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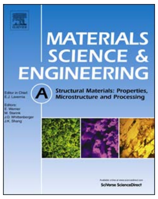

Enhancing fatigue strength of high-strength ultrafine-scale Cu/Ni laminated composites

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ABSTRACT

Fatigue strength of the Cu/Ni laminated composites with different thickness ratios of the Ni layer to the Cu layer was investigated. The result reveals that the Cu/Ni laminated composite with the thickness ratio of the Ni layer to the Cu layer of 9.0:1 not only has an ultrahigh strength (1361.80 MPa), but also is of a relatively high fatigue ratio approaching to 0.30 compared with ultrafine-grained and nanocrystalline Ni. The introduction of the ultrathin Cu layers into the ultrafine-scale Ni leads to alternate variation of local delamination and crack deflection crossing the layers in the Cu/Ni laminated composites subjected to fatigue loading, maximizing the cracking resistances in spatial directions.

1. Introduction

Fatigue limit of a metal usually can be enhanced by raising of the ultimate tensile strength (UTS) either by chemical composition of an alloy or by heat treatment/mechanical processing, which essentially increases the hardness. Generally, there is the proportionality between fatigue limit and UTS, following the fatigue limit is about 0.5 times of UTS for steels, cast iron and Ti alloys, but about 0.35 times of UTS for Al alloys [1]. Metals with ultrafine length scales, such as some ultrafine-grained (UFG) metals prepared by severe plastic deformation technique [2–4] and thin metal films prepared by physical vapor deposition [5–8], have exhibited high tensile strength and good fatigue properties compared with their coarse-grained counterparts. The origin for such high fatigue strength of the metals may result from the suppression of fatigue extrusions/intrusions by small length scales (grain size or microstructural scale), leading to the difficulty in fatigue crack initiation [9–11]. However, for ultrahigh strength steels or some nanocrystalline metals, the fatigue limit could not always increase simultaneously with UTS, and even become degraded as the length scale decreases down to ultrafine scales [12–14]. The main cause is that the ultrahigh strength metals are likely to become more sensitive to flaws and defects in the metals, leading to catastrophic propagation of the crack once a microcrack initiates from the flaws [15]. A key question is whether we can have a strategy to further enhance the fatigue strength in the regime of ultrahigh strength, such as for nanocrystalline and UFG metals.

Taking UFG Ni as a model material, here we report a new method to resist catastrophic propagation of the fatigue crack in the ultrahigh-strength UFG Ni. We found that the introduction of the ultrathin Cu layers in the ultrafine-scale Ni leads to alternate variation of local delamination and crack deflection crossing the layers in the Cu/Ni laminated composites subjected to fatigue loading, maximizing fatigue cracking resistances in spatial directions.

2. Experimental

Cu/Ni laminated composites were prepared using dual-bath electrodeposition technique at 50 °C. Ni and Cu layers were deposited on a Ti substrate alternately. The electrolyte of Ni consisted of 15 g/L H_3BO_3, 15 g/L NH_4CL, 150 g/L $NiSO_4{\cdot}6H_2O$ and 0.1 g/L sodium dodecyl sulfate (SDS) in deionized water, while the electrolyte of Cu was composed of 150 g/L $CuSO_4$, 40 g/L H_2SO_4, 0.08 g/L NaCl and 0.05 g/L polyethylene glycol (PEG) − 6000 in deionized water. The Ni layers were electrodeposited by the direct current with a current density of 0.03 A/cm^2, and the Cu layers were electrodeposited by the pulsed current with a current density of 0.015 A/cm^2. In all composites, the Ni layer thickness was kept constant using the deposition time of 120 s, while the Cu layer thickness was changed using different deposition times of 5, 30, 60 and 120 s. Thus, the as-deposited laminated

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composites had four different thickness ratios ($r_{Ni:Cu}$) of the Ni layer to the Cu layer. After the deposition, the freestanding laminated composites were removed from the Ti substrates due to the poor adhesion between the Ni layer and the Ti substrate.

Dog-bone shape tensile and fatigue specimens with gauge dimensions of 8 × 3 mm^2 and 4 × 2 mm^2, respectively were machined by electro-discharge method. Tensile tests were conducted on an electronic universal testing machine (Instron 5848) at a strain rate of 1×10^{-3} s^{-1} at room temperature. The tensile strain was measured using a non-contact laser extensometer (MTS LX 300). Fatigue tests were performed using an Instron E1000 testing machine under tension-tension cyclic loading with a stress ratio of 0.1 and a frequency of 30 Hz at room temperature. The in-plane grain size of the Ni layers in the composite was characterized by a transmission electron microscope (TEM, Tecnai G2 F20). A plan-view TEM sample was thinned by a twin-jet polishing machine. The electrochemical double spray solution for Ni was composed of 10% $HClO_4$ (perchloric acid) and 90% C_2H_5OH (alcohol). The cross-section morphologies and fracture surfaces of Cu/Ni laminated composites were examined using field-emission high resolution scanning electron microscope (SEM, LEO Supra 35) and laser scanning confocal microscope (LSCM, OLS4000).

3. Results

3.1. Microstructures

Table 1
Thicknesses of Ni and Cu layers in the laminated composite and tensile properties of the composites.

