Could stronger, tougher paper replace metal?

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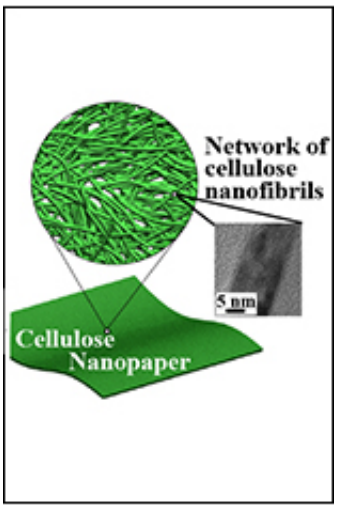

Researchers at the University of Maryland recently discovered that paper made of cellulose fibers is tougher and stronger the smaller the fibers get. For a long time, engineers have sought a material that is both strong (resistant to non-recoverable deformation) and tough (tolerant of damage).

"Strength and toughness are often exclusive to each other," said Teng Li, associate professor of mechanical engineering at UMD. "For example, a stronger material tends to be brittle, like cast iron or diamond."

The UMD team pursued the development of a strong and tough material by exploring the mechanical properties of cellulose, the most abundant

renewable bio-resource on Earth. Researchers made papers with several sizes of cellulose fibers – all too small for the eye to see – ranging in size from about 30 micrometers to 10 nanometers. The paper made of 10-nanometer-thick fibers was 40 times tougher and 130 times stronger than regular notebook paper, which is made of cellulose fibers a thousand times larger.

"These findings could lead to a new class of high performance engineering materials that are both strong and tough, a Holy Grail in materials design," said Li.

High performance yet lightweight cellulose-based materials might one day replace conventional structural materials (i.e. metals) in applications where weight is important. This could lead, for example, to more energy efficient and "green" vehicles. In addition, team members say, transparent cellulose nanopaper may become feasible as a functional substrate in flexible electronics, resulting in paper electronics, printable solar cells and flexible displays that could radically change many aspects of daily life.

Cellulose fibers can easily form many hydrogen bonds. Once broken, the hydrogen bonds can reform on their own—giving the material a 'self-healing' quality. The UMD discovered that the smaller the cellulose fibers, the more hydrogen bonds per square area. This means paper made of very small fibers can both hold together better and re-form more quickly, which is the key for cellulose nanopaper to be both strong and tough.

"It is helpful to know why cellulose nanopaper is both strong and tough, especially when the underlying reason is also applicable to many other materials," said Liangbing Hu, assistant professor of materials science at UMD.

To confirm, the researchers tried a similar experiment using carbon nanotubes that were similar in size to the cellulose fibers. The carbon nanotubes had much weaker bonds holding them together, so under tension they did not hold together as well. Paper made of carbon nanotubes is weak, though individually nanotubes are arguably the strongest material ever made.

One possible future direction for the research is the improvement of the mechanical performance of carbon nanotube paper.

"Paper made of a network of carbon nanotubes is much weaker than expected," said Li. "Indeed, it has been a grand challenge to translate the superb properties of carbon nanotubes at nanoscale to macroscale. Our research findings shed light on a viable approach to addressing this challenge and achieving carbon nanotube paper that is both strong and tough."

More information: "Anomalous scaling law of strength and toughness of cellulose nanopaper." *PNAS* 2015 112 (29) 8971-8976; published ahead of print July 6, 2015, DOI: 10.1073/pnas.1502870112

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