

Article

Enhanced Tensile Plasticity in Ultrafine Lamellar Eutectic Al-Cu Based Composites with α -Al Dendrites Prepared by Progressive Solidification

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Featured Application: The developed Al-Cu ultrafine lamellar eutectic composites with excellent mechanical properties have potential widely applications in the realms of aviation, aerospace and automotive.

Abstract: In this paper, a new class of Al-Cu based composites which combine the ultrafine lamellar eutectic matrix (α -Al + θ -Al₂Cu) and micron-sized primary α -Al dendrites was prepared by progressive solidification. By adjusting the alloy composition and solidification process, the formation of favorable microstructural and micromechanical features can be achieved. The ultrafine lamellar eutectic composite Al₉₄Cu₆ exhibits excellent mechanical properties with 472 MPa fracture strength and 7.4% tensile plastic strain. The plasticity of the ultrafine lamellar eutectic composite relies on the volume fraction and work hardening ability of micron-scale primary phase. The present results provide a new perspective for improving the plasticity of the ultrafine lamellar eutectic alloys.

Keywords: ultrafine lamellar eutectic structure; composite; plasticity

1. Introduction

Bulk nanocrystalline alloys have been highlighted since the first report by Gleiter et al. [1] in the 1980s, because of their high strength and low elastic modulus in comparison with conventional coarse-polycrystalline alloys. Several synthesis methods for the bulk nanocrystalline alloys have been developed, such as powder consolidation [2], amorphous crystallization [3], severe plastic deformation [4] and electrodeposition [5–7]. However, these methods have multiple processing steps and are not easily commercially viable. Recently, some nano/ultrafine lamellar eutectic alloys have been developed just using the simple and low-cost single step casting [8–10] and have attracted much attention for both significant science and engineering interests. However, like the most bulk nano-structured alloys and bulk metallic glasses (BMGs), these nano/ultrafine lamellar eutectic alloys usually fail catastrophically at ambient temperature by the highly localized deformation behavior, which severely restricts their commercial application as structural materials.

To block the high localized shear deformation, some inhomogeneous microstructures such as the micron-scale soft and ductile dendritic phase have been introduced into the nano/ultrafine matrix [11–19]. Although these nano/ultrafine structured composites exhibited an excellent compressive plasticity, they still exhibited very limited macroscopic plasticity under tensile stress. For example [19], the compressive plasticity of the Ti-based alloys with ultrafine lamellar eutectic structure is as high as 30%, while the tensile plasticity is less than 1%. Similar to the nano/ultrafine structured composites,

the BMG composites containing in situ soft and ductile dendrites were developed in 2000, which also exhibit high compressive plasticity and very limit tensile plasticity [20]. In 2008, Hofmann et al. [21] made a breakthrough in tensile plasticity in BMG composites. They proposed two basic principles based on matching fundamental micromechanical characteristics and microstructural length scales to design the ductile BMG composites, which were: (1) introduction of 'soft' elastic/plastic inhomogeneities to initiate local shear banding; and (2) matching of microstructural length scales to the characteristic length scale R_p (plastic shielding of an opening crack tip) to suppress the instability propagation of shear bands and micro-cracks. Subsequently, numerous ductile BMG composites with large tensile plasticity were developed [22–26].

The authors proposed that these principles are applicable to the nanocrystalline and ultrafine lamellar eutectic alloys. In this study, we select the simple Al-Cu binary alloy system, which has significant scientific and commercial interests due to its high specific strength and relatively low cost. By matching the characteristics of the in situ ductile dendrites, including size, volume fraction and hardness, the bulk Al-Cu ultrafine lamellar eutectic composites with enhanced tensile plasticity were developed using simple casting. The effects of the microstructure and micromechanical features on the macromechanical properties of ultrafine eutectic composites are also discussed in detail. Our current findings give a new clue for developing nanoscale or ultrafine-grained composites with excellent mechanical properties.

2. Experimental Procedures

The master alloys of $\text{Al}_{83}\text{Cu}_{17}$, $\text{Al}_{90}\text{Cu}_{10}$ and $\text{Al}_{94}\text{Cu}_6$ (at. %) were prepared from the Al and Cu pieces with industrial purities of 99.2 (wt. %) by arc-melting. The master alloys were then cast into Cu molds to form the rod-shaped samples with 7 mm diameter. To minimize the cast flaws, these rods were remelted and progressively solidified at a withdrawal velocity of 4.0 mm/s under the directional solidification device. The temperature gradient was about 17 K/mm.

