Acta Materialia 156 (2018) 52–63

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Plasticity of laser-processed nanoscale Al–Al_2Cu eutectic alloy

S.J. Wang [a], G. Liu [b], D.Y. Xie [b], Q. Lei [a], B.P. Ramakrishnan [c], J. Mazumder [a, c], J. Wang [b, *], A. Misra [a, **]

[a] Department of Materials Science and Engineering, College of Engineering, University of Michigan, Ann Arbor, MI, 48109-2136, USA
[b] Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE, 68588, USA
[c] Department of Mechanical Engineering, College of Engineering, University of Michigan, Ann Arbor, MI, 48109-2136, USA

A R T I C L E I N F O

Article history:
Received 17 April 2018
Received in revised form
21 June 2018
Accepted 21 June 2018
Available online 26 June 2018

Keywords:
Plasticity
Nanoscale Al–Al_2Cu eutectic
Slip transmission
Microstructure

A B S T R A C T

Deformation behavior of as-cast and laser re-melted Al–Al_2Cu eutectic alloys subjected to room temperature rolling was investigated by transmission electron microscopy. For as-cast alloys, with interlamellar spacing of a few micrometers, Al_2Cu layers exhibit brittle behavior but plastic co-deformation was observed in rolled, laser processed nanoscale alloys. The nanoscale Al_2Cu lamellae, constrained by nanoscale Al, deform via defects not previously reported in monolithic Al_2Cu intermetallic: localized shear on $\{011\}_{Al2Cu}$ planes and shear-induced faults on $\{121\}_{Al2Cu}$ planes. Based on crystallographic analysis of slip continuity across the interface, the unexpected plasticity mechanisms are ascribed to the slip continuity across interface between α-Al and θ-Al_2Cu layers associated with the orientation relationship in Al–Al_2Cu eutectics. The difference in shear mechanisms on the two planes is attributed to low energy faulted structures associated with shear on $\{011\}_{Al2Cu}$ and $\{121\}_{Al2Cu}$ planes, as examined by first-principles density functional theory calculations. These findings demonstrated that nanoscale microstructures promote plastic co-deformation in metallic composites with soft and hard phases.

1. Introduction

Al-based eutectic composites, such as Al–Si, Al–Ni, Al–Cu etc. have been extensively studied because of their potential applications at ambient to elevated temperatures [1,2]. Taking Al–Cu as an example, the α-Al/θ-Al_2Cu eutectic comprises alternate lamellae of α-Al and θ-Al_2Cu phases. α-Al with a face centered cubic (*fcc*) structure is ductile because of the available slip systems {111}⟨110⟩. θ-Al_2Cu with a C16 body centered tetragonal (*bct*) structure [3] is brittle at room temperature due to high lattice friction stress for dislocation motion [4]. Experimental observations [5–9] and theoretical calculations [4,10] based on crystal structure revealed possible Burgers vectors ⟨001⟩, ½⟨111⟩, ⟨100⟩ and ⟨110⟩ and possible slip planes {110}, {100}, {011} and {112} in θ-Al_2Cu phase. In our earlier study [4,10], using Molecular Dynamics (MD) simulations, it was shown that only edge dislocations associated with (110)⟨001⟩, (010)⟨001⟩ and (310)⟨001⟩ slip systems could glide at room temperatures due to planar-extended core. Experimental observations confirmed a limited number of slip systems and restricted cross-slip at temperatures lower than 300 °C in θ-Al_2Cu single crystal [6,9] or θ-Al_2Cu layers in the Al–Al_2Cu eutectic with microscale layer thickness [7,11]. The brittle-ductile transition temperature (DBTT) of θ-Al_2Cu phase was reported as 375 °C in θ-Al_2Cu single crystals and polycrystals [12] and 300 °C in the microscale Al–Al_2Cu eutectic [7]. The lower DBTT in Al–Al_2Cu composite as compared to monolithic Al_2Cu indicates that geometric constraint associated with layered microstructure may facilitate plastic deformation of θ-Al_2Cu phase.

