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Press Release

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Nanoscale contact optimizes adhesion

Optimal adhesion of geckos and insects based on shape optimization and contact surface size reduction, report Max Planck researchers in Stuttgart, Germany

The nanometer size of hairs (spatulae) on the feet of geckos and many insects may have evolved to optimize adhesion strength, according to new research conducted at the Max Planck Institute for Metals Research in Stuttgart. The scientists discovered that there exists an optimal shape of the contact surface of the tip of such hairs which gives rise to optimal adhesion to a substrate via molecular interaction forces. For macroscopic objects, such optimal shape design tends to be unreliable because the adhesion strength is sensitive to small geometrical variations. It is shown that this limitation can be remedied via size reduction. The key finding of this research is that there exists a critical contact size around 100 nanometers below which optimal adhesion can be reliably achieved independent of small variations in the shape of the contact surface. In general, optimal adhesion can be achieved by a combination of size reduction and shape optimization. The smaller the size, the less important the shape. This result provides a plausible explanation why the characteristic size of hairy attachment systems in biology fall in a narrow range between a few hundred nanometer and a few micrometers and suggests a few useful guidelines for designing adhesive structures in engineering. (PNAS, Early Edition, 17 May 2004)

Welding, sintering, diffusion bonding and wafer bonding are some of the widely used engineering strategies of joining different structural components or objects together. Normally, if two objects are joined together by adhesion and then subject to an externally applied load, stress concentration is expected to occur near the edge of the joint. As the load increases, the stress intensity ultimately reaches a critical level to drive a small crack to propagate and break the joint. Under these circumstance, the material in the joint is not being used most efficiently because only a small fraction of material is highly stressed at any instant in time. The failure occurs by incremental propagation of crack-like flaws. How to achieve robust and reliable optimal adhesion between different structural components has so eluded engineers.

Biological adhesion mechanisms that have been tested and improved through evolution are of interest not only to biologists but also to engineers. Geckos and many insects have adopted nanoscale hairy structures on their feet as adhesion devices. The density of surface hairs increases with the body weight of animals, and the gecko has the highest density among all animal species that have so far been studied. Different mechanisms, such as capillary forces, have been proposed in the past to explain adhesion mechanisms in biology. However, there is now strong evidence that molecular adhesion via van der

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Waals interaction plays a dominant role in the attachment of geckos. This may appear somewhat surprising because it takes a much greater force to pull a gecko away from a ceiling than removing a human hand off a table, even though the same van der Waals force is expected to exist in both situations. A question thus arises: What determines the adhesion strength? The chemical nature of materials cannot explain why the same van der Waals force results in strong adhesion in gecko but not in human. Apparently, nature has evolved mechanisms to utilize weak van der Waals forces in animal species for which adhesion is crucial for survival.

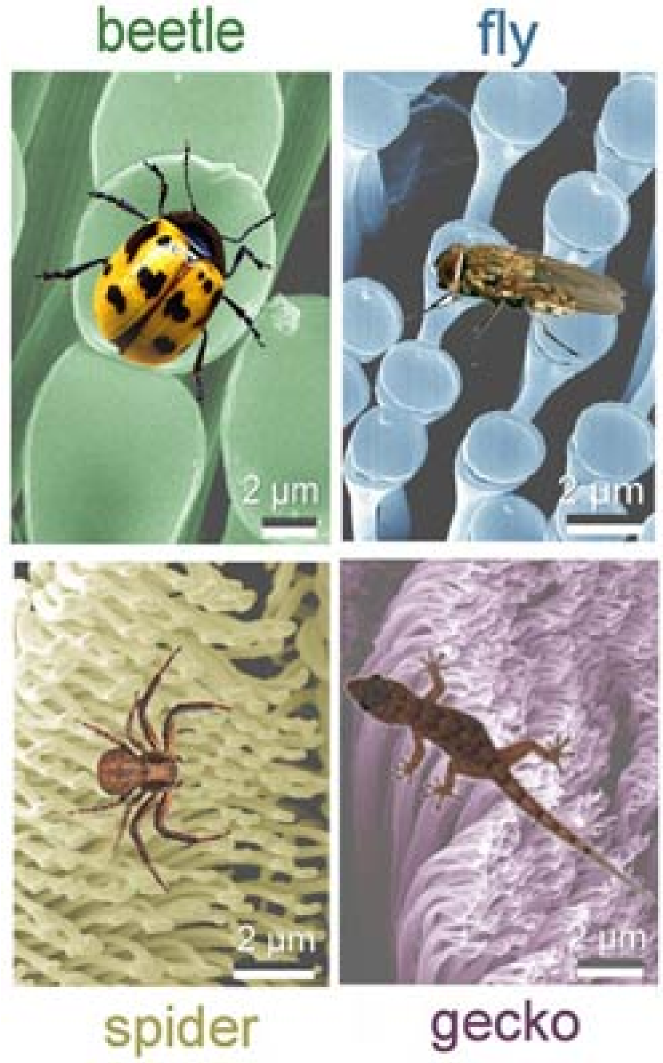

Fig. 1: *The nanoscale fibrillar structures in the hairy attachment pads of beetle, fly, spider and gecko. The density of surface hairs increases with the body weight of animal, and the gecko has the highest density among all animal species.*

Image: Max Planck Institute for Metals Research/Gorb

The scientists (H. Gao and H. Yao) of Max Planck Institute for Metals Research in Stuttgart developed a model for adhesion between a single fiber and a substrate via van der Waals interaction. According to their model, the shape of the tip of the fiber strongly affects the adhesion strength. It is shown that there exists a specific shape, called the optimal shape, for which the adhesive strength reaches the theoretical strength of the van der Waals interaction. For the optimal shape, the adhesive force is uniformly distributed over the contact area at the instant of pull-off, corresponding to the optimal use of material against detachment.