X-ray diffractometry (XRD) and optical microscopy (OM) were used to observe the microstructure. The element distribution in the solidified microstructures was determined by energy dispersive X-ray spectrometer (EDS) attached to the scanning electron microscopy (SEM) JSM-6380LV (JEOL Ltd., Akishima, Tokyo and Japan). The tensile specimens with a 12.4 mm gauge length and 2.5 mm diameter were machined and tested on an Instron-8801 testing machine under quasistatic loading at an initial engineering strain rate of $5 \times 10^{-4} \cdot \text{s}^{-1}$. A CSM-NHT2 (CSM Instruments, Peuseux and Switzerland) nano-indentation instrument was applied to investigate the hardness and elastic modulus (E) of composites. The nano-indentation tests were loaded to 50 mN and kept for 10 s. Each sample was measured at least five times to ensure that the results are reproducible and statistically meaningful. The fracture surfaces were carefully observed through SEM.

3. Results and Discussion

The XRD patterns and optical microscopies of the alloys are presented in Figure 1. As shown in Figure 1a, the three alloys show very similar diffraction patterns, indicating that all the alloys are composed of α -Al solid solution and θ - Al_2Cu phase. However, the microstructures of alloys are obviously different. The $\text{Al}_{83}\text{Cu}_{17}$ alloy exhibits a typical ultrafine lamellar eutectic microstructure, in which the white α -Al and black θ - Al_2Cu are arranged alternately. The lamellar spacing is about 0.6 μm , as shown in Figure 1b. In a previous study, Park et al. [27] reported that the lamellar spacing was 0.2–0.3 μm for the $\text{Al}_{83}\text{Cu}_{17}$ alloy which was only for 1 mm diameter rod-shaped samples prepared by Cu mold casting. Obviously, the cooling rate in present study is much lower than previously reported. However, the increase in lamellar spacing is not very significant, only from 0.2–0.3 μm to 0.6 μm , which is very beneficial to industrial production.

