

# Preface

## Performance of Biological and Bio-inspired Attachment Systems in Real Environment

The field of biological and bio-inspired adhesive systems underwent enormous developments during the past 15–20 years. Starting from curiosity-driven science with questions like “Why does the gecko or the fly not fall from the wall?”, it developed into one of the most exciting interdisciplinary fields of research, where biologists, chemists, materials scientists, even theoretical physicists, and engineers meet together to unravel nature’s mystery of temporary, strong, and reliable adhesion. Although enormous efforts, to understand attachment principles of biological prototypes, such as geckos, spiders, flies, and beetles were recently undertaken, until now, only very few biomimetic materials, inspired by the feet of these animals, are commercialized.

What could be the reasons for the shortage of such bio-inspired products? One potential reason could be that we are still limited in industrial processes capable of mass production of structures with such extreme complexity and small feature size. Another reason could be that we still have not properly understood functioning of biological prototypes. The latter reason might be due to the fact that we lack information about the way *how the animals use their attachment systems in real environment*. Also biologically inspired artificial attachment devices are usually tested on smooth flat substrates under laboratory conditions. This approach is perfectly fine as a first step of the biomimetic technical development, but not lead to the development of real-world applications.

Additionally, if we want to fix things quasi-permanently on the wall, we should not necessarily consider gecko-inspired materials. Geckos and Co are fast-running animals with an attachment system optimized for short-term and highly dynamic adhesion. Therefore, these attachment systems mainly rely on elaborate nanoscopic thin film-like spatula-shaped contact elements. Instead, we should search for other specialized biological prototypes, for example, organisms, which utilize long-term adhesion. Their strong and, most important, passive attachment systems mainly rely

either on glue, a mushroom-shaped contact geometry, or on the combination of both.

Chapter 1 of this book is devoted to a meta-analysis of the available literature on biologically inspired adhesives. Niewiarowski et al. applied for the first time a bibliometric analysis of gecko adhesion to gain more insight from the past research for the future directions and transfer to technical applications. Using analysis of citations, co-citations, and patents, they confirmed that the theme ‘gecko adhesion’ in the broader context of ‘biomimetic adhesion’ is the most influential one. Moreover, the authors noticed that some capabilities of geckos (and other climbing animals), such as adhesion to wet and/or dirty surfaces, do not show up as major themes in the context of bio-inspired adhesives. The authors speculate that this may potentially be due to a lack of research focus on such environmental effects. The next three chapters by Heepe et al. and Gorb et al. present such attempts to understand environmental effects on the attachment ability in one of the biological model adhesive systems: the seven-spotted ladybird beetle *Coccinella septempunctata*.

In Chap. 2, the authors investigated the effect of ambient humidity on the beetle attachment ability. Surprisingly, beetles, which have a so-called wet hairy adhesive system, showed a similar dependency on relative humidity as spiders and geckos which exhibit a so-called dry hairy adhesive system. The obtained results indicate an optimal range of relative humidity with a maximum in attachment ability. At very low and very high humidity, the beetle attachment ability is considerably lower. Potential mechanisms, responsible for such nontrivial humidity dependence, are discussed.

In Chap. 3, the question “What is the dominant factor of the surface effecting the attachment ability of beetles: chemistry or roughness?” was asked. To answer that question, the authors systematically measured insect traction forces on various substrates with similar surface roughness but different surface chemistry and on substrates with similar surface chemistry but different surface roughness. Although surface chemistry indeed affected the attachment ability, the surface roughness was shown to be the dominant factor determining the beetle attachment ability.

In Chap. 4, the influence of the substrate stiffness on the attachment ability of female and male ladybird beetles was investigated. Natural habitats of climbing animals may provide a variety of substrate stiffness ranging from rigid rock surfaces to soft, biofilm covered ones. The authors used a custom-build centrifugal tester, to measure the attachment ability of beetles on smooth silicone elastomer substrates with stiffness ranging from about 0.3 MPa to about 2.2 MPa. Whereas in females, the attachment ability was not affected by the substrate stiffness within the range of tested stiffness, males showed decreasing attachment ability with decreasing substrate stiffness. This sexual dimorphism in attachment ability is explained by the contacts mechanics of a specialized, discoidal seta type in males, which is not present in females. In general, the overall level of attachment ability was reduced if compared to results obtained on rigid substrates.

In Chap. 5, structural effects on the adhesive properties of another biological prototype, spider silk anchorages, are thoroughly discussed and reviewed by Jonas

Wolff. Spider webs hang between, for example, tree trunks and plants. For the purpose of web attachment to such substrates, spiders produce a specific hierarchical structure called silk anchors, which are made of a two-compound secretion. Due to their hierarchical organization, discontinuous contact area, and material composition with embedded compliant fibers, these anchors allow secure fixation to vegetation, which is often characterized by anti-adhesive and anti-wetting properties. That is why, a proper understanding of the functional principles of silk anchors may potentially lead to novel strategies in bonding technology.

