Materials

Introduction:

Geckos and other lizards as well as many species of insects utilize fibrillar contact surfaces to enhance their ability to adhere to a wide variety of natural surfaces. The arrays of tiny setae found on the contact surfaces of these organisms are typically between 0.5 and 5 µm in diameter and range in length from 5 to nearly 100 µm. Previous researchers have determined that the mechanism of adhesion for the fibrillar structures found in nature is non-covalent (predominantly van der Waals) interactions [1].

In theoretical work, we have shown that a fibrillar surface in contact with a substrate can possess both larger adhesion force and larger fracture energy than a corresponding flat interface of the same materials [2]. In addition, fibrillar surfaces are locally more compliant at the interface than flat ones due to the ability of fibrils to bend [3]. We have shown in other theoretical work that this allows a fibrillar surface to adhere better to rough surfaces than a flat surface [4]. Seeking to confirm these theoretical ideas with quantitative experimental data and to understand the functioning of the natural surfaces more fully, we built several model fibrillar arrays that mimic the biological exemplars.

Summary:

Our first attempt was at macroscopic length scales, using manual fabrication methods. We constructed fibrils approximately 1 mm in diameter from the rubbery polymer poly(vinyl butyral) and showed via tensile pull off tests that the fibrillar samples have about an order of magnitude larger adhesion energy than flat control samples [5]. The caveat with these samples is that uniform adhesive contact is difficult to achieve, and heat treatment at the interface was required to attain it. However, at smaller length scales, surface forces become stronger relative to the elastic restoring forces of the fibrillar structures. Hence, at small length scales, it should be possible to bring a fibrillar surface into intimate adhesive contact simply by placing it in proximity to the desired adherend.

Because of this, and because our theory predicts even larger adhesion strength as the diameter of the fibril is reduced, we set about to build microscopic fibrillar arrays. Using tools at CNF, we carried out two separate processes to produce arrays of fibrils with diameter between 1 and 15 µm and length between 5 and 100 µm. The first process used standard photolithography and deep reactive ion etching to produce holes in Si with the desired cross-sections and depths. This Si master surface was then used to mold poly(dimethylsiloxane) (PDMS), which was cured and removed from the master to give fibrils of the same shape and size as the holes in the Si surface.

In the second process, photolithography and a wet chemical etch were used to pattern an array of circles on an Al layer atop a cured polyimide (PI) film. A reactive ion etch was then used to remove PI except where masked by the Al circles. The result was circular PI fibrils with approximately 1 µm diameter and lengths between 5 and 10 µm, depending on the etch time.

In preliminary results for the adhesion of microscopic samples, we found in a tensile test that the pull off force of the fibrillar PDMS samples was about 80% that of the flat control [2]. Although the adhesion force is slightly smaller, one must note that the area of contact is about 20 times as large for the flat sample. Future work will involve maximizing the contact area for microscopic fibrillar samples, as well as adding more complex geometry to the ends of the fibrils, to increase compliance and increase the contact area and adhesion.

References:
Natural fibrillar surfaces provide improved adhesion in animals (Figure 1).

Theory shows fibrillar surfaces are stronger than flat surfaces.

Large aspect ratio fibrils more compliant than flat surfaces, allowing better contact with rough surfaces.

Synthetic fibrillar surfaces fabricated by molding (Figure 2) or direct reactive ion etching (Figure 3).