Lessons from Nature: Adhesion and Structure

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Introduction

Nature provides awe-inspiring lessons in designing materials structures from simple building blocks to achieve necessary performance. In these designs, ubiquitous forces are utilized to impart control of both structure and performance. For example, forces associated with differential growth lead to the formation of complex structures, such as fingerprints. Likewise, van der Waals and capillary forces are used by geckos to achieve a unique balance of adhesion and locomotion through a differentiated hierarchy in their foot structure. In this paper, we will summarize two current projects that represent broader efforts within our research group to learn from Nature not only in the design of materials but also in concepts that lead to fundamental understanding of materials properties. The first project focuses on the challenge of developing scalable adhesive interfaces that have the ability to sustain high loads, yet release with minimal force or energy loss upon obtaining a critical condition. The second project explores the possibility of adapting shape-forming strategies found in the development of biological tissues into scalable manufacturing processes for fabricating advanced surface structures at small length scales.

Bio-Inspired Adhesion

Over the past decade or more, a concerted international effort among academic, government, and industrial research laboratories has focused on developing adhesives that display similar attributes to those presented by biological organisms that use adhesion in the process of locomotion. The best known example in Nature is the gecko, yet numerous organisms ranging from beetles to spiders to lizards display similar impressive capabilities. A unifying feature among these examples is the presentation of fibrillar features, which are primarily made from keratin, a rigid protein material.[1] These fibrillar features typically have diameters with micron or sub-micron dimensions and lengths of several to tens of microns,[2] as seen in Figure 1. Although significant progress has been made in developing synthetic analogs to these fibrillar surface features,[3][4][5] the ability to produce materials that can be scaled to macroscopic sizes while maintaining "gecko-like" attributes has not been demonstrated convincingly. This difficulty suggests that other lessons need to be learned from Nature to enable scaling of adhesive performance over specimen sizes ranging several orders of magnitude.
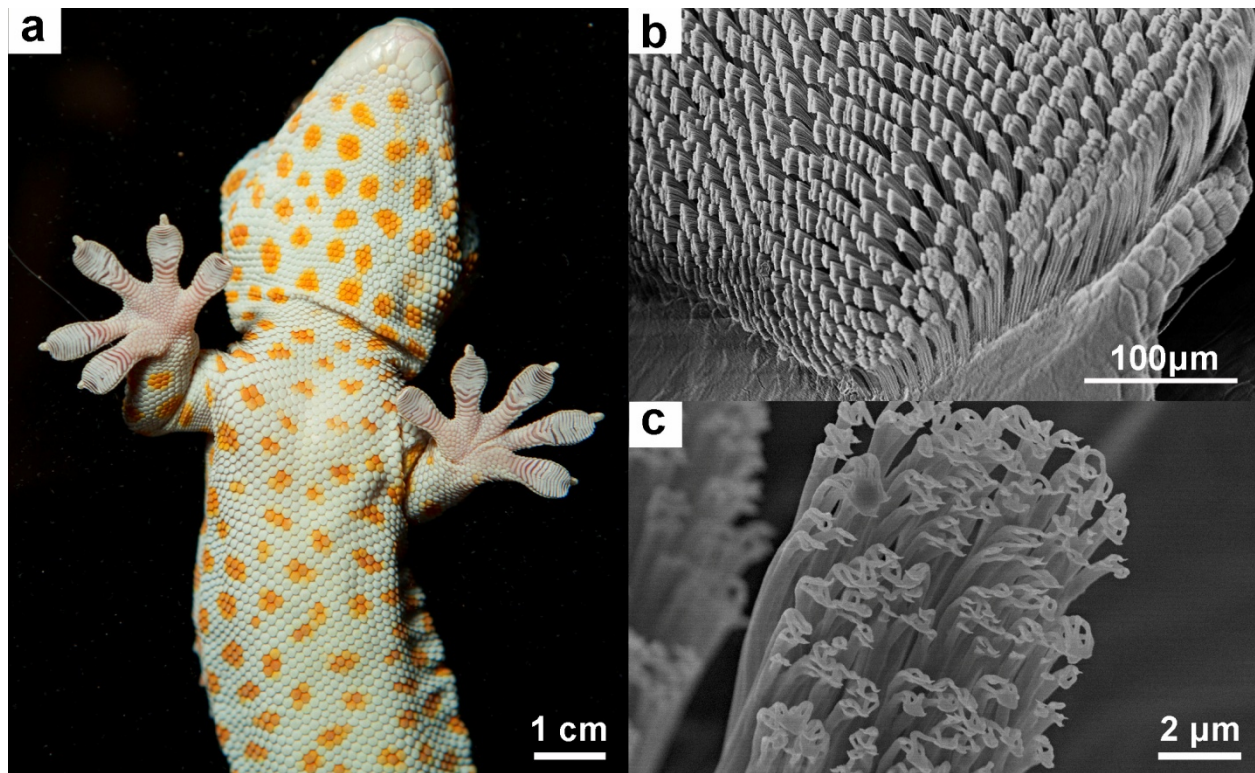
Figure 1- a) Ventral view of a tokay gecko, displacing adhesive toe pads. **b)** SEM images of rows of setae from a toe pad and **c)** the tip of a single seta, displaying the spatular features.

