

Weathering the elements

As perovskites continue on their meteoric rise, several challenges remain. Foremost among them is the stability of the cells. Good solar cells need to last for decades, even as they're exposed to harsh weather conditions. But the perovskites sublime at relatively low temperatures and dissolve in water. Although the cells are sealed against rain-

fall, they can leak. That not only damages the cell but introduces toxic lead into the environment. Some researchers are looking for similarly effective materials that replace the lead with the less harmful tin.

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Nanoscale ordering from bulk processing

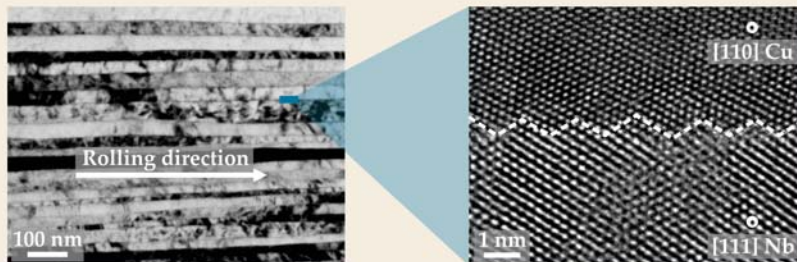
When a metal is forged, stamped, or otherwise strained, it hardens. The change in mechanical properties arises from dislocations in the crystal lattice that enable adjacent planes of atoms to slide past each other. As the metal is worked, the dislocations accommodate the strain; but in doing so, they become entangled, pile up at existing grain boundaries, and produce countless new ones that impede the dislocations' movement and make the metal harder to deform.

For decades, materials scientists have known that nanostructuring a metal—deforming it plastically until the grains shrink to submicron dimensions—can increase its yield strength by as much as an order of magnitude. But many of the newly formed interfaces are unstable: In the harsh environment of a hot jet engine, say, or an irradiating nuclear reactor, grains can grow larger or become decorated by voids due to the agglomeration of lattice vacancies. In either case, the metal loses strength.

The stability of an interface is closely tied to how ordered it is; the greater the order, the lower its formation energy. Epitaxial vapor deposition and other near-equilibrium growth techniques are known to produce nearly perfectly ordered films, layer by layer, from chemically immiscible metals. In addition to their high strength—interfaces between the different metals are even more effective obstacles to dislocation movement than are grain boundaries—such heterostructures possess extraordinary thermal stability and radiation tolerance. Unfortunately, vapor-deposition techniques are limited to thin films and coatings and are not scalable to the bulk materials used in engines, reactors, armor, and the like.

Irene Beyerlein and her colleagues at Los Alamos National Laboratory have now shown that a simple bulk processing method can produce similarly stable and ordered interfaces, provided enough strain is applied.¹ Their method could hardly be more straightforward. By subjecting an alternating stack of millimeter-thick copper and niobium sheets to a metalworking technique known as accumulative roll bonding—repeatedly rolling the sheets thin and then cutting and restacking them like croissant dough—the researchers reduced the layers of Cu and Nb to as thin as 20 nm, as shown in the figure. That's equivalent to stretching a nickel coin to a length of 2.2 km.

Astonishingly, at such enormous strain, all the bimetallic interfaces took on the same low-energy zigzag structure, with nearly defect-free layers of Cu and Nb on opposite sides. Says Beyerlein, "No materials scientist would have expected that, based on our current understanding of interface evolution." Using neutron diffraction, the researchers measured the bimetal's texture—its distribution of crystallographic orientations—after several stages of the plastic deformation. When the layers became



thinner than about 700 nm, the texture changed sharply and only one crystallographic orientation emerged from the relatively large number (roughly 25) of orientations prevalent above that thickness. The result stands in stark contrast to the several orientations that are stable in Cu or Nb when rolled alone.

Cutting open the bimetal laminate, the Los Alamos researchers examined several interfaces using transmission electron microscopy, which explicitly revealed their uniformity. The group's molecular dynamics simulations later explained it: The emergent orientation corresponds to one of the minima in the interface formation-energy landscape of the material. Only one orientation actually survives the strain of deformation because it must do more than just closely align the natural facets of the Cu and Nb planes being joined. It must also not change as the two metals rotate and stretch together along independent slip planes while being squeezed into more interfacial area.

The two stability criteria, Beyerlein argues, offer a powerful paradigm for predicting the favored interfaces that are likely to emerge in other metallic laminates besides Cu-Nb. What's more, the criteria can be applied to other strain paths—say, rolling across the layers instead of along them—and used to predict which interface emerges in response to the change and how that, in turn, influences the mechanical properties of the composite.² As she puts it, "Altering the deformation pathway can be used to tune the atomic structure of the interfaces and thus engineer different kinds of stable materials—that's where we want to take this."

So far, her group has made meter-long, millimeter-thick sheets of the Cu-Nb laminate. Characterization tests have found that the material maintains its hardness of about 4 GPa up to 500 °C; by contrast, the hardness of nanocrystalline Cu (1.8 GPa at room temperature) drops by 66% if heated so much. Also unlike Cu, the composite doesn't develop damaging voids when irradiated with ions. And it remains remarkably ductile, a property usually lost in work-hardened metals.

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