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Toward an understanding of post-necking behavior in ultrafine-scale Cu/Ni laminated composites

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ABSTRACT

Cu/Ni laminated composites with the same total thickness of 128 μm, but different modulation wavelength λ (the sum of monolayer thickness of constituent layers) of 32 μm and 3 μm, respectively were prepared using a dual-bath electrodeposition technique. The tensile testing results and the quantitative characterization of strain gradient in the post-necking region of the composites reveal that the $\lambda = 3$ μm composites have the higher tensile strength and the better strain hardening ability, as well as the stronger resistance to post-necking compared with the $\lambda = 32$ μm ones. A high density of layer interfaces in the ultrathin laminated composite may play a key role in delaying the development of unstable plastic deformation along the layer thickness direction through periodical strain gradient and a number of geometrically necessary dislocations near the interfaces. Thus, the fatal localized plastic deformation along the through thickness direction has to be spread over along the loading direction, leading to the large neck breadth in the ultrathin laminated composites.

1. Introduction

Metals and their alloys with both high strength and good ductility are expected as an ideal candidate for engineering structural components. Unfortunately, it is hard to balance both the strength and the ductility of the materials. Laminated composites may be a good candidate, which can integrate many advantages of the constituent layer elements and interfaces, generating excellent mechanical properties such as high strength [1–3], hardness [4,5], outstanding toughness [6,7] and high wear resistance [8,9] etc. In general, the strength and ductility of laminated composites were mainly related to the modulation wavelength (λ) of constituent layers, a sum of monolayer thickness of the constituent layers [7,10,11] and/or the number and properties of interfaces [12,13]. Interfaces may have an evident effect on the mechanical behavior of laminated composites. The work hardening capability of metals and their alloys is directly related to the number of mobile dislocations during plastic deformation [14]. A high work hardening capability mainly results from either stress gradient, which may help to improve the storage capacity of dislocations [15,16], or strain gradient, which is beneficial to plastic deformation by producing geometrically necessary dislocations (GNDs) [17–21].

In general, a number of investigations on mechanical behavior of metals and their alloys mainly focus on uniform plastic deformation [12,15,17], whereas experimental researches on the plastic deformation behavior after necking were not enough at present, and the investigations about the post-necking hardening behavior were mainly based on the finite element simulations [22–25] in recent years. For some metals possessing better plastic deformation capacity, a diffuse necking is usually generated after the occurrence of necking instability and a lower diffuse necking rate will obtain a better global ductility. Hart [26] investigated the diffuse necking rate first and revealed the influence of strain rate sensitivity exponent on the plastic deformation after necking. Ghosh [27,28] has ever investigated the plastic deformation behavior after necking in sheet metals and several factors influencing diffuse necking. However, the interior factors which may improve the work hardening capacity of post-necking are still not analyzed deeply. Mobile dislocations, as a direct influence factor of plastic deformation, should be taken into account and the relationships between the post-necking hardening capacity and mobile dislocations are important to be explored.

For the experimental investigations of deformation behavior and stress/strain gradients of materials, laminated composites might be a good candidate owing to their lamellar structures in which the out-of-plane strain in the multi-area near fractures of the composites can be characterized easily [15]. In this work, Cu/Ni laminated composites with $\lambda = 32$ μm and 3 μm, respectively were designed and prepared

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using the dual-bath electrodeposition technique. Post-necking deformation behavior of the laminated composites was investigated quantitatively. The mechanism on the large neck breadth in the ultra-thin laminated composites is elucidated.

2. Experimental

Two types of Cu/Ni laminated composites with λ = 32 μm and 3 μm were prepared at 50 °C using a dual-bath electrodeposition technique. The electrolyte solutions for the deposition of the Cu layers [29] and the Ni layers [30] were used following our previous reports, and the current density was 15 and 40 mA/cm^2, respectively. The different thicknesses of the individual Cu and Ni layers were obtained by changing electrodeposition time respectively. In order to obtain the freestanding laminated composites, the Ni and Cu layers were electrodeposited alternately on the pure titanium substrates owing to the poor adhesion between a Ni layer and the titanium substrate.

Dog-bone shape specimens for tensile testing were prepared using an electro-discharge machine, and dimensions of the gauge section of the specimens are 4 × 2 × 0.128 mm^3. All the specimen surfaces were electropolished using the electrolytic solution [30]. Uniaxial tensile tests were performed on the universal mechanical testing machine (Instron® E1000 Microtester) at a constant strain rate ($\dot{\varepsilon}$) of 1 × 10^{-3} s^{-1} at room temperature. The deformation and fracture behaviors of the specimens were characterized by a scanning electron microscope (SEM, LEO Supra35).

3. Results

3.1. Microstructure

SEM cross-sectional images of the λ = 32 μm and λ = 3 μm composites are shown in Fig. 1(a) and (b), respectively, where typical lamellar structures can be seen evidently. A thickness ratio of a Cu layer to a Ni layer for two types of composites is about 0.71 even if the λ value is different. Fig. 1(c) presents a close observation on the region at the Cu/Ni layer interface in the λ = 32 μm composite and a corresponding EBSD characterization. One can see that the Cu and Ni layers are mainly composed of ultra-fine grains (UFGs) and parts of submicron columnar grains. It seems that the grain size distribution of the Cu and Ni layers is similar even though the grain sizes are not too homogeneous. The average grain sizes of the Cu and the Ni layers in the λ = 32 μm composite are 0.35 ± 0.16 μm and 0.37 ± 0.18 μm, respectively for the UFGs and parts of bigger columnar grain sizes are more than 2 μm. The grain size distribution is almost the same as that of the λ = 3 μm composite.