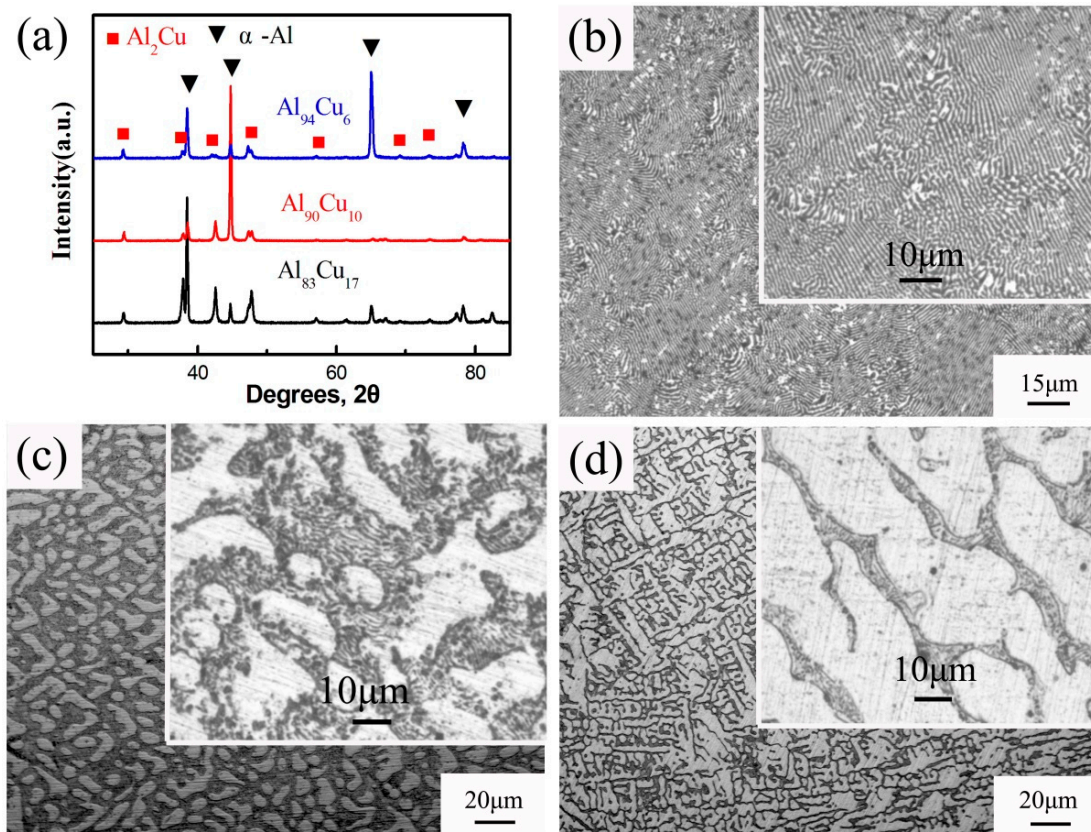


Figure 1. (a) X-ray diffractometry (XRD) patterns of alloys and their optical microscopy (OM) micrographs of the (b) Al₈₃Cu₁₇, (c) Al₉₀Cu₁₀ and (d) Al₉₄Cu₆. The up-insets in (b–d) show their magnified views of the corresponding microstructures.

The hypoeutectic Al₉₀Cu₁₀ alloy shows a typical composite structure, in which white particles are uniformly embedded in the eutectic matrix. According to the EDS analysis (see Figure 2), the primary phase is enriched in Al and can be identified as the α-Al phase with the average compositions of Al_{92.9}Cu_{7.1}. The volume fraction and average grain size of the α-Al phase in the Al₉₀Cu₁₀ alloy is about 44% and 7 μm, respectively. It is noteworthy that the eutectic matrix is still composed of the ultrafine lamellar α-Al + θ-Al₂Cu eutectic microstructure, and the lamellar spacing is similar to the Al₈₃Cu₁₇ alloy. For the Al₉₄Cu₆ alloy, the volume fraction of α-Al phase increases to 74%, and the grain morphology changes from particle to the dendrite. While the average compositions of the primary α-Al phase is Al_{97.8}Cu_{2.2} in the Al₉₄Cu₆ alloy, which obviously has a lower Cu content than that of the Al₉₀Cu₁₀ alloy.

Figure 3 presents the engineering stress-strain curves and nano-indentation load-displacement curves of the alloys. The corresponding mechanical properties are summarized in Tables 1 and 2. As shown, the Al₈₃Cu₁₇ alloy exhibits the highest hardness and tensile strength, which are 2.5 GPa and 758 MPa, respectively, because of its completely ultrafine lamellar eutectic structure. However, the Al₈₃Cu₁₇ alloy fails catastrophically without any plasticity. In the previous study [27], the Al₈₃Cu₁₇ alloy with finer lamellar spacing also fails in a brittle manner under the room compressive tests. This brittle fracture is mainly due to the lack of a work hardening mechanism, resulting in highly localized deformation.

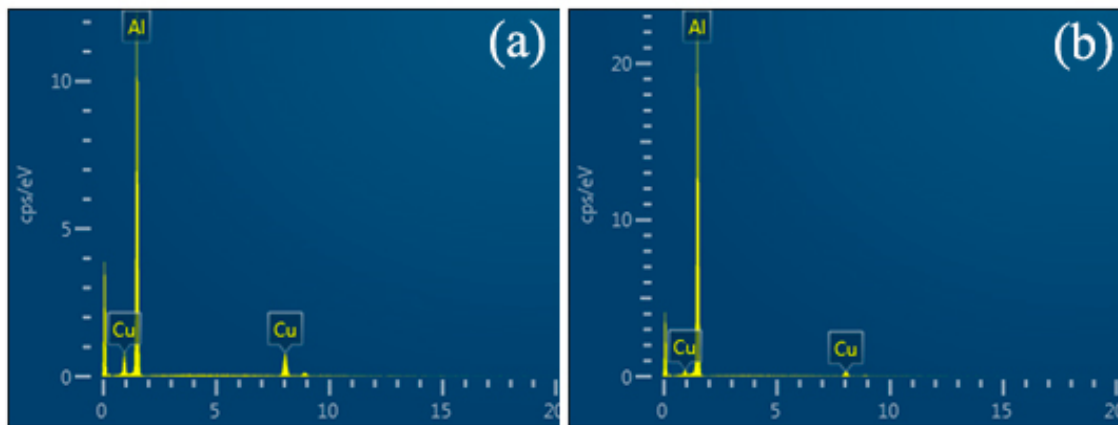


Figure 2. The SEM-EDS analysis of α -Al phase in alloys $\text{Al}_{90}\text{Cu}_{10}$ (a) and $\text{Al}_{94}\text{Cu}_6$ (b).