With this premise, we have experimentally and analytically investigated the fundamental mechanisms of adhesion that link organisms that range in mass over four or five orders of magnitude. We have developed a scaling theory to link the maximum sustainable force for an adhesive interface as a function of three continuum-level parameters: 1) the interfacial adhesion energy per unit area; 2) the interfacial area; and 3) the compliance of the system. The validity of this scaling relationship rests on three assumptions: 1) the interface is in equilibrium prior to failure; 2) the system will behave in an unstable manner upon failure; and 3) the system, especially in the context of organisms that want to enable locomotion, will conserve energy.

Using the developed scaling relationship, we have been able to quantitatively link the maximum sustainable interfacial force for components in Nature from spatula (~100nm) to seta (~10μm) to rows of setae (~ 100μm) to whole body organisms (~ 10cm). This scalable understanding has been demonstrated for both lizards and beetles within the same context. Building upon these lessons, we have developed synthetic materials that also display high capacity, easy release attributes similar to the examples in Nature.

Synthetic Morphogenesis

Similar to the inspiration provided by high performing adhesive examples in Nature, we also take inspiration from Nature in developing methods to fabricate complicated hierarchical structures, both surface and near-surface, in a scalable manner. If we are mimicking Nature in terms of structure-performance relationships, should we not also consider mimicking Nature in process-structure relationships?

