15th International Conference on Fracture (ICF15)
June 11-16, 2023 Atlanta, GA USA

DAMAGE-TOLERANCE IN NATURAL AND ENGINEERING MATERIALS

Robert O. Ritchie

Materials Sciences Division, Lawrence Berkeley National Laboratory,
and Department of Materials Science & Engineering, University of California Berkeley, CA 94720, USA
email: roritchie@lbl.gov

Abstract
Fracture can be considered as a mutual competition between intrinsic resistance (induced largely by plasticity) to damage processes that operate ahead of a crack tip to promote crack advance and extrinsic crack-tip shielding mechanisms that act at, or behind, the tip to locally diminish crack-tip stresses and strains. We examine here how this mechanistic interplay is utilized to derive damage-tolerance in natural materials, *e.g*., bone, teeth, skin, sea shells and fish scales, compared to engineering structural materials such as aerospace ceramic-matrix composites, nuclear graphite, and advanced metallic materials, such as metallic glasses and high-entropy alloys.

1. Introduction
The ability of a material to undergo limited deformation is a critical aspect of conferring toughness in virtually all materials as this enables the local dissipation of high stresses which would otherwise cause fracture. The mechanisms of such deformation, however, can be diverse. Although plasticity from dislocation motion in crystalline materials is most documented, inelastic deformation can also occur via *in situ* phase transformations in certain metals and ceramics, sliding of mineralized collagen fibrils in tooth dentin and bone, rotation of such fibrils in skin, frictional motion between mineral "platelets" in seashells, and even by mechanisms that also lead to fracture such as shear banding in glasses and microcracking in geological materials and bone. Resistance to fracture, *i.e*., the toughness, is thus a compromise - a combination of two, often mutually exclusive, properties of strength and deformability, that lie between the two extremes of brittle fracture associated with atomic bond breakage at a crack tip and ductile fracture where the crack tip blunts, for example due to the emission of dislocations. The toughness in the latter case is naturally promoted by plasticity (intrinsic toughening), whereas for brittle fracture crack-tip shielding can play a prominent role (extrinsic toughening). This paper describes how these contrasting mechanisms are involved to achieve damage-tolerance in a broad class of both biological and engineering structural materials.

2. Results
The variation in fracture toughness as a function of strength varies markedly across material glasses, as shown for polymers, ceramics, and metals, alloys and metallic glasses in the Ashby plot shown in Fig. 1.

The combination of intrinsic and extrinsic toughening is first described for natural materials, including such topics as the fracture, aging and disease of human bone, the penetration resistance and toughening of seashells and fish scales, and the remarkable tear resistance of skin. These materials tend to benefit combination of intrinsic and extrinsic toughening mechanisms generated at multiple length-scales by their often hierarchical architectures coupled with ingenious gradients in composition, microstructure and form.

We then follow this with the primarily extrinsic toughening of brittle materials, especially at ultrahigh temperatures, including the failure of ceramic-matrix composites, specifically SiC-fiber reinforced SiC for modern gas turbine propulsion units, and that of nuclear graphite for reactor environments.

We finally discuss the primarily intrinsic toughening in ductile materials, with emphasis on advanced multiple element alloys including bulk metallic glasses and medium-/high-entropy alloys, where numerous unusual mechanisms can act *in concert*, such as those induced by the presence of local short-range order. It is in these latter materials, in particular the medium- and high-entropy solid-solution alloys such as CrCoNi, that arguably the highest fracture toughnesses ever recorded can be found. The fundamental origins of the damage-tolerance of these specific materials will be described in detail.

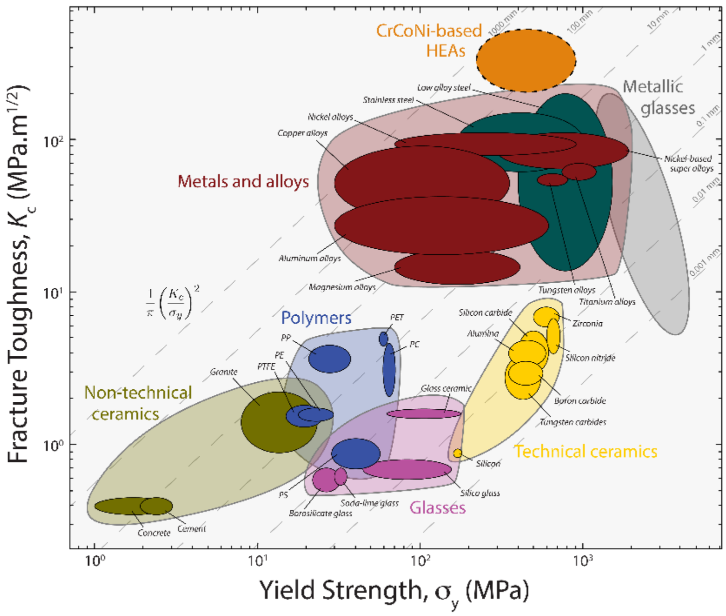

Fig.1 – Ashby map in terms of the fracture toughness, K_c, versus the yield strength, σ_y, for a broad class of materials. Note the remarkable fracture toughness of the CrCoNi-based medium- and high-entropy alloys, which appear to be the highest on record.

3. Conclusions

Designing materials with optimal damage-tolerance, *i.e.*, toughness without compromise in strength, remains a challenge, but the examples from Nature in the development of bioinspired structural materials has provided numerous fresh ideas, the relatively recent concept of high-entropy materials has resulted in the identification of ultrahigh toughness alloys, and the future prospects of metamaterials and additively manufactured materials where hierarchical structures can be artificially created, all reflect the notion that the future is bright in the continual quest for higher strength structural materials that are resistant to fracture.

Acknowledgements

The financial support of the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division under contract no. DE-AC02-05-CH11231 through the Lawrence Berkeley National Laboratory for studies on engineering materials is gratefully acknowledged. I am also grateful for the financial support of the corresponding research on natural materials which was primarily funded by a subcontract to the University of California Berkeley from the U.S. Office of Scientific Research as part of the University of California Riverside Multi-University Research Initiative under grant no. AFOSR-FA9550-15-1-0009.