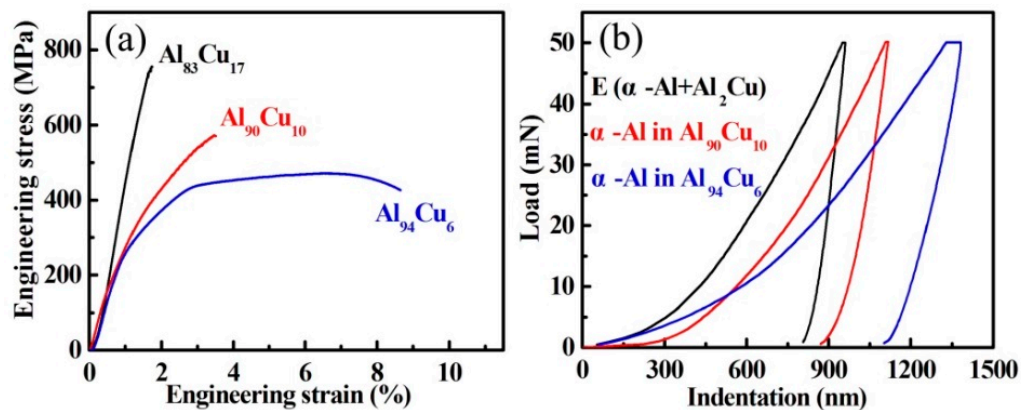


Figure 3. (a) Engineering tensile stress-strain curves of alloys, and (b) nano-indentation load-displacement curves of the ultrafine lamellar eutectic matrices and α -Al phase in alloys.

Table 1. Summary of yield strength (σ_y), tensile strength (σ_b) and tensile plastic strain (ϵ_p) of Al-based alloys.

Composition	σ_y (MPa)	σ_b (MPa)	ϵ_p (%)
$\text{Al}_{83}\text{Cu}_{17}$	-	758	-
$\text{Al}_{90}\text{Cu}_{10}$	392	571	2.0
$\text{Al}_{94}\text{Cu}_6$	306	472	7.4

Table 2. Hardness (H) and elastic modulus (E) of different structures in alloys, measured by nano-indentation.

Structure	H (GPa)	E (GPa)
Eutectic (α -Al + θ - Al_2Cu)	2.5 ± 0.2	86 ± 2
α -Al in $\text{Al}_{90}\text{Cu}_{10}$ alloy	1.8 ± 0.2	64 ± 3
α -Al in $\text{Al}_{94}\text{Cu}_6$ alloy	1.3 ± 0.2	40 ± 1

When some primary α -Al particles are precipitated on the ultrafine lamellar eutectic matrix as in the case of $\text{Al}_{90}\text{Cu}_{10}$ and $\text{Al}_{94}\text{Cu}_6$, the alloys present lower tensile strengths (Table 1). In general, like most composites, we proposed that the deformation behaviors of these ultrafine lamellar eutectic composites should follow a rule-of-mixtures relationship. According to the nano-indentation analysis, the hardness and E of the ultrafine eutectic matrix in the $\text{Al}_{90}\text{Cu}_{10}$ and $\text{Al}_{94}\text{Cu}_6$ alloys are almost the

same as that of the $\text{Al}_{83}\text{Cu}_{17}$ alloy, due to the similar compositions and lamellar spacing of ultrafine eutectic matrix in the three alloys. While the hardness and E of the α -Al phase in the $\text{Al}_{90}\text{Cu}_{10}$ and $\text{Al}_{94}\text{Cu}_6$ alloys are much lower than that of the ultrafine eutectic matrix (Table 2). Therefore, the yield strength of the ultrafine lamellar eutectic composites $\text{Al}_{90}\text{Cu}_{10}$ and $\text{Al}_{94}\text{Cu}_6$ obviously decreases with the precipitation of the α -Al phase.

