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Deformation Response of Bimodal Nanoscale Metallic Multilayers

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Sputter deposited, self-supported Cu-Nb multilayered foils were room temperature rolled to study the effect of nanostructuring on the deformation and fracture behavior at large plastic strains. At layer thickness of a few tens of nanometers, with as-deposited yield strengths exceeding 1 GPa, Cu-Nb multilayers exhibited extraordinary plastic stability undergoing uniform reduction in layer thickness of both Cu and Nb to high levels of plastic strain [1]. However, at layer thickness of a few nanometers, with as-deposited yield strengths exceeding 2 GPa, fracture by shear localization was observed at rolling reductions of only a few percent [2]. In this investigation, deformation response of bimodal multilayers is characterized. A multilayered stack of 40 nm Cu /40 nm Nb /4 nm Cu /4 nm Nb layers was repeated 175 times during sputter deposition to produce 15.4 μm thick coatings that were peeled off from the glass substrates, sandwiched between stainless steel sheets and rolled at room temperature. In the as-deposited state, the foils exhibited a textured, nanocrystalline structure (Fig. 1a) with Kurdjumov-Sachs orientation relationship: {110}Nb // {111}Cu and <111>Nb // <110>Cu (Fig. 1b). Unlike the 4 nm Cu /4 nm Nb multilayers that developed through thickness cracks in the first rolling pass of ≈ 5% reduction strain, the 40 nm Cu /40 nm Nb /4 nm Cu /4 nm Nb bimodal multilayers exhibited no shear cracks after 20% reduction in rolling.

Bright field (BF) transmission electron microscopy (TEM) image of the rolled bimodal multilayer (Fig. 2a) shows uniform reduction in layer thickness with no dislocation cell structure formation that was previously reported in Cu-Nb multilayers with micrometer-scale layers [2]. Thus, deformation mechanisms in nanolayered composites are such that dislocation cell structures do not form. Furthermore, diffraction patterns (Fig. 2b) indicate that the initial texture is preserved. Fig. 2a also shows that the 4 nm Cu and Nb layers co-deform with the 40 nm layers, i.e., no clear evidence of decohesion or shear cracking was observed. However, from the bright field images it is not clear if the 4 nm layers still have chemically sharp layers after rolling. Energy dispersive spectroscopy (EDS) line scan in a TEM with ≈ 1 nm probe size (Fig. 3) clearly shows the chemically discrete layers. High-resolution TEM image (Fig. 4) of the rolled material indicates crystalline layers supporting the EDS data that indicated no significant intermixing of the immiscible Cu and Nb layers across the interface. Some grains in Cu layers showed nanoscale twinning (Fig. 5) in the rolled sample. However, such twinning was also observed in the as-deposited samples and is likely to be growth-induced. In summary, this work highlights the unique deformation characteristics of nanolayered metals: uniform reduction in layer thickness to large plastic strains with no cell structure formation and no change in out-of-plane initial texture, and the stable co-deformation of layers as thin as 4 nm when constrained with relatively thicker 40 nm layers. Bimodal nanoscale multilayers may offer the best combination of high strength and plastic deformability in nanolayered systems.

