Editorial

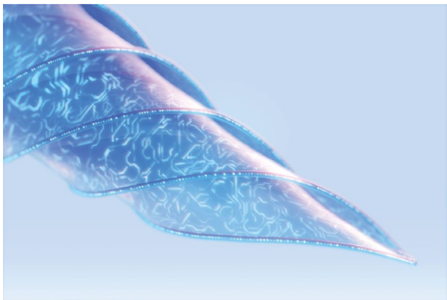
https://doi.org/10.1038/s41563-023-01686-y

Deforming brittle materials

Overcoming the intrinsic brittleness of inorganic glasses and ceramics improves structural reliability under operation, while also increasing their competitiveness for flexible devices.

Materials deform irreversibly when subject to sufficiently large loading, referred to as plastic deformation. This process involves the breaking of atomic bonds that allows a macroscopic change in the shape of the material, and the simultaneous formation of new bonds that prevent cracking. Plastic deformation can be mediated by the generation or movement of dislocations, twins, grain boundaries and shear bands as well as phase transitions, which are commonly observed in metallic materials. However, in glasses and ceramics, which have ionic or covalent bonds, much higher energies are required to break these bonds and move atoms. Hence, these materials are inherently brittle except at high temperatures. The intrinsic brittleness excludes the use of glasses and ceramics in many applications, and considerable efforts have been made to make them ductile at ambient conditions[1].

Room-temperature plasticity has been reported in a few ceramics. $SrTiO_3$ and MgO single crystals exhibit plasticity carried by dislocations[2]. Bulk layered Ag_2S and similar materials show metal-like ductility at room temperature[3], enabled by slip along certain weakly interacting planes. When reduced to the microscale or nanoscale, unusual plastic behaviour may emerge due to size effects and the elimination of unwanted defects in small samples, such as the recently discovered phase-transformation-induced plasticity of silicon nitride ceramics[4]. The plasticity in these ceramics has been demonstrated as simple tensile, compression or bending deformation. Now, in an Article in this issue of *Nature Materials*, Xiaocui Li and colleagues report that single-crystal micropillars of all-inorganic lead halide perovskites ($CsPbX_3$, X = Cl, Br or I) can substantially deform and morph into various shapes and geometries without cracking when subjected to continuous compression.



CREDIT: YUICHIRO CHINO/MOMENT/GETTY

Structural adaptation through shape morphing can endow materials with interesting functions for use in applications such as programmable actuators and robots, as well as flexible electronics and optoelectronics. Currently, materials that have intrinsic shape-morphing ability are mostly organic molecules or polymers, but they typically have inferior electrical and optical performance compared with their inorganic counterparts. Li and colleagues show that $CsPbX_3$ perovskites, which have gained a great deal of attention in recent years due to their outstanding optoelectronic properties, are a type of deformable inorganic semiconductor. Substantial plasticity is enabled by the successively and continuously activated partial dislocations of multiple low-energy-barrier $\{110\} < 1\bar{1}0 >$ slip systems, while the crystal structural integrity is maintained by the strong Pb–X bonds. Moreover, the optoelectronic performance or electronic band structures are not affected during deformation, which is of potential use in deformable devices. It would certainly be desirable to have device designs that can take advantage of this shape-morphing behaviour combined with excellent optoelectronic properties.

Glass is another typical type of brittle material, lacking microstructural components such as dislocations or twins that can carry plastic deformation. Introducing nanocrystals into glasses[5] can improve their toughness but can also deteriorate their optical transparency. In an Article by Hu Tang and colleagues, it is shown that a type of crystal-like medium-range-order structure, termed paracrystallites, can be generated in aluminosilicate glass upon high-temperature high-pressure annealing. This structure effectively improves the fracture toughness, without noticeable degradation in optical transmittance. Multiple shear bands that facilitate toughening are observed, which seem to be activated by the stress-induced destruction of the medium-range-order clusters. The beneficial effects of this annealing strategy to promote paracrystalline structuring and hence toughness have also been demonstrated in a high-entropy oxide glass. As commented in the corresponding News & Views article by Hewei Zhao and Lin Guo, it would be interesting to see whether this strategy can be used in bioinspired glasses with laminated structures to improve the interfaces and transmittance. Also, techniques that can reduce the temperature and pressure required and to obtain larger-sized samples need to be explored for practical considerations.

Ceramics and glasses are important structural and functional components in industry. Improving their damage tolerance is essential for safety and the service life management of the whole device or equipment, especially in scenarios that involve increasingly more complex environments and intricate systems, such as aerospace applications and highly integrated micromachines. Moreover, along with the sharply increasing demand for wearable electronics, implantable devices and soft robotics, development of inorganic semiconductors and insulators that can sustain large plastic deformation may break through current material limitations to achieve reliable and high-performance flexible devices.

References

1. Karch, J., Birringer, R. & Gleiter, H. *Nature* **330**, 556–558 (1987).
2. Pelleg, J. in *Mechanical Properties of Ceramics* 113–172 (Springer, 2014).
3. Shi, X. et al. *Nat. Mater.* **17**, 421–426 (2018).
4. Zhang, J. et al. *Science* **378**, 371–376 (2022).
5. Serbena, F. C. et al. *Acta Mater.* **86**, 216–228 (2015).