Class 1

Deformation of Bulk Metallic Nanolaminates

Introduction: Advances in severe plastic deformation processing have enabled the production of bulk nanocrystalline metallic laminates with ultra high strengths (~1 GPa). While it has long been recognized that strength increases with decreasing grain size, the deformation behavior of these materials has not previously been explored.

Bulk nanolaminates consisting of alternating layers of copper and niobium were synthesized using accumulative roll bonding (see Processing). Uniaxial layer-parallel compression tests were conducted using specimens with nominal layer thicknesses of 65, 30, and 15 nm. During deformation, bands of localized strain were observed, yet surprisingly these localizations did not lead to a loss of load carrying capacity.

Objectives: 1) Determine an effective imaging technique to reveal the deformation bands
2) Determine how the deformation bands affect the lamellar structure

Processing: Accumulative roll bonding (ARB) is an industrially scalable process that can create b... laminates consisting of alternating layers of immiscible metals (such as copper and niobium). T... iterative sequence of cleaning, stacking, roll-bonding, and cutting to create and refine the layere... **1 and 2**) while maintaining a near constant sheet thickness.

Fig. 1: Cross-sections of Cu-Nb laminates during ARB processing. LOM, BF illumination

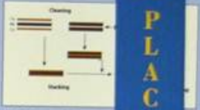

Fig 2: Schematic of the ARB proce...

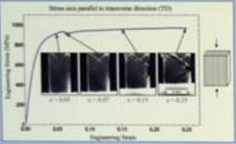

Fig. 3: Stress strain curve and images from in situ video recording for 65 nm layer thickness specimen compressed parallel to layers.

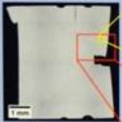

Fig 4: Post-test cross section of 65 nm Cu-Nb compression specimen. BF LOM, stitched.

Fig 5: Sub-region of Fig. 4 imaged using backscatter SEM.

Fig 6: Sub-region of Fig. 4 imaged using LOM C-DIC. Kink bands are revealed clearly.

Deformation Bands: The localized deformation and pronounced shape change during compression... 65 nm specimen in **Figure 3**. The dark bands evident during in situ imaging do not corresp... demonstrated using brightfield (BF) light optical microscopy (LOM) in **Figure 4**. Instead, these band... which the lamellar structure remains continuous and has been uniformly sheared and rotated (**Figures 5 and 6**). While backscatter scanning electron microscopy (SEM) produces excellent high magnification images, the low magnification SEM images needed to study large kink bands and groups of kink bands lack sufficient contrast (**see Figure 7a**). Successful imaging at both low and intermediate magnifications was obtained using LOM and either circular differential interference contrast (C-DIC) (**Figure 6**) or cross polarized light (**Figure 7b**). This unexpected result shows that, despite the cubic crystal structures, the nanostructured samples interact with polarized light.

Figures 8 and 9 show a region from the 15 nm compression specimen imaged using brightfield and cross polarized light respectively. A comparison of the two images demonstrates the importance of polarized LOM for revealing the complex networks of kink bands that form in these specimens. With kink bands revealed, the origins of surface ledges and protrusions becomes clear (**Figure 10**).

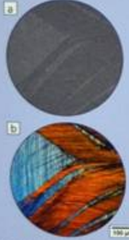

Fig. 7: Kink bands in a 65 nm Cu-Nb compression specimen imaged using (a) scanning electron microscopy and (b) polarized light microscopy. Note the very fine kink bands seen in (b) are not shown clearly in (a).

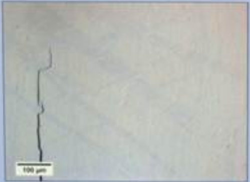

Fig. 8: Brightfield image of kink bands in the 15 nm Cu-Nb compression specimen. Delamination crack is evident, but kink bands are hard to distinguish.

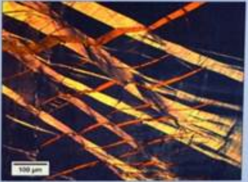

Fig. 9: Same field of view as Fig. 8 but imaged using cross polarized light. Excellent band contrast reveals the presence of small kink bands not evident in Fig. 8.

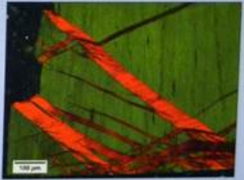

Fig. 10: Kink bands in the 15 nm specimen result in dramatic surface protrusions near the corner of the sample. Cross polarized LOM.

Conclusions: Cu-Nb nanolaminates form kink bands when compressed parallel to the layers. These bands allow for large local deformations without leading to crack formation and can form complex networks of localized strain.

Due the strong interaction with polarized light that occurs when the layer thickness is less than ~200 nm, these kink bands can be effectively studied using polarized light microscopy. Thus polarized light provides useful information about nanoscale microstructure while retaining the large field of view (>1 mm) of conventional light optical microscopy.

Metallographic Preparation

- Grinding: 240 - 1200 grit SiC
- Polishing: 3 µm diamond suspension on Buehler ...™ cloth
- Vibratory polishing: ... µm ... followed by ... µm colloidal ... on Buehler ...™ cloth

All samples viewed in the as-polished condition

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