Scientists develop strong yet reusable adhesive from smart materials

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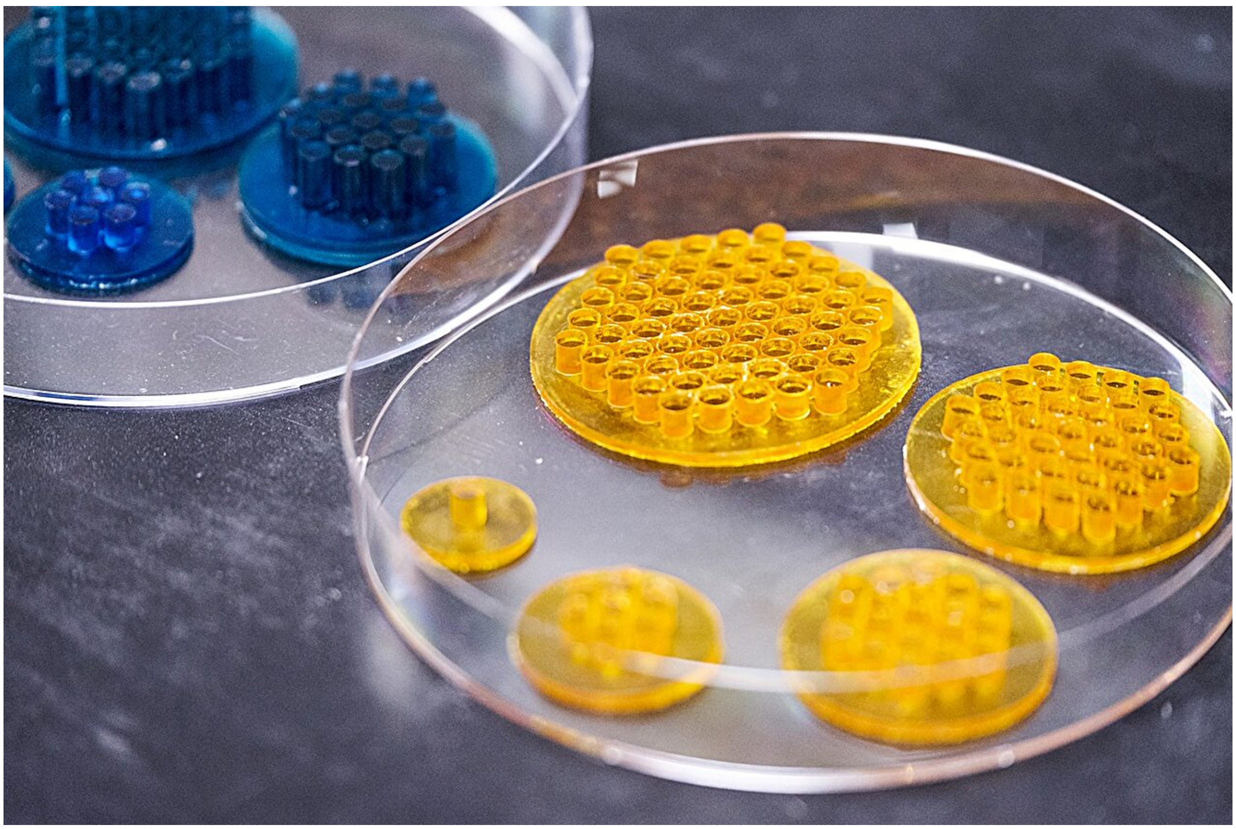

The NTU team designed shape-memory polymers, which are smart materials that can 'remember' their previous forms, in the form of hair-like fibrils which they found in their testing to provide maximum adhesive strength. Credit: Nanyang Technological University

Scientists from Nanyang Technological University, Singapore (NTU

Singapore) have developed a smart, reusable adhesive more than 10 times stronger than a gecko's feet adhesion, pointing the way for development of reusable superglue and grippers capable of holding heavy weights across rough and smooth surfaces.

The NTU research team, led by Professor K Jimmy Hsia, found a way to maximize the adhesion of the smart adhesives by using shape-memory polymers, which can stick and detach easily when needed simply by heating them.

Writing last month in the journal *National Science Review*, the team details their breakthrough in adhesion by designing the shape-memory polymer material in the shape of hair-like fibrils.

This smart adhesive can support extremely heavy weights, opening new possibilities for robotic grippers that allow humans to scale walls effortlessly, or climbing robots that can cling onto ceilings for survey or repair applications.

