A ceramic that bends instead of shatters

The microstructure of the ceramic silicon nitride can be tuned to create plasticity.

By **Erkka J. Frankberg[1]**

[1]Unit of Materials Science and Environmental Engineering, Tampere University, Tampere, Finland.

Email: erkka.frankberg@tuni.fi

Ceramic materials are, at least in principle, capable of plastic deformation at room temperature (1). If ceramics can be shaped by hammering, bending, or pulling without fracturing, this will vastly expand the range of applications for these materials. For example, the strong ionic and covalent bonding in ceramics, combined with this hypothetical plasticity, could lead to materials that are lighter and stronger than even the best metal alloys of today. On page 371 of this issue, Zhang et al. (2) present how silicon nitride (Si_3N_4), one of the most versatile engineering ceramic materials, can be made to exhibit plasticity at room temperature. Their proof-of-concept experiment and simulation results offer a potential route to realizing the dream of flexible ceramics.

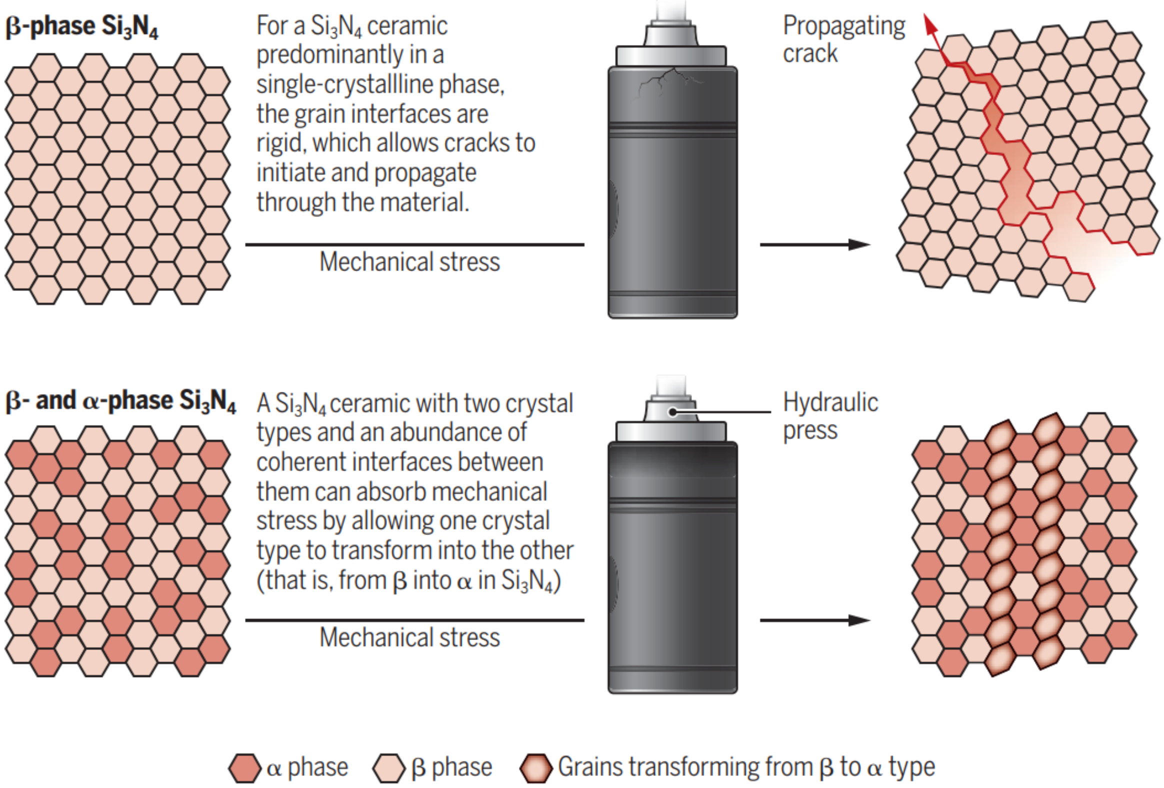
Plasticity in ceramic materials is rarely observed in nature. Because of the complicated structure of ceramics (compared with metals, for example), plasticity from simple dislocation—that is, the slipping of atoms against each other—is mostly limited to single crystalline ceramic and only happens at very high temperatures. For example, sapphire can become somewhat ductile, but only when the temperature is >1000°C. Zhang et al. show that under compressive loading at room temperature, the crystalline fragments in Si_3N_4 can undergo transformations that allow them to rearrange atoms and tolerate macroscopic strain without fracture. Specifically, the b-type crystals can transform into a-type crystals when the material is mechanically stressed. They observed that this plasticity-inducing transformation tends to occur at the coherent crystal interfaces, where neighboring crystals with different structures are in contact with each other where their atomic arrangements are similar. The mechanism bears some resemblance to the transformation-induced plasticity mechanism in steel, by which metastable iron crystals can transform under stress, leading to enhanced ductility and strength (3).