One intriguing example is the process of fingerprint formation in mammals. Fingerprints form due to a differential growth rate between two cell layers of the skin during the first twenty weeks of development.[6] This difference in growth rates between neighboring layers leads to the development of a compressive stress near the interface, similar to the stresses that can develop in synthetic bilayers exposed to thermal transitions.[7] Upon reaching a critical stress level, related to the onset of an elastic buckling instability, the skin layers wrinkle to form the fingerprint. Interestingly, the dimensions of the fingerprint patterns can be related to the dimensions and properties of the cell layers. Furthermore, the patterns can be related to curvature of the wrinkling layers and can range from ridge-based features to dimples across different species.[6] Although fingerprints are only one example, it provides the fundamental lesson that differential stresses in soft materials can yield well-defined patterns in a spontaneous manner.
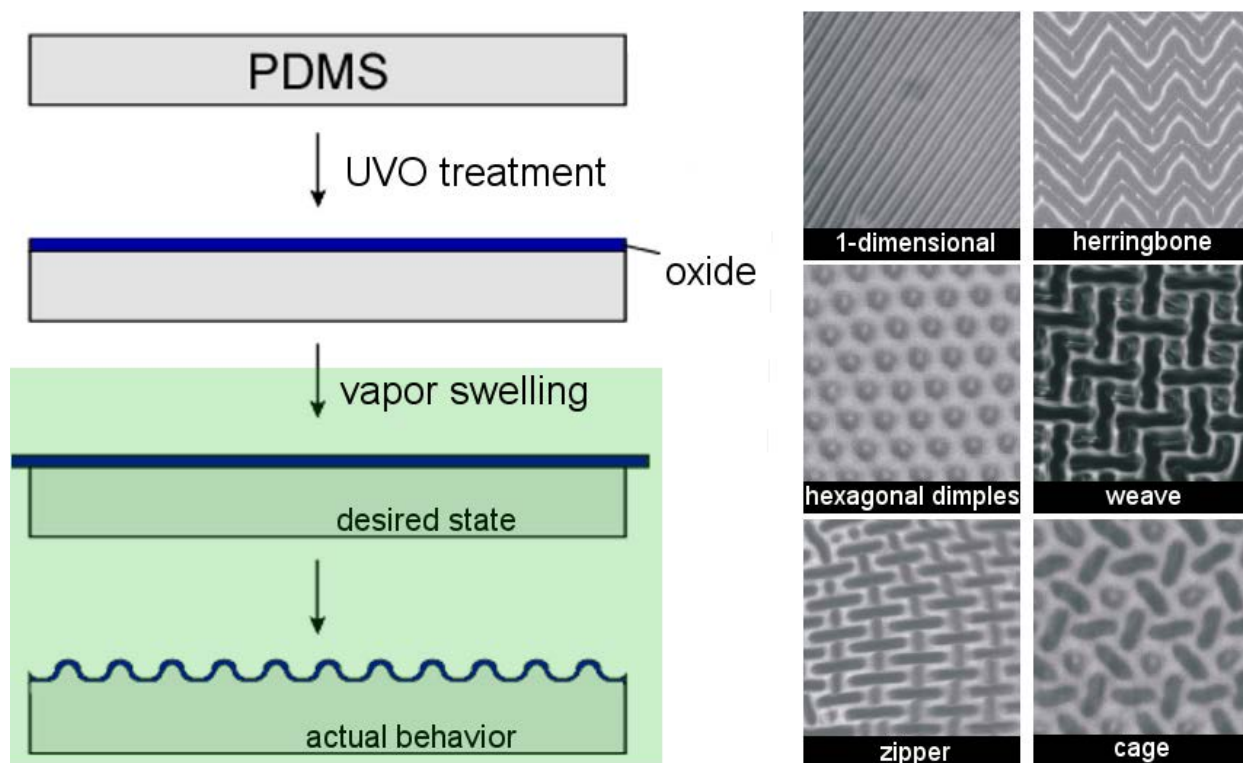

Figure 2- Left: Schematic of the swelling-based surface wrinkling process. PDMS is first treated with UV-ozone, forming a thin oxide layer. The oxidized samples are then exposed to solvent vapor which swells the oxide, producing wrinkles.

In our research[8-15], we have focused on understanding the relationship between materials properties, geometry, and stress state in controlling the formation of wrinkle-based patterns in soft synthetic materials. We present here experiments on composite materials comprised of a thin stiff film attached to a soft elastomeric substrate.[12] Specifically, a crosslinked polydimethylsiloxane (PDMS) (Dow Corning Sylgard™ 184) substrate is oxidized on one surface in an ultraviolet ozone chamber. The oxidation leads to the conversion of the surface material into a SiOx layer, which is approximately 100 nm thick. This oxidized substrate is then placed in a closed chamber on an inverted microscope to expose it to ethanol solvent vapor. Upon exposure, the SiOx is swollen by the ethanol vapor to a greater extent than the underlying non-modified polydimethylsiloxane substrate. Due to the differential swelling, a compressive stress develops at the SiOx/PDMS interface and wrinkling develops as a critical stress level, defined by the elastic modulus mismatch of the SiOx and PDMS materials, is exceeded. By controlling the extent of oxidation or the vapor pressure of ethanol solvent, we can

systematically change the morphology of the wrinkle patterns, as shown in Figure xx. The change in morphology is quantitatively linked to two control parameters: 1) the ratio of applied swelling stress to the critical stress for elastic instability; 2) the ratio of the two primary in-plane stresses experienced in the swollen SiOx layer. This wrinkling process can be adapted to a wide range of materials and swelling solvents and can be controlled over materials with large lateral length scales. These wrinkled features can either be fixed via crosslinking[8][9] or reversible via evaporation of the swelling solvent.[10][12] Importantly, we have performed parallel experiments on similarly wrinkled systems to quantify the impact and mechanism for controlling adhesion through the use of wrinkles.[13-15]

Summary
Both stories present important lessons not only in terms of adhesion but also in the fabrication of materials structures for a wide range of technologies. Understanding how materials properties balance with structural length scales is advantageous in the design of scalable solutions for different performance factors.

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