As expected, the precipitated α -Al phase can enhance the ductility of alloys. The $\text{Al}_{90}\text{Cu}_{10}$ alloy exhibits obvious work hardening and 2% tensile plastic strain, while the plastic strain of the $\text{Al}_{94}\text{Cu}_6$ alloy is significantly improved to 7.4%. Obviously, the volume fraction of the primary α -Al phase has significant effects on the plasticity of the composites. For high enough volume fractions, the precipitated α -Al dendrites not only bear more deformation in themselves, but also connect with each other and form a continuous network distribution of “hand-in-hand”, which are beneficial to suppress the local instability propagation of shear bands and micro-cracks. In previous studies, Lee et al. [28] also found that there was a critical content of 40 vol% primary soft dendrites, beyond which the ductility of the La-based BMG composites escalates rapidly. Moreover, as show in Figure 3b and Table 2, the hardness and E of the α -Al phase in the $\text{Al}_{94}\text{Cu}_6$ alloy are much lower than that of the $\text{Al}_{90}\text{Cu}_{10}$ alloy, indicating it has much higher ductility and stronger work hardening ability. Under the process of deformation, the primary α -Al phase with higher work hardening ability can promote the redistribution of stress and avoid excessive stress concentration, thus delaying the plastic instability and obtaining larger plasticity. Xia et al. [29] also found that with the same α -Al volume fraction and size, the tensile plasticity of the Cu–Al alloys with bimodal structures was significantly enhanced by increasing the work hardening ability of the micron-scale primary phase. These results indicate that the microstructure (volume fraction, size and morphology) and micromechanical properties (hardness, E and work hardening ability) of the micron-scale primary phase have a significant effect on the plasticity of the ultrafine lamellar eutectic composite. More quantitative analysis and discussion on the relationships between the microstructure, micromechanical features and macroscopic properties should be further studied in the future.

Figure 4 shows the fracture surface morphologies. As shown, the macroscopic fracture surface of the $\text{Al}_{83}\text{Cu}_{17}$ alloy (inset in Figure 4a) shows cleavage-like features, and only a few main cracks penetrate the whole fracture surface, indicating a brittle fracture. The detailed microscopic observation evidently shows that the deformation of α -Al layers is accompanied with pull-out and softening, as indicated by white arrows in Figure 4a. While the θ - Al_2Cu layers fail by a predominantly faceted cleavage fracture. As shown in Figure 4b, ultrafine lamellar eutectic composite $\text{Al}_{90}\text{Cu}_{10}$ shows a complex fracture surface with many isolated dimple-like patterns and some cleavage-like features, which are fractures characteristic of the ductile α -Al and brittle ultrafine lamellar eutectic matrix, respectively. For the $\text{Al}_{94}\text{Cu}_6$ alloy, the main fracture feature is similar to the $\text{Al}_{90}\text{Cu}_{10}$ alloy, but much more dimple-like patterns connect with each other and form a continuous distribution. Moreover, an apparent necking can be observed, indicating more plastic deformation.

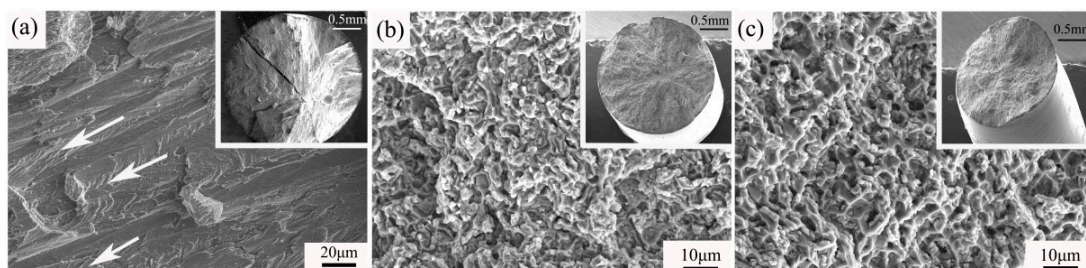


Figure 4. The microscopic fracture morphologies for alloys (a) $\text{Al}_{83}\text{Cu}_{17}$, (b) $\text{Al}_{90}\text{Cu}_{10}$ and (c) $\text{Al}_{94}\text{Cu}_6$ are shown. The insets in (a–c) show the macroscopic fracture surfaces of the corresponding alloys.

4. Conclusions

In conclusion, the ultrafine lamellar eutectic Al-Cu alloy and the composites with primary soft α -Al dendrites have been prepared by progressive solidification. Compared with the ultrafine lamellar eutectic alloy, the composites exhibit excellent mechanical properties combining high strength and large tensile plasticity. Moreover, the present results indicate that the microstructural and micromechanical features including volume fraction, distribution and hardness and E of the primary phase are very crucial to the mechanical properties of the ultrafine lamellar eutectic composites. These findings give a new clue for developing nanoscale or ultrafine-grained composites with excellent mechanical properties, especially in the binary or ternary ultrafine lamellar eutectic systems.

Author Contributions: J.C., Y.Y. and J.R.: Co-organized the work, prepared the materials, characterized the materials with OM, XRD and SEM, and wrote the manuscript draft.

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Conflicts of Interest: The authors declare no conflict of interest.

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