Professor Hsia, President's Chair in Mechanical Engineering, NTU School of Mechanical & Aerospace Engineering (MAE) and School of Chemistry, Chemical Engineering and Biotechnology, said, "This research is based on a fundamental understanding of the mechanisms of adhesion forces on rough surfaces. It can help us develop very strong, yet easily detachable, adhesives adaptable to rough surfaces. The technology will be very useful in adhesive grippers and climbing robots and might one day let humans climb walls like a real-life Spider-Man."

Shape-memory polymers are materials that can hold "memories" of their previous form and return to their original shape after they have been deformed by applying external stimuli such as heat, light or electrical current. These properties make them ideal to be used as switchable adhesives that can adapt to various surfaces.

In their testing, the researchers used a shape-memory polymer named E44 epoxy, a stiff and glass-like plastic at room temperature. Upon heating, the material turns into a soft rubber-like state that can conform and lock onto microscopic nooks and crevices. As it cools, it becomes glassy, creating extra-strong adhesive bonds due to a shape-locking effect.

When the material is reheated, it reverts to its rubbery state so it can be pulled away and easily detached from the surface it was clinging to.

The researchers found that the most effective adhesion came from designing the shape-memory polymer into an array of hair-like fibrils. Each fibril had to be carefully designed—larger fibrils had weaker adhesion, while the smaller fibrils were hard to fabricate and prone to collapse and degradation. The sweet spot was between 0.5 mm and 3 mm in radius, pushing the limits of adhesion while retaining structural integrity.

In their experiments, the researchers found that one fibril with a 19.6 mm^2 cross-section could support loads up to 1.56 kg. Every additional fibril allows for more weight to be supported. A palm-sized array of 37 fibrils weighing about 30 g can hold a weight of 60 kg—an adult human's weight.

The research paper's first author, NTU Research Fellow Dr. Linghu Changhong, said, "Our smart adhesive exemplifies how shape-memory polymers can maintain and even enhance adhesion as surface roughness increases. This overcomes the 'adhesion paradox,' which scientists have been puzzling over, where there is a decrease in adhesion strength on rough surfaces despite having more surface area for molecules to adhere to.

"Our tests showed that adhesion strength of the polymer increases along with surface roughness when in a solid state and decreases when in the rubbery state."

Co-corresponding author Professor Gao Huajian, formerly a Distinguished University Professor from NTU's School of MAE and currently the Xinghua University Professor at Tsinghua University, said, "For practical gripping purposes, the adhesive needs to be strong enough to stick onto a surface, yet also easily detach when needed. Switching between the two modes is vital for practical applications. Stronger adhesives can support heavier loading but tend to be harder to detach—this is what we call a 'switchability conflict.'

"Our research into shape-memory polymers has resulted in an adhesive that can easily harden to stick onto surfaces, and just as easily soften to detach, all the while being able to bear heavy weights including that of a human being."

Professor Hsia added, "The shape-memory polymer adhesives we designed overcame both the adhesion paradox and the switchability conflict, providing guidelines for developing stronger and more switchable adhesives adaptable to rough surfaces."

Paving the way for sticky climbing gear

Detaching the shape-memory polymer while it is attached to a surface in a glass state takes less than a minute of heating using a hair dryer to bring temperatures up to 60°C. Conversely, for attachment, it takes about three minutes for the material to cool down thoroughly and lock into place.

The temperature at which the polymer changes states can be controlled by adjusting the ratios of the components used to form the polymer. This allows the polymer to be used in extreme environments, such as hot weather conditions. In their testing, the researchers set the temperature at which the polymer detaches to 60°C, a temperature that falls outside most comfortable real-world conditions.

This ability of the material to attach and detach using only heat lets it act as a reusable superglue that does not leave behind sticky residue on walls. It can also be used as soft grippers capable of sticking onto objects with diverse surface textures and reliably holding them for extended periods.

Dr. Changhong said, "At this current stage, the heating and cooling times, as well as switching temperature, restrict the number of real-world use cases. However, our findings show that reducing the wait times to mere seconds is possible, and the switching temperatures can be lowered to near body temperature, dramatically opening up application possibilities.

"The stimuli to switch the material from one state to another can also be different, such as using electrical current or light instead."

Moving forward, the research team aims to reduce the cooling time required for adhesion. The team envisions that the adhesive might eventually be used in climbing equipment—such as gloves and boots—that will allow climbers to stick onto and scale walls. Robots could also be outfitted with the material to create wall-climbing robots, which are useful in many industries such as construction and building surveying.

More information: Changhong Linghu et al, Fibrillar adhesives with unprecedented adhesion strength, switchability and scalability, *National Science Review* (2024). DOI: 10.1093/nsr/nwae106