In layered composites comprising of soft/hard phases, plasticity in the hard layer may be facilitated by the interfaces through two mechanisms: (i) Interface ledges/steps/dislocations can act as dislocation sources due to high stress concentration and available Burgers vectors [13–15]; and (ii) slip transmission from soft (metallic) phase into hard phase [8,16–20]. Due to significant difference in elasticity and plasticity between soft and hard phases, soft layers are hardened due to back stresses associated with geometric constraint of interfaces. Hard layers are subjected to higher stresses due to higher elastic modulus as well as additional tensile or compressive stresses caused by the plastic incompatibility across interfaces [18]. For relatively thicker layers, high elastic stress in the hard phase generally result in tensile cracking or compressive

* Corresponding author.
** Corresponding author.
E-mail addresses: jianwang@unl.edu (J. Wang), amitmis@umich.edu (A. Misra).

https://doi.org/10.1016/j.actamat.2018.06.038
1359-6454/

instability [12,21]. With decreasing layer thickness, the interaction force among dislocations in the adjacent interfaces increases, and may facilitate nucleation and motion of dislocations in fine-scale hard phase [15,18,22]. In addition to the layer thickness, these dislocation mechanisms are strongly related to orientation relationships (ORs) between the two phases, and the structure and properties of interface planes (IPs). Slip transmission across interface is favored in the orientation relationship with a specific pair of parallel slip systems across the interface, but less favored in systems with significant crystallographic discontinuity in slip systems across the interface [23–26]. For example, in nanoscale Al–TiN multilayers with cube-on-cube orientation relationship, the hard TiN phase can plastically co-deform with the metal layers at room temperature when both layer thicknesses are reduced to 5 nm [18,27–29]. Recently, increased plasticity in chill-cast Al-based eutectic composites with bimodal and/or nanoscale structures has been reported [30–36]. A high compressive strain of 11% with fracture strength of ~1.1 GPa was reported in Al–Cu–Si eutectics which comprise of a binary cellular Al–Al_2Cu eutectic and a finer-scale ternary Al–Al_2Cu–Si eutectic [30].

In our earlier work on the Al–Al_2Cu eutectic, cracking was observed in the Al_2Cu microlayers with ~1–2 μm thickness after indentation at room temperature, but not in the Al_2Cu nanolayers with ~40 nm thickness [36]. However, the plasticity mechanisms as a function of microstructural scale and crystallographic orientation relationships have not been studied. In this work, we investigated plasticity mechanisms in as-cast and laser re-melted Al–Al_2Cu eutectic alloys deformed by rolling at room temperature. Transmission electron microscopy (TEM) was used to characterize the deformation mechanisms, and first-principles density functional theory (DFT) calculations were used to compute the defect energetics. The results show brittle failure without measurable plasticity in Al_2Cu layers in as-cast alloys, while plasticity through unexpected defect mechanisms was noted in the nanoscale laser re-melted alloys.

2. Methods and characterization of as-processed materials

2.1. Processing

The ingots of Al-32.7 wt.% Cu alloys were fabricated by arc melting under protective Argon gas environment at Materials Preparation Center, Ames Laboratory, Iowa State University. The as-cast ingots were nominally 50 mm in diameter and 20 mm thick. Plates with dimensions of 5 × 5 × 1.5 mm^3 were cut from the cast ingots for laser remelting experiments. Before laser treatment, the samples were polished to 800 grit SiC paper in order to enhance absorption of the laser beam. Laser surface remelting experiments were conducted on solid-state disk laser (TRUMPF Laser HLD 4002) at a wavelength of 1.03 μm. The absorption was further improved by coating the sample with graphite (Bonderite L-GP G aerosolized graphite lubricant) prior to remelting. Argon shielding gas (flow rate of 9.4 L/min) was also used during the laser remelting process. Ultra-rapid solidification velocity together with high thermal gradient and rapid heating/cooling rate can be achieved by laser surface remelting. This technique has been applied to refine the interlamellar spacing of the Al–Al_2Cu eutectics effectively, such as a minimum interlamellar spacing of 17 nm was achieved in Al–Cu eutectic alloy [37]. Based on the previous results [36], the depth and major axis of the half-ellipse shape melt pool is ~0.6 mm and ~1.7 mm under the condition of 500 W laser power, 2 mm spot size and 30 mm/s scanning speed. The interval/spacing between two scans was 0.5 mm. The laser re-melted surface was fine-polished by several microns to get a clean and flat surface, and the sample was back-thinned to 0.55 mm to ensure laser re-solidified microstructure throughout the sample thickness.