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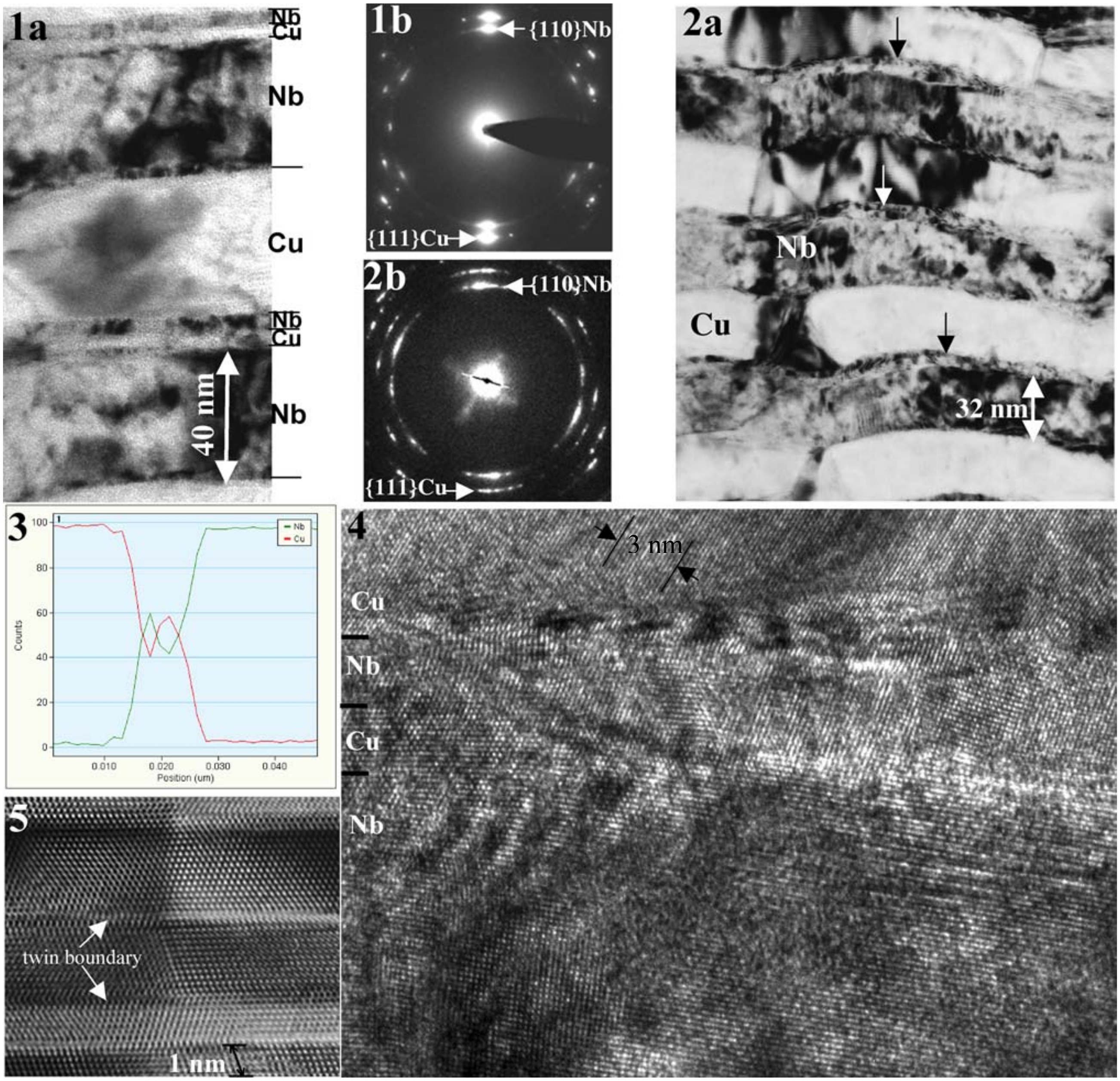

Fig. 1 (a) BF TEM image and (b) corresponding selected area diffraction pattern (SADP) of a sputter-deposited 40 nm Cu /40 nm Nb /4 nm Cu /4 nm Nb multilayer.

Fig. 2 (a) BF TEM image and (b) corresponding SADP of a 40 nm Cu /40 nm Nb /4 nm Cu /4 nm Nb multi-layers rolled to ≈ 20% reduction. Arrows indicate the location of the 4 nm layers.

Fig. 3 EDS line scale, with a nanometer probe size, from the rolled sample.

Fig. 4 HRTEM image showing crystalline layers and co-deformation of the 4 nm layers with the 40 nm layers after rolling.

Fig. 5 HRTEM image of growth-induced nanoscale twins in the Cu layer.

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