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Glass Stronger than Steel

A new type of damage-tolerant metallic glass, demonstrating a strength and toughness beyond that of steel or any other known material, has been developed and tested by a collaboration of researchers from Berkeley Lab and Caltech.

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Drop a glass and it breaks, right? But there's a kind of glass that while not exactly unbreakable, can be unusually strong. It's not transparent, and it's actually made of metal, but it's a "glass" in the technical sense—that is, a solid whose underlying structure resembles that of a liquid. These so-called "metallic glasses" are among the more interesting and useful new materials devised by modern materials scientists, and they possess valuable mechanical, electrical, and magnetic properties.

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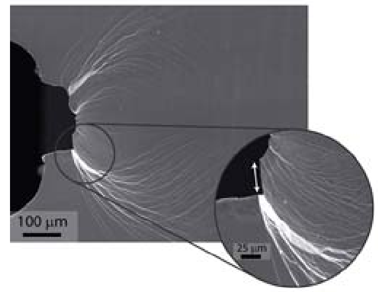

Image courtesy of R. Ritchie and M. Demetriou

Highly magnified image shows a sharp crack introduced into palladium-based metallic glass and the extensive plastic shielding, marked by the white shear lines extending out from the crack, prevent the crack from opening the glass any further. Inset is a magnified view of the shear lines (arrow) developed during plastic sliding.

Now a collaboration of researchers with the U.S. Department of Energy (DOE)'s Lawrence Berkeley National Laboratory (Berkeley Lab) and the California Institute of Technology (Caltech) has just produced a new version of metallic glass that is stronger and tougher than steel, or any other known material. What's more, even better versions of this new glass may be on the way.

Glassy materials have a non-crystalline, amorphous structure that makes them inherently strong but invariably brittle. Whereas the crystalline structure of metals can provide microstructural obstacles (inclusions, grain boundaries, etc.,) that inhibit cracks from propagating, there's nothing in the amorphous structure of a glass to stop crack propagation.

The problem is especially acute in metallic glasses, where single shear bands can form and extend throughout the material leading to catastrophic failures at vanishingly small strains. The new metallic glass is a microalloy featuring palladium, a metal that counteracts the intrinsic brittleness of glassy materials. It marks the first use of a new strategy for metallic glass fabrication that should yield even stronger and tougher glass in the future, according to Robert Ritchie, a Berkeley Lab materials scientist who led the Berkeley contribution to this research.

"In our new palladium-containing glass, the energy needed to form shear bands is much lower than the energy required to turn these shear bands into cracks," Ritchie says. "The result is that our glass undergoes extensive plasticity in response to stress, allowing it to bend rather than crack."

Ritchie, who holds joint appointments with Berkeley Lab's Materials Sciences Division and the University of California (UC) Berkeley's Materials Science and Engineering Department, knows a lot about strong and tough materials. Two years ago, he and his research group mimicked the structure of mother of pearl to create what may well be the toughest ceramic ever produced. Through the controlled freezing of suspensions in water of an aluminum oxide (alumina) and the addition of a well known polymer, polymethylmethacrylate (PMMA), they produced ceramics that are 300 times tougher than their constituent components. Prior to that, he and his group had undertaken a study to determine why the bones of elderly people are more prone to fractures than the bones of younger people.

Using state-of-the-art imaging, testing techniques, and detailed mechanical analysis, they learned that as people grow older, their bones lose their ability to resist the formation and growth of cracks that lead to breaks.

This earlier research in material strength and toughness paved the way for the investigations into metallic glass. The first metallic glass fabricated by the Berkeley-Cal Tech collaboration was dubbed "DH3."

In DH3, the propagation of cracks was blocked by the introduction of a second, crystalline phase of the metal. This crystalline phase, which took the form of dendritic patterns permeating the amorphous structure of the glass, erected microstructural barriers to prevent an opened crack from spreading. Now the collaboration has produced a pure glass material whose unique chemical composition acts to promote extensive plasticity through the formation of multiple shear bands before the bands turn into cracks.

"Our game is to try and extend this approach of inducing extensive plasticity prior to fracture to other metallic glasses through changes in composition," Ritchie says. "The addition of the palladium provides our amorphous material with an unusual capacity for extensive plastic shielding ahead of an opening crack. This promotes a fracture toughness comparable to those of the toughest materials known. The rare combination of toughness and strength, or damage tolerance, extends beyond the benchmark ranges established by the toughest and strongest materials known."

The initial samples of the new metallic glass were microalloys of palladium with phosphorous, silicon and germanium that yielded glass rods approximately one millimeter in diameter. Adding silver to the mix enabled the Cal Tech researchers to expand the thickness of the glass rods to six millimeters. The size of the metallic glass is limited by the need to rapidly cool or "quench" the liquid metals for the final amorphous structure.

"The rule of thumb is that to make a metallic glass we need to have at least five elements so that when we quench the material, it doesn't know what crystal structure to form and defaults to amorphous," Ritchie says. "Traditionally strength and toughness have been mutually exclusive properties in materials, which make these new metallic glasses so intellectually exciting. We're bucking the trend and pushing the envelope of the damage tolerance that's accessible to a structural metal."

While the most immediate applications of this new metallic glass are likely to be in the electronics industry, or in medical devices, such as orthodontics or spinal implants, Ritchie envisions a future in which metallic glass could be used in airplane engines or large structures, such as bridges. Metallic glass might eventually even be used to make stronger and tougher containment vessels for nuclear reactors that would be more resistant to catastrophic failure.

"This metallic glass is probably the best damage-tolerant material we've ever seen," he says.

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Publication

M.D.Demetriou et al. "A damage-tolerant glass," *Nature Materials* **10** 123 (2011).

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For more information on the research of William Johnson visit the Website at http://www.its.caltech.edu/~vitreloy/index.htm