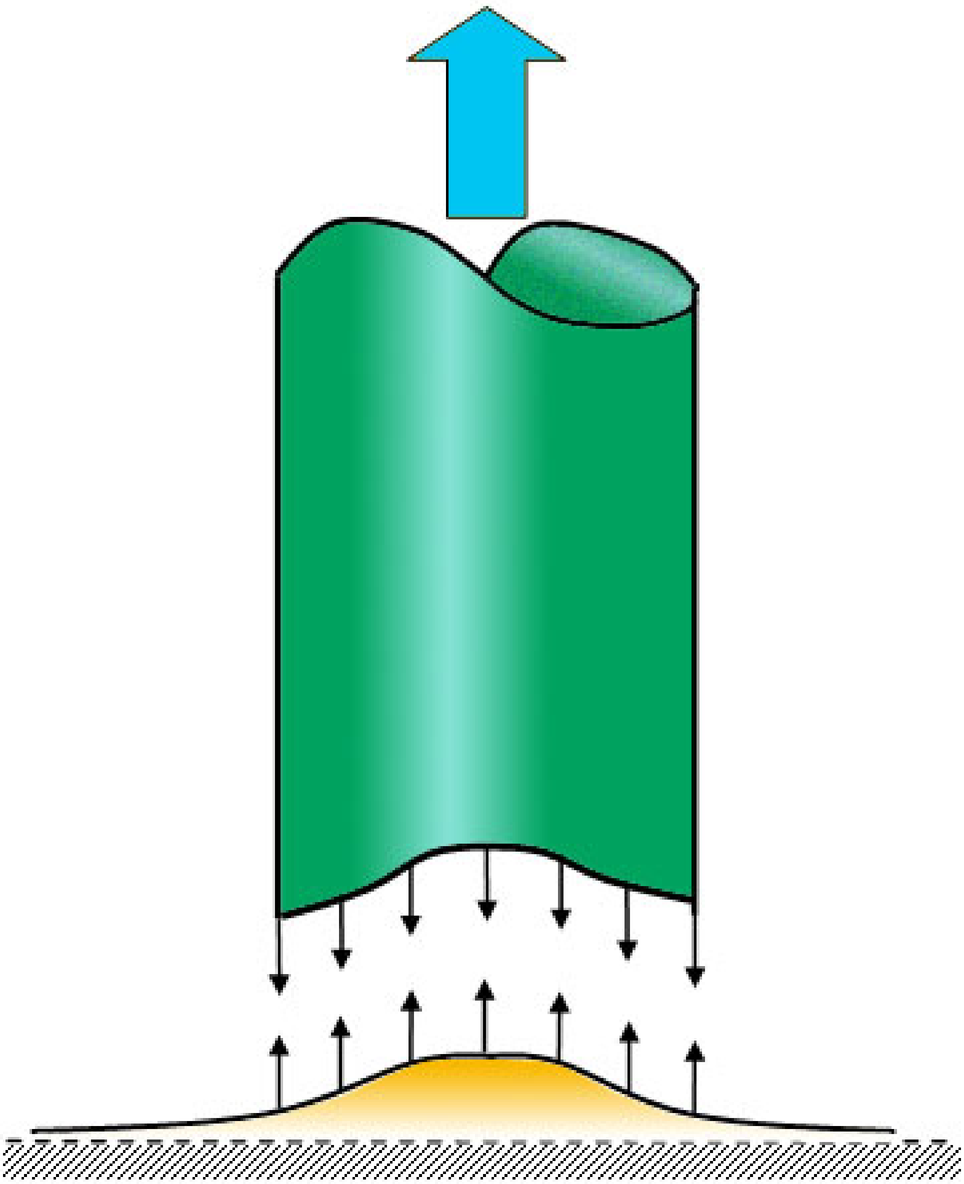

Fig. 2: *The optimal shape of adhesion for two objects in contact over a prescribed surface area is defined as such that the stress distribution is uniform and equal to the theoretical adhesion strength of molecular (e.g., van der Waals) interaction at pull-off. Robust optimal adhesion is achieved when the contact size is reduced to around 100 nanometers. At this critical size scale, the adhesion strength becomes insensitive to small deviations from the optimal shape.*

Image: Max Planck Institute for Metals Research

Why hasn't such an optimal shape been used in engineering? One problem is that the adhesion strength is found to be highly sensitive to small variations in geometry. For example, for a fiber with radius equal to 1 mm, the pull-off force is found to drop by more than two orders of magnitude with only 1-2% deviation from the optimal shape. Interestingly, this hypersensitivity in shape can be eliminated by size reduction. As the fiber size is reduced to a critical size estimated to be 100 nanometers, the adhesion strength remains at the theoretical strength independent of small variations in shape.

Therefore, in nature and in engineering, optimal adhesion could be achieved by a combination of size reduction and shape optimization. The smaller the size, the less important the shape becomes. At large contact sizes, optimal adhesion could still be achieved if the shape can be manufactured to a sufficiently high precision. From a practical point of view, it is necessary to reduce the contact size to achieve robust optimal adhesion. These principles could be of great value to artificial materials design.

[HG/AT]

Original work:

H. Gao, H. Yao
Shape insensitive optimal adhesion of nanoscale fibrillar structures
Proceedings of the National Academy of Sciences of the USA, 2004, Vol. 101, no. 21, pp. 7851-7856, Early Edition, published May 17, 2004, 10.1073/pnas.0400757101

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