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The Quest for Stronger, Tougher Materials: A Letter and a Response

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The Quest for Stronger, Tougher Materials

The perspective "Structural Nanocomposites" (Y. Dzenis, 25 January, p. 419) describes a quest for improved structural materials and indicates that composites with nanoscale reinforcements would have "exceptional mechanical properties." Is this true?

Why would reinforcements that are small in size or volume offer any particular benefit over larger-scale reinforcements? As the Perspective correctly asserts, if the composite material is to be used for a small-volume structure, clearly the reinforcements must also be small. In addition, small-volume reinforcements are stronger, as has been known since the early days of research on whiskers (*1*). In this regard, reinforcement by carbon nanotubes, for example, which are thought of as one of the strongest materials in existence (*2*), would seem ideal.

The problem with this notion is that new materials are not limited by strength, but by resistance to fracture (also known as fracture toughness). It is not by accident that most critical structures, such as bridges, ships, and nuclear pressure vessels, are manufactured from materials that are low in strength but high in toughness. Indeed, the majority of toughening mechanisms mentioned by Dzenis—i.e., crack deflection, plastic deformation, and crack bridging—are promoted by increasing, not decreasing, reinforcement dimensions [e.g., (*3*)]. Is it any surprise that "results obtained so far are disappointing"?

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Response

Ritchie's rejection of strength in favor of toughness is perfectly suitable for ceramics but can be less appropriate when applied to other materials, such as polymers or even metals. Advanced polymer composites—a class of lightweight, strong, and stiff materials based on high-performance continuous fibers—are now being used in a variety of critical applications, such as primary aerospace structures. Unlike metals, these composites do not experience large deformations before failure. Instead, a degree of toughness is provided by multiple damage and crack accumulation and deflection mechanisms, many involving strong fibers. There is high interest in further improving composites' strength and other mechanical properties, as exemplified by the continuous industrial effort to produce stronger reinforcing fibers. For some of the fibers (e.g., carbon, glass, and ceramic fibers), higher strength has been linked, among other factors, to finer fiber diameters.

From a composites perspective, it was only natural to try to use the strength of nanoscale reinforcement, such as carbon nanotubes, in a superstrong and lightweight composite. Early predictions were optimistic (*1*–*3*). However, as Ritchie correctly asserts, the question of whether nanoscale materials will be beneficial to bulk structural materials is still open to discussion. Experience with high-strength polymer composites calls for a strong interface and high volume fraction of nanoreinforcement. Research to date has not uncovered any fundamental drawbacks for achieving these, except for possible deterioration of the intrinsic carbon nanotube strength as a result of covalent bonding, as mentioned in the Perspective. The situation is more complex with regard to toughness. The benefits of larger reinforcement diameters mentioned by Ritchie may not be universal. After all, there are multiple toughening mechanisms in composites, and some of them can be expected to benefit from the enhanced strength and resilience of nanoreinforcement and/or its larger surface-tovolume ratio. There is experimental evidence of improvements in toughness of brittle materials as a result of carbon nanotube nanoreinforcement (*4*, *5*). Continuous nanofibers (*6*) are also expected to produce improvements while removing some of the problems associated with discontinuous nanomaterials. Yet, clearly more studies are needed to elucidate the fundamentals of fracture in the nanoreinforced materials, including possible limiting effects of small scale.

Finally, toughness and strength are not always mutually exclusive. True, for the intrinsically ductile materials, such as metals, improvements in strength usually come at the expense of toughness. However, for brittle materials, such as ceramics, in the presence of flaws that individually cause fracture, strength can be proportional to toughness. In the example used in the Perspective, we used nanoscale reinforcement to toughen the thin interfacial layers in advanced composites. We expect this to result in improvements in composite strength, as well as fatigue durability and impact resistance. Similar effects can be predicted for other medium-term applications described in the Perspective. We will continue to hope for a time when we can demonstrate the existence of bulk supernanocomposites (defined as nanocomposites exceeding the performance of modern advanced fiberreinforced composites).

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