Nanoarchitectured interpenetrating nanocomposites offer pathway to multifunctionality

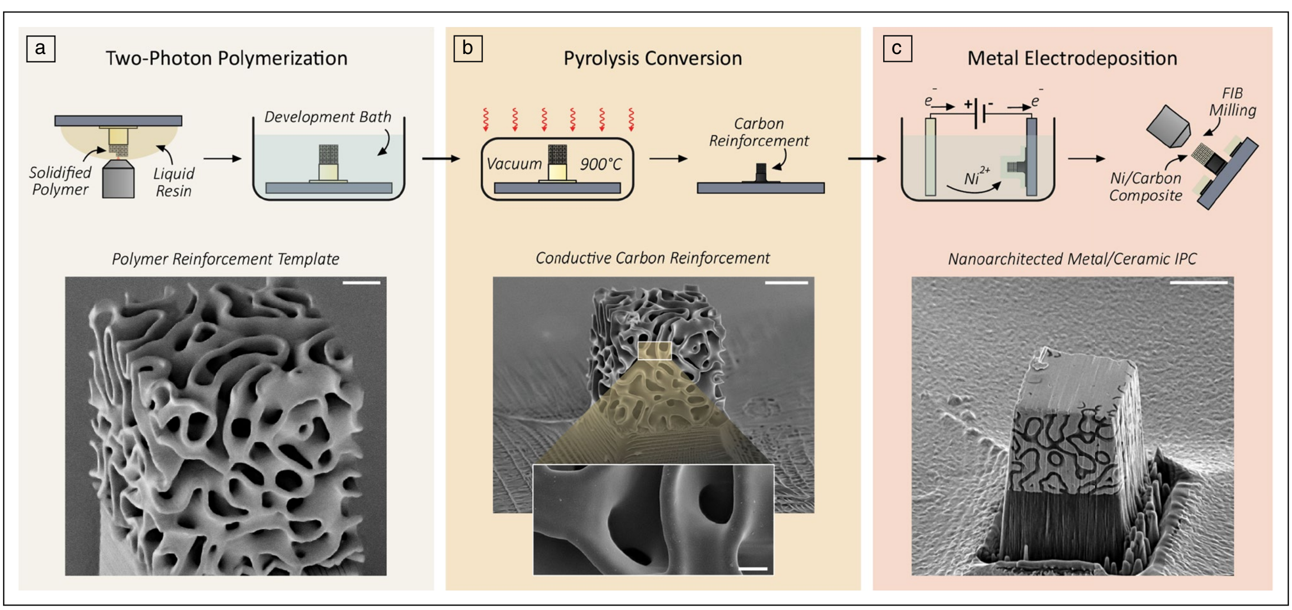
Composite materials are being used in several demanding engineering applications owing to their superior properties that derive from a synergy between the constituent materials. There exists a size effect in materials such that the smaller a material, the stronger it tends to be; designing nanoarchitectured materials takes advantage of this phenomenon. Why not explore the concept of nanoarchitecture beyond monomaterials such as metals and ceramics, to composites? This would take advantage of the size effect and the synergy among the components to create superior properties. This was a question that Lorenzo Valdevit and his research team at the University of California, Irvine, sought to answer in their recently published article in *Science Advances* (https://doi.org/10.1126/sciadv.abo3080).

"Manufacturing of dense materials at such small length scales is faced with several complexities and this has restricted the field to monomaterial cellular/porous nanoarchitectures. A suitable fabrication route is required to help exploit the potential of nanoarchitectured composites," says Valdevit. The team utilized a two-photon direct laser writing three-dimensional printing technique to create a polymeric platform, which was then pyrolyzed to obtain a carbon shell as the reinforcement phase. Nickel was electrodeposited on the surfaces of the carbon shell and this approach resulted in a near fully dense composite with two interpenetrating phases.

The researchers studied nickel/carbon interpenetrating phase composites (IPCs) with varying topologies—gyroid and spinodal surfaces. The nickel/carbon volume ratio was varied from 80/20 to 50/50, and the samples were uniaxially compressed to measure the compressive strength and strain energy absorption. The IPCs possessed a much higher compressive strength and strain energy absorption than their monolithic variants. Despite having almost 50% brittle carbon, the 52/48 gyroid IPC absorbed about five times as much strain energy as monolithic carbon and twice as much as nickel.

These values were also higher than rule-of-mixture predictions (which consider the volume ratios and individual properties of the constituents). This hints at a much more complex interaction between constituents, inherent in the interpenetrating design, which significantly inhibits crack propagation and increases the strength. These IPCs also have more isotropic properties than regular fiber-reinforced composites, as well as higher specific compressive strength and strain energy absorption (normalized by density), which makes them suitable for applications requiring high-performance, lightweight materials.

"Despite the challenges of scalability with the current fabrication technique, this work helps demonstrate how the concept of IPCs can be exploited to produce structures with significantly improved mechanical properties over their monolithic counterparts," Valdevit says. "Also, by studying both highly periodic and randomly arranged topologies (gyroid and spinodal), we demonstrate[d] that the topologies of



(a) Two-photon direct laser writing prints polymer-reinforcement templates with minimal surface topologies. (b) Accompanied by ~80% linear isotropic shrinkage, pyrolysis transforms the templates into electrically conductive carbon structures composed of 200-nm-thin shells. (c) Electrodeposition conformally grows nickel matrices into the carbon reinforcements; focused ion beam (FIB) milling removes excess metal on the specimen surface. Scale bars, 5 μm (overviews) and 500 nm [inset in (b)]. IPC, interpenetrating phase composite. Credit: *Science Advances.*

constituent phases can affect the resulting properties and should therefore be considered in designing these architectures."

"The advantage of IPCs with co-continuous structures is that the interlocking mechanism and mutual constraints between the two phases inhibit crack propagation and thus increase mechanical properties such as strength, toughness, and energy dissipation. To take advantage of these advanced composites, it is crucial that a low-cost and scalable fabrication method is sought in addition to exploring routes for increasing the functionality of these composites," says Lifeng Wang, a professor in the Department of Mechanical Engineering at Stony Brook University, The State University of New York, who was not involved in the study.

Henry Quansah Afful