Probing Nanoscale Composites, Interfaces, and Damage Gradients with In-situ and Ex-situ Multiscale Mechanical Methodologies

N.A. Mara*

* Center for Integrated Nanotechnologies and the LANL Institute for Materials Science, Los Alamos National Laboratory, Los Alamos, NM 87545, USA, namara@lanl.gov

ABSTRACT

This work reports on recent findings within the Center for Integrated Nanotechnologies that determine the effects of interfacial structures and damage gradients on mechanical response at length scales varying from nanometers to millimeters. Three focus areas are presented: 1.) Enhanced structural performance of BULK metallic layered nanocomposites processed via Severe Plastic Deformation as a function of decreasing layer thickness. 2.) In-situ TEM and SEM straining of metallic and metal-ceramic nanocomposites with enhanced toughness and 3.) High-throughput mechanical probing of nanoscale radiation damage gradients.

Keywords: Nanomechanical testing, Nanocomposites, High Strength, Accumulative Roll Bonding, In-situ TEM

1 ENHANCED STRUCTURAL PERFORMANCE OF BULK METALLIC NANOLAYERED COMPOSITES

In bulk multi-phase composite metals containing an unusually high density of heterophase interfaces, the bi-metal interface controls all defect-related processes. Quite unconventionally, the constituent phases play only a secondary role. With the 'right' characteristics, these bi-material interfaces can possess significantly enhanced abilities to absorb and eliminate defects. Through their unparalleled ability to mitigate damage accumulation induced under severe loading and/or severe environments (such as elevated stress, high strain rate, high temperature, and radiation environments), they will provide their parent composite with a highly effective healing mechanism and

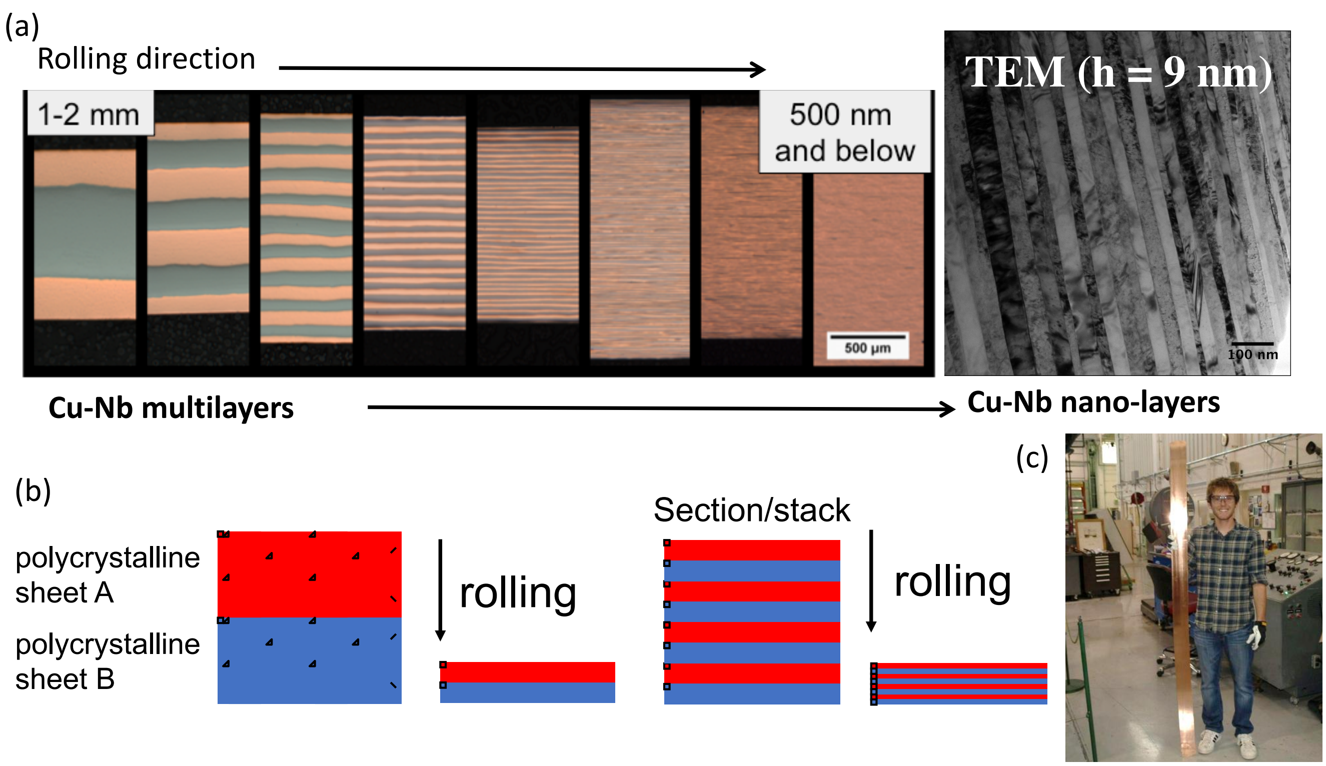


Figure 1: (a) Optical and TEM micrographs showing lamellar structure of bulk Cu/Nb composites with individual layer thicknesses ranging from millimeters to nanometers. (b) Schematic of the Accumulative Roll Bonding (ARB) process used to fabricate the composites in (a). (c) Photograph of student holding a sheet of ARB processed bulk composite material.

