## **METAMATERIALS**

## Graphene makes ceramics multifunctional

An ultralight and superelastic metamaterial is prepared by combining two brittle components, graphene and alumina, through a simple bottom-up method. As Qiangqiang Zhang, Gary J. Cheng and colleagues report in *Advanced Materials*, their graphene–ceramic composite material is not only tough, ultralight and ductile, but is also electrically conductive and thermally insulating.

Materials science is full of tradeoffs. One of the trickiest of these is that between ductility and strength. Take ceramics for example, which are generally very strong, but also dense, brittle, inelastic and have poor fatigue resistance. Reducing the density introduces another trade-off, as this generally deteriorates the mechanical properties, limiting the suitability of ceramics for ultrahighstrength-to-weight applications. Different strategies have been used to engineer ceramics and ceramic composites on the micro- and nanoscale to achieve both high strength and ductility. However, these approaches fail at low densities, are not scalable or come at the expense of desirable properties, such as thermal insulation and electrical conductivity.

To overcome ceramic brittleness while preserving high strength and good thermal properties at very low density, the researchers made a composite using graphene. This idea stems from the previous observations that graphene can improve the mechanical properties of brittle matrices and that a drastic reduction in ceramic grain size greatly enhances the strain rate. "One of the most popular approaches to improve the mechanical properties is the design and fabrication of micro- and nanoscale building blocks

arranged in an ordered hierarchy," explains Zhang. With this in mind, they adopted a bottom-up synthesis method, beginning with a large-area graphene oxide precursor that forms a graphene aerogel with shell-shaped multilayer cellular walls or 'microcells' upon hydrothermal treatment and freeze-drying. Then, using atomic layer deposition,

the ceramic precursor was deposited on these microcells. Crucially, subsequent formation of the ceramic involved chemical bonding to the graphene substrate.

The composite material displayed an impressive set of properties. With an ultralow density of just a few milligrams per cubic centimetre, it exhibited reversible compressibility, high fatigue resistance, high electrical conductivity and excellent thermal insulation, making it an attractive candidate for flame-retardant and thermally insulating coatings, as well as in sensors and as shock absorbers. These properties result from the microstructure of the material: "Attributed to shelled elastic cellular walls, designed ceramic layer (~10 nm) and the chemically bonded interface of the nanolayered alumina ceramic-graphene cellular walls, the material successfully overcomes the issue of brittleness, demonstrating improved ductility with 80% superelastic compressibility and fatigue resistance over hundreds of cycles," says Cheng.

Although the excellent properties are attributed to the microstructure of the metamaterial, a detailed mechanistic understanding is missing. "Our future work will involve studying the mechanism of the property enhancement through grain-boundary creep analysis on different length scales as we change certain features from the micro- to nanometre scale," notes Zhang. On a more practical level, Cheng's group will focus on scalable additive manufacturing of multifunctional structures, as well as controlling the microstructure design and macroscropic features to tune the material properties.

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