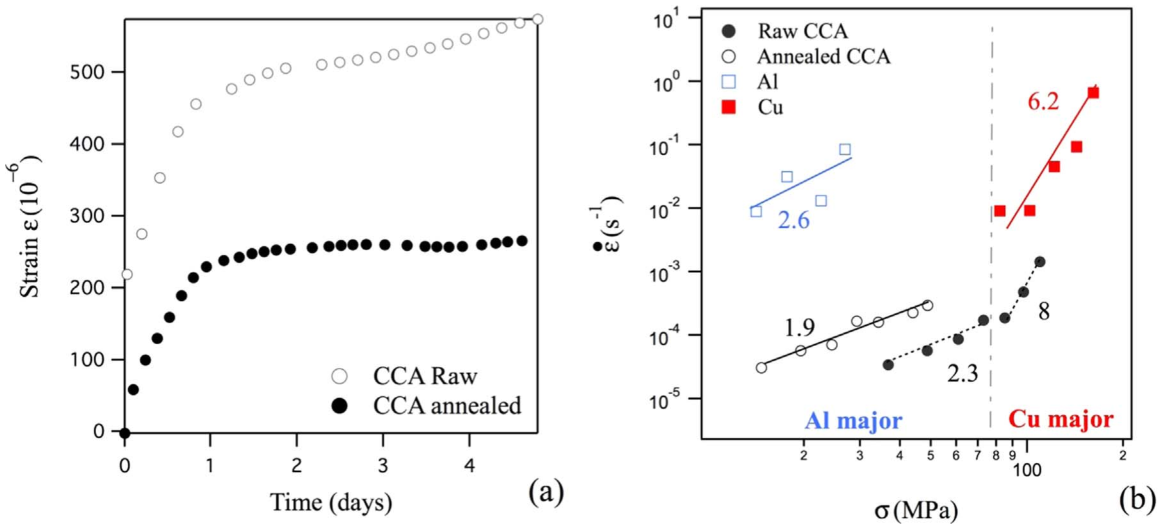

Fig. 1. (a) Typical creep curves of RD and AD wires at 150 °C and 0.4σ_e; (b) Strain rate $\dot{\varepsilon}$ in the secondary creep stage versus stress level σ (logarithmic plots) for Cu, Al, RD and AD wires (T = 150 °C). Numerical values represents the Norton coefficient ***n***.

θ-θ para focusing Bragg-Brentano geometry high-resolution Bruker AXS D8 Advance in the angular range 25° < 2θ < 85°. Tests were performed in vacuum (10^{-3} mbar) to avoid oxidation.

Microstructural analysis of the interface between copper and aluminum was performed in order to understand the development of the IMC during the thermomechanical creep loading. FIB (Ga^+ ion single beam FEI 200XP) and SEM (ZEISS Supra 55) systems were used to prepare and observe longitudinal cross-sections along the wire axis. TEM observations were performed in a JEM 2010 TEM-STEM-FEG, operating at 200 kV. The thin lamellae were gradually thinned by FIB using a lift-out in situ preparation technique.

3. Results and discussion

Typical creep curves are displayed in Fig. 1(a) for a stress level of 0.4 σ_y. These curves clearly exhibit the two first stages of creep behavior. In this study, creep behavior is described using the steady-state creep rate $\dot{\varepsilon} = d\varepsilon/dt$, assimilated to the slope of the second stage. The most common relation to describe stress and microstructure dependence of the steady-state creep rate at constant temperature is given by the well-known Norton power law [15]:

$$\dot{\varepsilon} = C\sigma^n \tag{1}$$

C is a coefficient function of temperature and activation energy and n is the Norton power law exponent. n was computed for RD and AD samples, plotting $\dot{\varepsilon}$ in function of the applied stress σ in Fig. 1(b) (logarithmic plot for σ).

AD wires exhibit a single creep behavior in the overall elastic stress range, with a weak value of the Norton exponent $n = 1.9 \pm 0.2$. Concerning RD wires, two distinct tendencies are evidenced separated by a critical value of stress $\sigma = 0.7\sigma_y$. In the first stage (low stress levels), RD wires follow the same trend than AD wires with $n = 2.3 \pm 0.3$. For σ higher than $0.7\sigma_y$, $\dot{\varepsilon}_{ss}$ strongly increases and the Norton exponent reach values of 8.0 ± 0.6.

To the best knowledge of the authors, no similar work was found in the literature to compare with these experimental results. Due to the bimetallic structure, these results cannot be correlated in a straightforward way to creep experiments performed on pure copper [16] and aluminum [17]. Results obtained by creep tests performed on copper and aluminum are also displayed in Fig. 1 and are in agreement with literature [18,19]. AD wires follow a similar behavior as aluminum one in all the stress range. This indicates that creep mechanisms in these wires are driven by the mechanical properties of aluminum. The two distinct creep tendencies identified for RD wires are the result of a competition between the aluminum behavior at low stresses and copper mechanical properties above $0.7\sigma_y$. Moreover, global strain rate levels reached by CCA wires are significantly lower than in pure metals. In this study, the interface seems to play a role of hard bonding in decreasing the creep velocity. In order to better understand these experimental results, XRD measurements were performed in temperature on AD and RD wires (Fig. 2).

As observed in previous works [20–22] concerning Al-Mn-Si alloys obtained by severe plastic deformation, the summary of intensity fluctuations for crystallographic planes can be evidenced by using $\left[\left(\frac{I}{I_{\max}}\right)^{\{hkl\}}\right]$ factor whose calculations are presented in Table 1.

As seen in this table, no metallurgical evolution is depicted after an

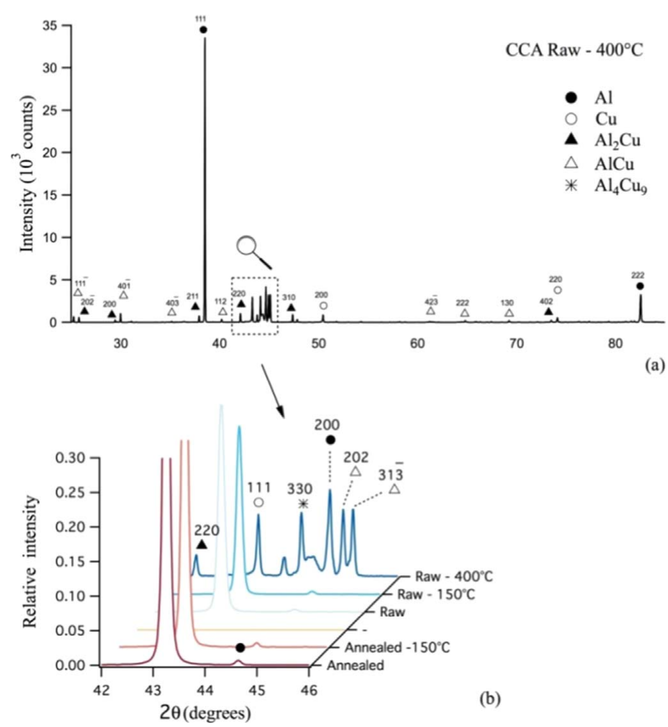

Fig. 2. (a) Temperature X-Ray diffractograms of a RD wire after an annealing at 400 °C. (b) Focus on a specific region of interest of XRD patterns obtained on AD and RD wires before and after annealing at 150 °C and 400 °C.