Ni layer thickness t_{Ni} (nm)	Cu layer thickness t_{Cu} (nm)	Thickness ratio $r_{Ni:Cu} = t_{Ni}:t_{Cu}$	UTS (MPa)	EF (%)
1400	~ 30	47.0:1	1270.9	3.8
1400	~ 155	9.0:1	1361.8	3.4
1400	~ 310	4.5:1	1358.5	2.3
1400	~ 645	2.2:1	971.3	4.1

Fig. 1(a)–(d) present SEM cross-sectional views of the as-prepared composites with four different $r_{Ni:Cu}$. Based on the images, the individual Ni layer thickness (t_{Ni}), Cu layer thickness (t_{Cu}) and $r_{Ni:Cu}$ of the laminated composites were characterized and presented in Table 1. t_{Ni} is kept as a constant value of 1400 nm, while t_{Cu} is in a range from 30 to 645 nm, generating four kinds of the composites with $r_{Ni:Cu}$ = 47.0:1, 9.0:1, 4.5:1 and 2.2:1, respectively. It is worth noting that as the deposition time was 5 s, the Cu layers with $t_{Cu} \approx 30$ nm in the $r_{Ni:Cu}$ = 47.0:1 composite became discontinuous, as shown in Fig. 1(a) and (e) for a TEM cross-sectional view. Owing to the formation of the discontinuous Cu layer, some Ni grains have continuously grown into the Cu layer, becoming large columnar grains. A TEM plan-view of the Ni layer in the composite indicates that the mean grain size is 395.63 ± 202.84 nm, as shown in Fig. 1(f). Since the Cu layer is too thin to prepare a TEM plan-view, the in-plan grain size of the individual Cu sheets (~ 50 μm-thick) electrodeposited at the same condition was determined to be 2.56 μm [16]. We expect that the grains in the Cu layers with a thickness ranging from 30 to 645 nm in the present composites may be finer than that of the pure Cu sheets.

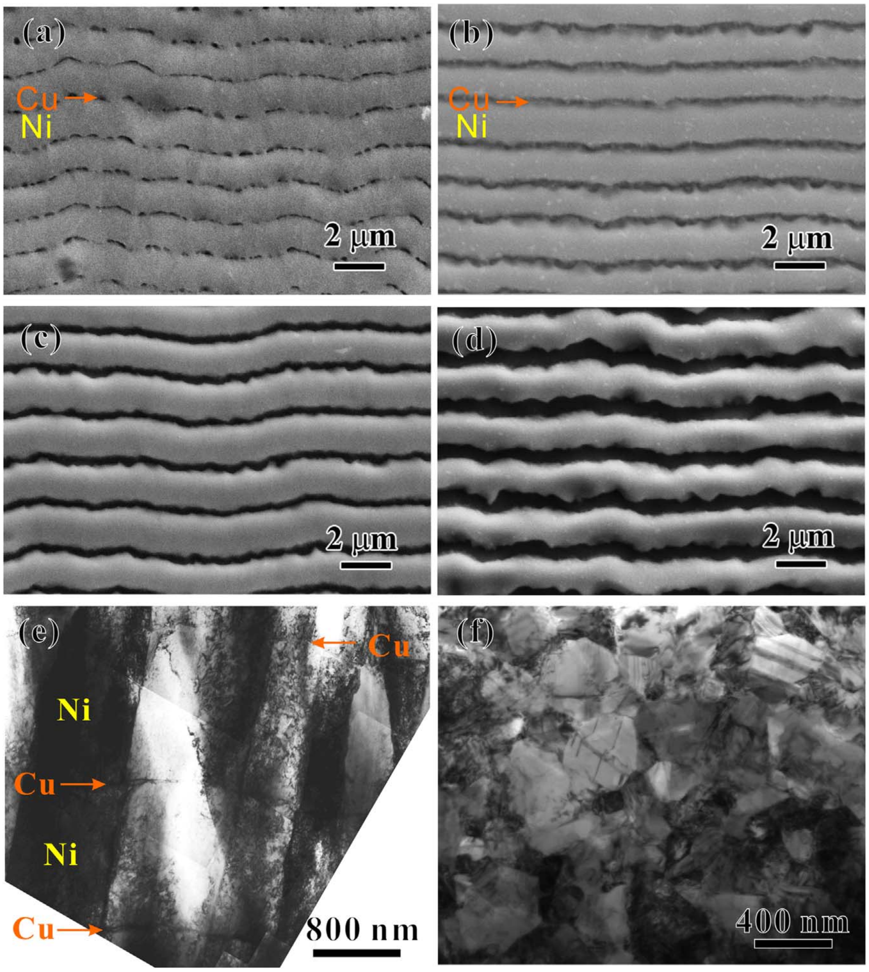

Fig. 1. SEM cross-sectional images of laminated structure in the composite with (a) $r_{Ni:Cu}$ = 47.0:1 (discontinuous Cu layers), (b) $r_{Ni:Cu}$ = 9.0:1, (c) $r_{Ni:Cu}$ = 4.5:1 and (d) $r_{Ni:Cu}$ = 2.2:1, respectively. (e) TEM cross-sectional view of the $r_{Ni:Cu}$ = 47.0:1 composite and (f) TEM plan-view of the $r_{Ni:Cu}$ = 9.0:1 composite.