3.2. Tensile properties

Fig. 1(d) presents both tensile true stress (σ_t) versus true strain (ε_t) curves and strain hardening rate ($\Theta = \frac{d\sigma_t}{d\varepsilon_t}$) versus ε_t curves of the λ = 32 μm and λ = 3 μm specimens. The λ = 3 μm specimen exhibits a better synergy between tensile strength and ductility compared with that of the λ = 32 μm one. The yield strength and uniform elongation of the λ = 3 μm specimens are 599.75 ± 29.39 MPa and 2.86 ± 0.15%, respectively, which are higher than those of the λ = 32 μm ones, 463.79 ± 18.21 MPa and 2.38 ± 0.08%, respectively. Moreover, the λ = 3 μm specimen has a higher Θ value than that of the λ = 32 μm one. After the σ_t values and the Θ values reach the corresponding intersecting points of σ_t-ε_t curves with Θ-ε_t curves, the plastic deformation of the λ = 32 μm and λ = 3 μm specimens starts to become unstable through diffuse necking, which is corresponding to ε_t = 5.08% for the λ = 3 μm specimen, being larger than ε_t = 4.25% for the λ = 32 μm one.

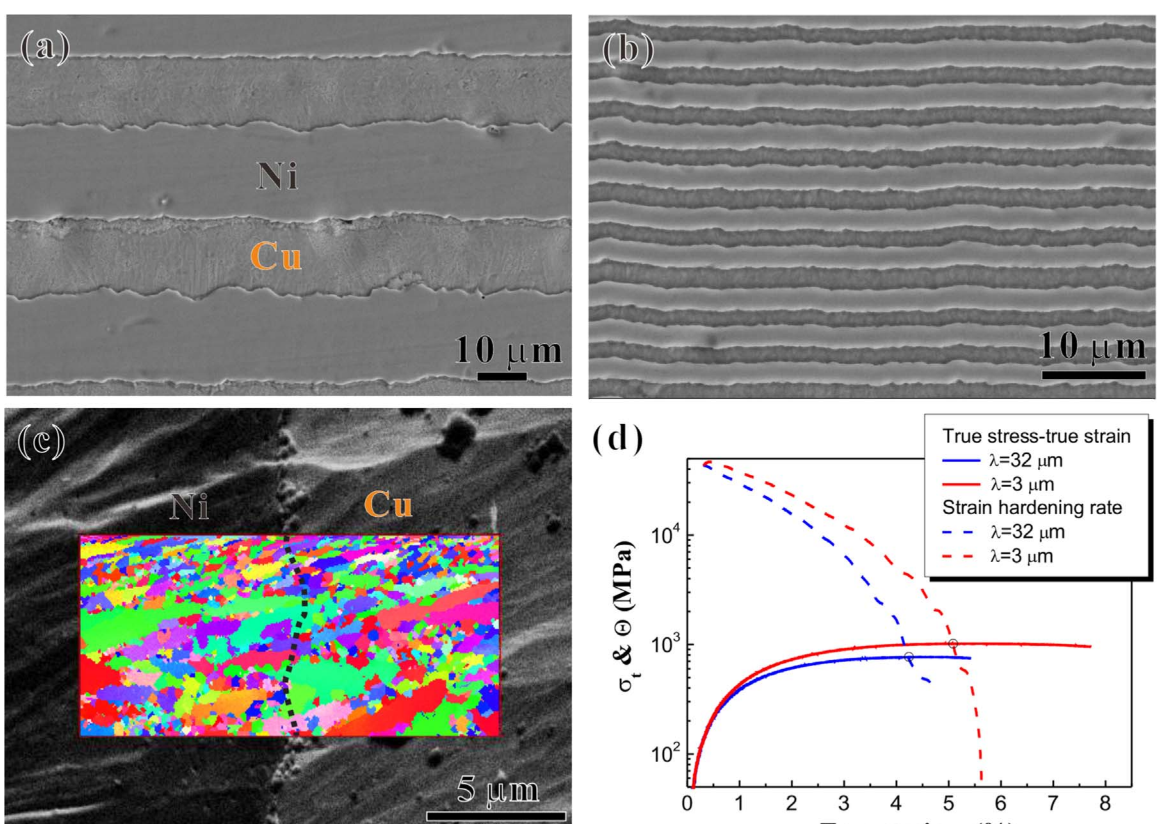

Fig. 1. SEM cross-sectional images of Cu/Ni laminated composites with (a) λ = 32 μm and (b) λ = 3 μm, (c) EBSD characterization of the Cu/Ni interface region in the λ = 32 μm composite; (d) true stress versus true strain curves and strain hardening rate versus true strain curves for the λ = 32 μm and the λ = 3 μm composites.