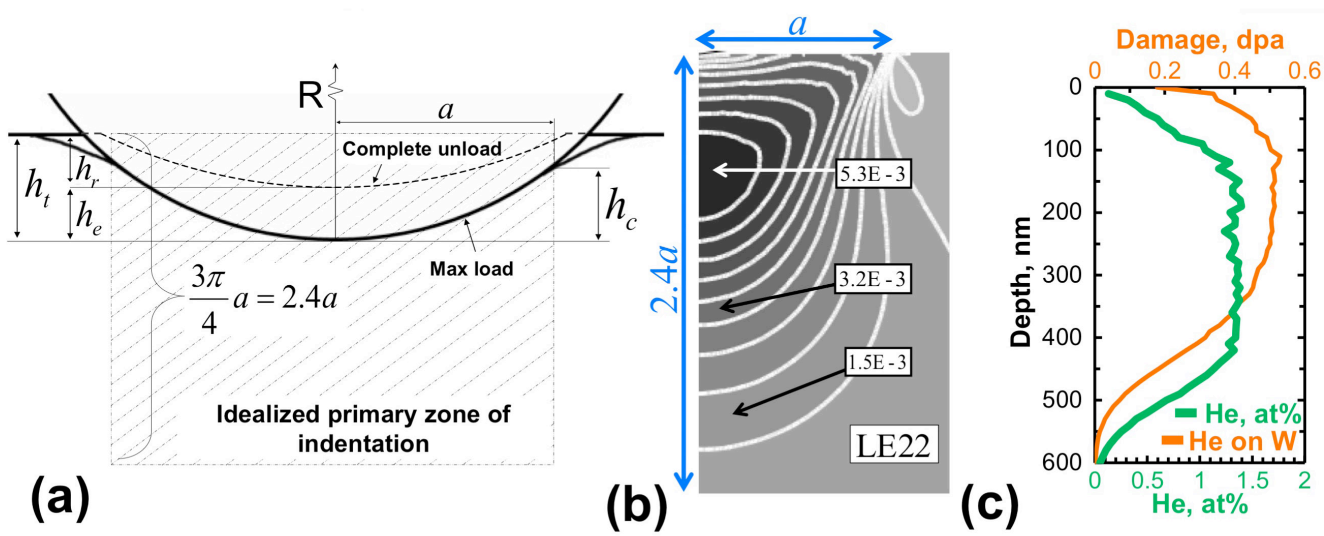
consequently a robustness not possible in existing advanced structural materials. Bulk (> cm^3) laminar composites with controllable layer thicknesses down to the submicron or nano-scale range can be fabricated via accumulative roll bonding (ARB), a severe plastic deformation (SPD) processing technique. The ARB process itself is an extreme condition. Imposing over thousands of percent strain, ARB refines the microstructure of ordinary coarse-grained composite metals down to submicron and nanoscales. ARB is an ideal model material processing technique for three reasons: a) it produces a 2-D layered microstructure, b) it imposes monotonic deformation in a familiar manner (rolling), and c) it allows for controllable accumulated strain and layer thickness (from 1 mm to 10 nm). Figure 1 demonstrates the nanolayered microstructure of these composites, which can be manufactured in kilogram quantities of sheet material. [1-3]

2 IN-SITU TEM AND SEM STRAINING OF METALLIC AND METAL-CERAMIC COMPOSITES

When layer thicknesses in nanocomposites drop below 10nm, materials with limited room temperature ductility and toughness such as ceramics and Magnesium can take on new interface-dominated properties including enhanced deformability to large strains. In Al-TiN nanolaminates with layer thickness 5 nm and below, cracking in ceramic TiN was suppressed with codeformation evident in both layers. In-situ TEM straining demonstrates a profound size effect in enhancing plastic co-deformability in nanoscale metal-ceramic multilayers, as well as direct validation of ex-situ and 3-D elastic-plastic deformation models. [4, 5]

3 HIGH-THROUGHPUT MECHANICAL PROBING OF NANOSCALE RADIATION DAMAGE GRADIENTS

We discuss applications of spherical nanoindentation stress-strain curves in characterizing the local mechanical behavior of materials with modified surfaces (See Figure 2). Using ion-irradiation on tungsten as a specific example, we show that a simple variation of the indenter size (radius) can identify the depth of the radiation-induced-damage



(d)

Indenter radius, R	Indentation depth, h_t	Contact radius, a	Indentation zone ~2.4a
1 μm	~10 nm	60 nm	144 nm
10 μm	~20 nm	250 nm	600 nm
100 μm	~40 nm	1,200 nm	2,880 nm
1000 μm *	>200 nm	12,800 nm	30,720nm

Figure 2: (a) Schematic of spherical indentation showing the idealized primary zone of indentation. (b) Logarithmic strain field (along the indentation direction) for a spherical indenter in the indentation zone (~2.4a, where a is the contact radius) close to the indentation yield. The contact radius a, and the volume probed by indentation, can be controlled by chosen indenter radius. This approach is thus ideally suited for probing the (c) damage caused by He irradiation on a tungsten sample. (d) Table showing indentation depth (h_t), contact radius (a) and indentation zone size (~2.4a) at yield for W using 4 different indenter radii.

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zone, as well as quantify the behavior of the damaged zone itself. Using corresponding local structure information from electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) we look at (a) the elastic response, elasto-plastic transition, and onset of plasticity in ion-irradiated tungsten under indentation, and compare their relative mechanical behavior to the unirradiated state, (b) correlating these changes to the different grain orientations in tungsten as a function of (c) irradiation from different sources (such as He, W, and He+W). [6, 7]

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