The hierarchical organization of biological attachment systems, both in climbing animals and silk anchors, is taken up as a general principle, in Chap. 6, to explain optimization strategies observed in these biological systems. Brely et al. perform, based on a multiple peeling theory, a computational study of different hierarchical and multiple peeling configurations including contact tapering, gradually changing material properties, and their combination. Further, a first detailed experimental proof of the multiple peeling theory is reported in Chap. 7. Using elastic adhesive tapes in the so-called double-peeling configuration, Heepe et al. found a very good agreement of experimentally obtained results with predictions of the multiple peeling theory.

Another general concept of adhesion in biological attachment systems is proposed in Chap. 8. Tan et al. discuss the success of biological adhesive systems considering the effective stiffness of their adhesive organs. Two successful examples in biological attachment systems with sufficiently low effective stiffness, responsible for making intimate contact with a substrate, are reviewed: (1) the hierarchical organization of gecko adhesive setae and (2) material gradients in insect adhesive setae. Based on these biological observations, current biomimetic structured adhesive materials are analyzed and improvements for next generation bio-inspired structured adhesives are proposed.

In Chap. 9, various aspects of adhesion in hairy attachment systems, such as the role of surface roughness, optimal elasticity, shear activation, hierarchical architecture including 3D configuration (see also Chaps. 5 and 6), and material gradients, are reviewed by Filippov et al. using rather simple, but effective numerical models of different parts of hairy attachment systems.

Chapter 10 by Borodich and Savencu provides a review of various models of engineering rough surfaces, including multilevel models, hierarchically structured models, and appropriate multi-scale models of contact interactions between rough surfaces with an emphasis on the historical development and evolution of such models. Moreover, a self-consistent terminology of rough surface models is introduced and further applied to bio-inspired structured adhesives.

A brief historical background of the development of bio-inspired structured adhesives is given in Chap. 11. Dan Sameoto highlights the development in contact geometry of individual adhesive elements and reviews milestones of both structured adhesives and manufacturing approaches. A detailed discussion and summary of current manufacturing possibilities in combination with advantages and disadvantages of different classes of materials with respect to the upscaling of production of

such adhesives is given. Based on this information, potential future routes for commercialization are presented.

An analysis of the development of bio-inspired structured adhesives, as done in Chap. 11, reveals that currently the majority of such adhesives rely on a mushroom-shaped contact geometry of individual elements. It was shown that this tip shape provides highest normal adhesion if it is compared to other kind of geometries. A physical explanation for the enhanced adhesion of this particular geometry is reviewed in Chap. 12. Carbone et al. review their latest theoretical and experimental results on the contact formation, interfacial stress distribution, pull-off force, tilt angle dependence, and detachment dynamics of individual mushroom-shaped adhesive microstructures (MSAMSs). For a simplified T-shaped variant of MSAMSs, optimal design parameters for maximal pull-off forces are predicted. The optimal design of MSAMSs is also the topic of Chap. 13. According to a previous, alternative contact mechanical model of MSAMSs, based on a Dugdale-Barenblatt cohesive zone model, Gorumlu et al. present experimental results of the adhesion performance of MSAMSs with well-defined tip geometries of individual adhesive elements, including variations in tip wedge angle. For a comparison, the simple T-shaped variant of MSAMSs (see Chap. 12) has a tip wedge angle of  $90^\circ$ . The authors demonstrated good agreement between their obtained experimental results and their recent theoretical model.

The concept of fibrillar adhesive elements is extended in Chap. 14 to the concept of shape complementarity. It has been employed to achieve high and reversible adhesion between an elastomer and a soft gel. Paretkar et al. investigated two configurations of elastomer–gel interfaces: (1) a ridge channel and (2) a fibril-hole configuration. For the ridge-channel structure, reversible adhesion was observed, i.e., a re-closure was possible. For the fibril-hole structure, only a strong first-time adhesion was observed. Adhesion enhancement, if compared to a smooth control interface, was shown to mainly rely on frictional sliding during extraction of the fibril or ridge from its complementary hole or channel. Such shape complementarity concept for robust bonding of very soft materials may be of interest in medical applications, involving, e.g., skin adhesion.

So far, the main focus of this book was on the adhesion control by structural effects rather than by surface chemistry. In the Chap. 15, Chinh Ngo et al. focus on the functionalization of silicone with respect to bio-adhesion. Usually, silicone surfaces are functionalized by plasma treatments and/or grafting. Here, the authors present an alternative approach by the incorporation of block copolymers. Combining advanced atomic force microscopic techniques and bio-adhesion experiments with mussels with two model systems, the authors showed that these organisms attach preferably to block copolymer-filled coatings after immersion in water due concomitant molecular reorganization at the top surface of the copolymer-filled coatings. These observations provided evidence for the significant role played by the selected amphiphilic block copolymers to promote bio-adhesion on surface-treated silicone coatings.

In summary, this book presents an overview of current research activities on performance of biological and bio-inspired attachment systems in real environment.

Different chapters provide experimental and theoretical novices in the field of biomimetics of adhesive systems. The volume is intended for use by researchers who are active, or plan to become active, in the field. The appeal of this topic is expected to be broad, ranging from biology and biomechanics to tribology and surface engineering.

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