Mechanisms of Fracture and Damage-Tolerance in New Metallic Alloys*

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Two radically different approaches have *come to the fore* of late for developing unprecedented levels of damage-tolerance (toughness without compromising strength) in structural metals and alloys. The first of these involves the use of multiple principal element alloys, popularly referred to as high-entropy alloys; the second involves simple single-element metals where the desired combination of strength and toughness is created, as in Nature, by imparting gradients. Each will be described in turn.

Certain high-entropy alloys (HEAs), specifically the single-phase face-centered cubic (*fcc*) CrCoNi-based alloys, can display exceptional combinations of strength, tensile ductility and fracture toughness, properties that can be further enhanced at cryogenic temperatures. Body-centered cubic (*bcc*) refractory HEAs, conversely, can show exceptional strength and compressive ductility at elevated temperatures, but are often compromised by poor lower-temperature behavior. The damage-tolerance of the *fcc* CrCoNi-based HEAs can exhibit some of the highest fracture toughnesses on record with no loss in strength. These properties are primarily associated with the development of a synergy of deformation mechanisms – slip, stacking fault formation, twinning, transformation plasticity – which promotes prolonged strain hardening; this obviously raises the strength but also increases ductility by delaying the necking instability The presence of local short-range order has also been detected in these concentrated solid-solution alloys, which may offer a means to further enhance their structural properties.

However, despite the exceptional damage-tolerance of the *fcc* HEAs, these alloys with their multiple principal elements can be expensive. An alternative route, which in material costs would be far less costly, is to utilize simple metals and impose, by processing and thermomechanical treatments, gradients in structure, grain size, grain shape, or composition, *etc*. to create combinations of strength and toughness akin to many natural materials with their graded hierarchical structures. To date, most “man-made” examples of this have only been achieved at small (micron to sub-micron) size-scales. Nevertheless, we show here the development of centimeter-scale gradients in grain size (varying from microns to nanometers) in pure nickel where multiple combinations of high strength and high toughness (approaching that of some of the HEAs) can be realized. The material costs are lower, but the required “bottom-up” processing to create the gradients is difficult to achieve with traditional methods, particularly at bulk dimensions. However, the future development of advanced 3-D printing techniques may be able to solve this problem in order for synthetic structural materials in the future to be developed with unprecedented levels of damage-tolerance in simple inexpensive materials.

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