Microstructural transformation can induce improvement of mechanical performance in crystalline materials, such as ceramics. Zirconium oxide (ZrO_2) is an example of a ceramic material that is used because of its strength, for example, in dental applications. ZrO_2 can withstand pressures upward of 1500 MPa before fracture (4) because of its ability to undergo microstructural transformations when mechanically stressed (5). These transformations have even been shown to induce minor plasticity in ZrO_2 at room temperature (6, 7). To date, the microstructural transformation–induced mechanisms in ZrO_2 remain one of the most important areas of research in engineering ceramics (8). Unlike ZrO_2, Si_3N_4 is a nonoxide and covalently bonded material, in which plasticity was not expected to occur by a similar mechanism. Thus, the plasticity discovered in Si_3N_4 provides an opportunity to extend the understanding of how plasticity can occur in ceramics at low temperatures.

Zhang et al. were able to control the portion of coherent interfaces that occur between the two main types of crystals of Si_3N_4. When this portion reaches ~32%, the material can withstand up to ~11 GPa of pressure with a plastic strain of up to ~20% before fracture. The authors conclude that the ultimate strength and plastic strain are correlated to the abundance of coherent interfaces and could be enhanced further if the total amount of coherent interfaces were to increase. The microstructural transformations at the interfaces allow atoms to change their locations and spread out the mechanical stress, thus preventing cracks from emerging and propagating (see the figure). This is different from a

Science AAAS
Accepted Manuscript: This is the author's version of the work. It is posted here by permission of the AAAS for personal use, not for redistribution. The definitive version was published in Science,(2022-10-27), DOI: 10.1126/science.ade7637

typical brittle ceramic material in which atoms are rigidly held in place by their crystal structure and are forced to break their bonds with neighboring atoms when stressed, leading to macroscopic fracture. In addition to the correlation between coherent interfaces and plasticity, Zhang et al. also revealed that the trans-formation mechanism of b-type to a-type crystals only happens one way and not the other way around. These transformations allow changes to the macroscopic shape of the material without fracture.



(Figure caption) The stress-strain behavior of Si3N4 ceramics. The ceramic material silicon nitride (Si_3N_4) can be engineered to possess plasticity and strength comparable to that of high-strength steel. This surprising property can be attributed to how its two main types of crystals interact when the material is under mechanical stress.

Synthetic Si_3N_4 has been used in industrial and commercial applications for almost a century (9), for example, in cutting tools, bearings, and combustion engine components (10, 11). One specific application of Si_3N_4 is the microshutters used by the near-infrared spectrometer instrument on board the James Webb Space Telescope (12). For these applications, Si_3N_4 is used primarily because of its balance of properties: It is lightweight, durable, and resistant to high temperatures. A ductile version of this already versatile material will usher in a host of new applications. However, it is worth noting that the samples tested by Zhang et al. are at the nanoscale and thus free of any macroscopic flaws. However, if the synthesis process is scaled up, the material may form pores and cracks that would make the material more susceptible to fracture initiation.

There is a long road ahead before the full potential of ductile ceramics is realized. However, considering the apparent scarcity of plastic ceramics at room temperature, each discovery of a plasticity mechanism should be regarded highly. A scaled-up, ductile ceramic material would offer a versatile and economically attractive alternative to metals in many applications, for example, by reducing the weight of machine components; increasing machinery uptime with higher wear, fatigue, and corrosion tolerance; and increasing the energy efficiency of thermal power engines by allowing them to run at higher temperatures. Future studies should investigate whether bulk Si_3N_4 gains similar benefits from the stress-induced microstructural transformations as ZrO_2 and whether the required coherent interfaces remain stable at temperatures and process conditions that are relevant for practical applications. How to control the number of coherent interfaces and process flaws in a bulkier material will also need to be clarified. Although ceramics are already a tremendously important group of functional materials, without plasticity, their full potential remains untapped.

REFERENCES AND NOTES

1. P. W. Bridgman, Studies in Large Plastic Flow and Fracture (Harvard Univ. Press, 1964).

2. J. Zhang et al., Science 378, 371 (2022).

3. M. Soleimani, A. Kalhor, H. Mirzadeh, Mater. Sci. Eng. A 795, 140023 (2020).

4. B. D. Flinn, A. J. Raigrodski, L. A. Mancl, R. Toivola, T. Kuykendall, J. Prosthet. Dent. 117, 303 (2017).

5. R. C. Garvie, R. H. J. Hannink, R. T. Pascoe, Nature 258, 703 (1975).

6. G. A. Gogotsi, V. P. Zavada, M. V. Swain, J. Eur. Ceram. Soc. 15, 1185 (1995).

7. A. Liens et al., Acta Mater. 183, 261 (2020).

8. J. Chevalier, L. Gremillard, A. V. Virkar, D. R. Clarke, J. Am. Ceram. Soc. 92, 1901 (2009).

9. F. L. Riley, J. Am. Ceram. Soc. 83, 245 (2000).

10. H. Klemm, J. Am. Ceram. Soc. 93, 1501 (2010).

11. N. R. Katz, Ceram. Ind. 149, 33 (1999).

12. M. J. Li et al., in Proceedings SPIE, vol. 6687, H. A. MacEwen, J. B. Breckinridge, Eds. (Paper 668709, Society of Photo-Optical Instrumentation Engineers, 2007).