

## Co-deformation of crystalline-amorphous nanolaminates

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Deformation of ductile crystalline-amorphous nanolaminates is not clearly understood due to the complex interplay of interface mechanics, shear banding and deformation-driven chemical mixing. In this work, we synthesized and indented model nanolaminates consisting of nanocrystalline Cu and amorphous CuZr (Fig1a-c). In order to study both, nanostructural and atomic-scale chemical deformation effects at the same specimen position we performed a joint analysis by transmission electron microscopy (TEM) and Atom Probe Tomography (APT).

For the correlative TEM-APT analysis, tip-shaped specimens containing deformation shear bands were prepared by site-specific preparation, mounted onto an electro-polished bisected TEM Cu grid, and thinned by annular FIB milling. APT was performed with a local electrode atom probe (LEAP 3000X HR). Samples were analyzed at a base temperature of 60 K, applying 532 nm wavelength 10 ps laser pulses of 0.4 nJ with at a repetition rate of 250 kHz. The datasets were reconstructed and analyzed using the software IVAS 3.6.6 (CAMECA Instruments).

Fig. 1 reveal zones with a large and very sharp, abruptly sheared Cu layer offset >30nm. The layer is not completely disconnected from the sheared region though. Instead, it is heavily deformed at a 70.5° tilt angle to the interface plane, which corresponds to the angle of the {111} planes in fcc Cu. In the shear band region, the Cu layers are subjected to a huge true shear strain of  $4.0 \pm 0.2$ , as calculated from the Cu layer displacement. The observations indicate dislocation slip on {111} planes in the Cu layer. The large displacement (>30nm) of the sheared and hence fragmented Cu layer shown in Fig. 1e suggests that large numbers of Cu dislocations accommodate the shear inside the crystalline phase, extending it across the Cu/CuZr interface into the initially amorphous layer.

We have probed several compositional profiles across the Cu enriched region inside the shear band using small sampling volumes (size:  $5 \times 5 \times 15 \text{ nm}^3$ ). This analysis reveals that deformation-induced mixing in the sheared regions of the Cu layer is caused by the shear band running through it: In this mixing zone the Cu concentration varies from 64.6 at.% to 95.4 at.% within a narrow shear layer thickness range of only 2~3 nm. Regions outside of the shear band have the same interface width and chemical concentration profiles as the as-deposited layers, i.e. they do not undergo deformation-driven mixing.

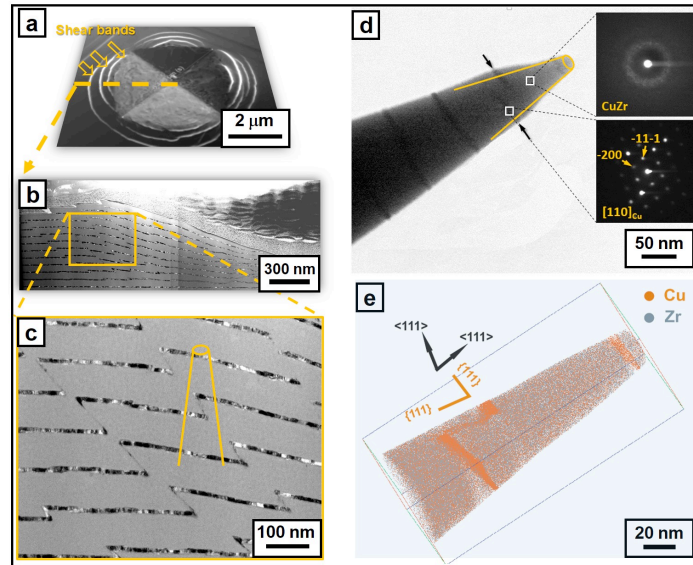
Fig. 2 shows TEM obtained from the sheared offset region of shear bands in the CuZr/Cu multilayer specimen. NBD patterns taken along the shear band penetrating the initially amorphous CuZr layer show both, an inner halo ring (amorphous material) as well as some weak discrete diffraction spots

(crystalline material) outside of the inner halo ring (see small arrows, NBD spots 3,4,6). This indicated that in the shear banded Cu-enriched zones the initially amorphous CuZr forms an amorphous plus crystalline nanocomposite.

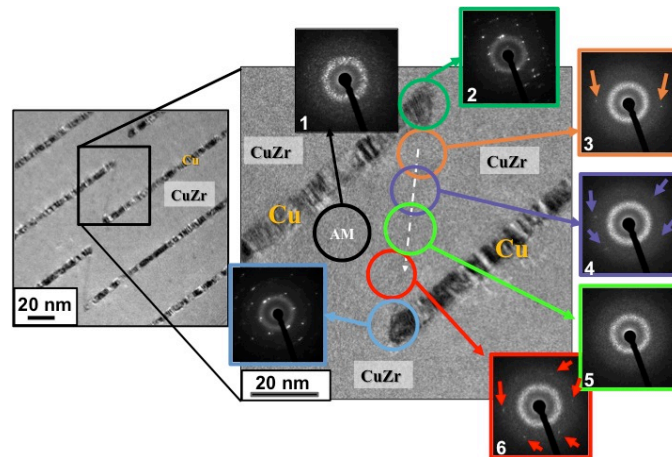
The present observation can explain several co-deformation and shear-induced mixing phenomena: (i) Local thinning of the Cu phase can be attributed to the high density of gliding dislocations. (ii) Cu atoms are dragged across the hetero-interface when dislocations release their shear step into the amorphous CuZr phase. The associated Cu enrichment can lead to local crystallization. (iii) Besides such dislocation driven solute mixing, nm-sized portions of crystalline Cu are in compact form displaced into the amorphous CuZr phase.

#### References:

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 [2] W Guo *et al*, Mater. Sci. Eng. A. **628** (2015) 269-280.  
 [3] The authors acknowledge fruitful discussions with Dr. Daniel Haley and Dr. Michael Herbig.



**Figure 1.** Correlative TEM/APT analysis of a shear band in amorphous CuZr / nanocrystalline Cu nanolaminates.



**Figure 2.** TEM observation of cross-phase shear bands in 100 nm CuZr / 10 nm Cu nanolaminates.