

World's hardest material, diamond, is flexible

Discovery by NTU's Prof Subra Suresh and his international research team that diamonds can be stretched by up to 9% without breaking

Diamond, the world's hardest natural material, is also flexible when made into nanoscale needles, according to a paper published in *Science* today about a surprising discovery by an international team of scientists that includes **Prof Subra Suresh, President of Nanyang Technological University, Singapore (NTU Singapore)**.

The research team demonstrated that diamond nano-needles - about a thousand times thinner than a strand of human hair - can be bent and stretched up to nine per cent, before bouncing back to their original state when pressure is removed.

Bulk diamond, in sizes easily visible to the naked eye, would be expected to stretch by well below one per cent, while a similar lack of deformability is also observed for other typically strong and brittle materials, and attempts to flex them cause them to break.

The scientists predict that their discovery may lead to new applications in bioimaging and biosensing, drug delivery, data storage, opto-electronic devices and ultra-strength nanostructures. Using elastic strains induced by mechanical deformation, such as bending, also opens up new avenues to tailor electrical, magnetic, optical and other physical properties.

Published today (20 Apr) in the journal *Science*, the finding was made by an interdisciplinary team whose senior author is **Prof Subra Suresh**, President and also Distinguished University Professor at NTU Singapore. Other corresponding authors include **Prof Yang Lu** and **Prof Wenjun Zhang** from the City University of Hong Kong, **Dr Ming Dao** from the Massachusetts Institute of Technology (MIT) in United States, with other co-authors from Hong Kong, United States and South Korea.

Using a scanning electron microscope to 'video record' the process in real time, the team used a diamond probe to put pressure on the sides of the diamond nano-needles, which were grown through a special process called chemical vapour deposition and etched into final shape. The team measured how much each needle could bend before it fractured.

"Our results were so surprising that we had to run the experiments again under different conditions just to confirm them," said Prof Suresh. "We also performed detailed computer simulations of the actual specimens and bending experiments to measure and determine the maximum tensile stress and strain that the diamond nano-needles could withstand before breaking.

"This work also demonstrates that what is usually not possible at the macroscopic and microscopic scales can occur at the nano-scale where the entire specimen consists of only dozens or hundreds of atoms, and where the surface to volume ratio is large."

The team ran hundreds of computer simulations alongside their experimental tests to understand

and explain how the diamond needles underwent large elastic strains, as brittle materials usually stretch less than one per cent.

“After two years of careful iterations between simulations and real-time experiments, we now know that the deformed shape of a bent nano-needle is the key in determining its maximum tensile strain achieved,” Dr Dao explained. “The controlled bending deformation also enables precise control and on-the-fly alterations of the maximum strain in the nano-needle below its fracture limit.”

Previous theoretical studies found that when elastic strain exceeds one percent, quantum mechanical calculations indicate significant physical or chemical property changes. The possibility of introducing elastic strains in diamond by flexing it up to 9% provides new avenues for fine-tuning its electronic properties. In addition, this phenomenon could be used to tailor mechanical, thermal, optical, magnetic, electrical, and light-emitting properties to design advanced materials for various applications.

In addition to showing up to 9% tensile stretch in single crystal diamonds, Prof Suresh and his collaborators also showed that polycrystalline diamond nano-needles, where each needle comprises many nano-size grains or crystals of diamond, can withstand a reversible, elastic stretch of up to 4% before breaking.

When maximum flexibility can be changed in real-time to between 0 to 9 per cent in nano-diamonds, there is a lot of potential for exploring unprecedented material properties.

Examples of specific potential applications for the nano-diamonds include design of better ultra-small biosensors for greater performance. Another application area of particular significance is the nitrogen-vacancy (NV) emission centres in diamond which are extremely sensitive to magnetic fields, temperatures, ion concentrations and spin densities. Since changes in elastic strains are sensitive to magnetic fields, potential applications could include such fields as data storage where lasers could encode data into diamonds.

As diamonds are known to be biocompatible, they could also be useful for drug delivery into cells where strong yet flexible nano-needles are needed.

In biosensing applications, NV could also be used in Magnetic Resonance Imaging (MRI) or Nuclear Magnetic Resonance (NMR) to achieve even higher accuracy and resolutions as well as 3-dimensional imaging for complex nanostructures and biomolecules.

This discovery shows new pathways for producing novel diamond architectures for mechanical applications as well as a variety of functional applications in devices, biomedicine, imaging, micro-testing, and materials science and engineering.

In addition to Drs. Subra Suresh, Yang Lu, Weijun Zhang and Ming Dao, the list of authors includes: Amit Banerjee (lead author), Hongti Zhang (co-lead author), Muk-Fung Yuen, Jianbin Liu, and Jian Lu from the City University of Hong Kong; Daniel Bernoulli (co-lead author) from MIT; Jichen Dong from the Institute for Basic Science, Ulsan, Korea; and Feng Ding from the Ulsan Institute of Science and Technology, Korea.

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Media contact:
Lester Kok
Manager
Corporate Communications Office
Nanyang Technological University
Email: lesterkok@ntu.edu.sg