The as-cast and laser re-melted samples were deformed through rolling at room temperature. The size of the as-cast and laser re-melted samples for cold rolling are 5 mm × 5 mm × 0.9 mm and 5 mm × 5 mm × 0.55 mm, respectively. Multi-pass was applied on as-cast and laser treated samples until the samples were fractured. The reduction per pass was ~0.02 mm. The final thickness of as-cast and laser treated samples after rolling are 0.37 mm and 0.35 mm, respectively.

2.2. Characterization of as-processed alloy

Microstructure characterizations were performed on Helios 650 Nanolab SEM, JEOL 3011 and JEOL 3100R05 Double Cs-Corrected high-resolution (HR) TEM/scanning TEM (STEM). Electron transparent TEM foils were prepared using focused ion beam (FIB) milling with a final voltage of 2.0 KeV and beam current of 23 pA in FEI Helios 650 Nanolab SEM/FIB.

The microstructures of the as-cast and laser re-melted materials shown in Figs. 1 a and b reveal that these alloys comprise lamellar Al–Al_2Cu eutectic colonies with random lamellar growth directions. The phases in the bright and dark contrasts are Al_2Cu and Al, respectively, in the backscattered electron (BSE) images. The Al and Al_2Cu layers in each colony have roughly same thickness and hold the similar orientation relationship according to EBSD and TEM [38–40]. The main differences between as-cast and laser treated materials are the colony size and lamellar thickness, ~30–50 μm and ~0.5–1 μm in as-cast material, and ~2–5 μm and ~20–150 nm in laser re-melted material.

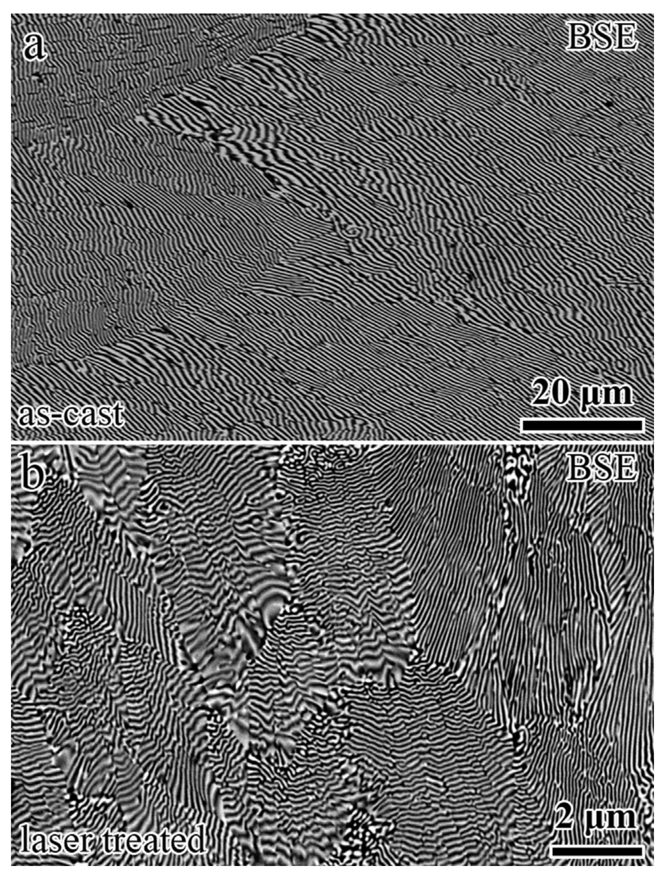

Fig. 1. The microstructures of Al–Al_2Cu lamellar eutectics. (a) As-cast material with microscale lamellae. (b) Laser treated material with nanoscale lamellae. The phases in the bright and dark contrasts are θ-Al_2Cu and α-Al, respectively.