Nano Today (2012) 7, 496—513

Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/nanotoday

REVIEW

Nano meets beetles from wing to tiptoe: Versatile tools for smart and reversible adhesions

Changhyun Pang[a,c], Moon Kyu Kwak[b], Chanseok Lee[c], Hoon Eui Jeong[d], Won-Gyu Bae[e], Kahp Y. Suh[a,c,e,*]

[a] *School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Republic of Korea*
[b] *School of Mechanical Engineering, Kyungpook National University, Daegu 702-701, Republic of Korea*
[c] *World Class University Program on Multiscale Mechanical Design, Seoul National University, Seoul 151-742, Republic of Korea*
[d] *School of Mechanical and Advanced Materials Engineering, Ulsan National Institute of Science and Technology, Ulsan 689-798, Republic of Korea*
[e] *Interdisciplinary Program of Bioengineering, Seoul National University, Seoul 151-742, Republic of Korea*

Received 15 May 2012; received in revised form 21 September 2012; accepted 20 October 2012
Available online 17 November 2012

KEYWORDS
Beetle;
Dry/wet adhesion;
Wing locking;
Interlocker;
Microrobot

Summary Nanoscale observation of beetle's attachment systems has revealed various exquisite multiscale architectures for essential functions such as wing fixation, crawling, mating, and protection from predators. Some of these adhesion systems are mediated by liquid secretion (capillary force), whereas some are purely operated by direct interlocking of high-density microfibers or contact of mushroom-like hairy structures (van der Waals force). In this review, we present an overview of recent advances in beetle-inspired, artificial dry and wet adhesives in the context of nanofabrication and material properties. For convenience, the beetle's adhesions from wing to tiptoe are classified into four types: hair interlocking, mushroom-shaped pads, oil-assisted spatula-shaped pads, and claws. After introducing the structural features and functions of these systems, we describe how the current nanofabrication methods can be applied to mimic or exploit the systems. Furthermore, relevant beetle-inspired structural materials, devices (fastener, medical tape, electric connector, etc.) and microrobots are briefly overviewed, which would shed light on future smart, directional and reversible adhesion systems.

Introduction

Nature has created unique structural surfaces with various functions such as adhesion, wetting, friction, and optics using multiscale architectures and materials. These surfaces have proven extremely useful in various disciplines and have impacted virtually on every scientific area.

* Corresponding author at: School of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-742, Republic of Korea.
E-mail address: sky4u@snu.ac.kr (K.Y. Suh).

1748-0132/$ — see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.nantod.2012.10.009

Examples include directional wetting of spider net [1,2] and fibers [3—7], insect compound eye [8], water-repellency of lotus leaf [9—14], gecko and insect adhesions [15—23], and locomotion for microrobots [24—27]. Recently, these bio-inspired functional surfaces have paved the ways to the development of innovative bioactive or energy conversion systems such as nanoelectric scaffolds [28,29], skin-like flexible sensors [30—32], homeostatic biomechanics [33], leaf-like photovoltaics [34], artificial photosynthesis [35], and autostereoscopic displays [36].

More recently, smart adhesive properties of beetles have been emerging as a new natural source of versatile tools for nano-electronics as well as biomedical systems. In comparison to the previous well-known animals including gecko lizards, spiders, etc., one distinct feature of beetle's adhesion systems lies in their versatility with unique functional micro/nano-structures in different locations on its body. In particular, the beetle's adhesion systems from wing to tiptoe can be classified into four types: hair interlocking, mushroom-shaped pads, oil-assisted spatula-shaped pads, and claws.

The beetle has ability to take advantage of each adhesion system under different surface conditions and situations, such as flying, resting, mating, crawling locomotion and wet-assisted protection. In order to carry out these functions efficiently, the structures of beetle's adhesion systems are diverse and well-adapted to each function, including microfiber arrays, mushroom-shaped pads, and oil-assisted spatula pads. Moreover, the beetle's adhesion systems are distinguishable from those of gecko, in the sense that the structures of gecko toe-pad are highly organized in a hierarchical fashion and slanted so as to maximize dry adhesion and locomotion [15—17,23,37,38]. In contrast, the beetle's adhesion is mediated via capillarity- or van der Waals forces with relatively simple structures depending on the specific function. It is worthwhile noting that, when properly utilized, the above structural functions of beetle can be adapted into useful materials or devices in the forms of reversible fasteners [39—42], electric connectors [43], mushroom-shaped dry/wet adhesives [44—49] and their (bio)medical and robotic applications [50—52], and capillary-based switchable adhesion [53,54] using the beetle's defensive foot-adhesion [55,56].

In this review, we provide an overview of various structural functions of beetles as well as recent advances in beetle-inspired, artificial dry/wet adhesives with an emphasis on geometry and material properties. This review consists of five sections: in the first section, the beetle's adhesive structures are described to explain why a particular structure is needed for its designated function. Representative applications for each function are also briefly introduced. In the following sections, specific beetle-inspired materials and devices are overviewed, including the wing-locking device (2nd section), mushroom-shaped dry adhesives (3rd section), and oil-assisted wet adhesive devices and robots (4th section). From 2nd to 4th sections, each section is accompanied by relevant micro/nanofabrication methods, materials, and theoretical modeling. In the last section, we provide perspectives and future directions for beetle-inspired research beyond the current conceptual prototypes. For the next level, several issues are proposed for the limitations and challenges in terms of durability and cost-effective scalable fabrication methods.

Adhesive structures of beetles and their applications

Tremendous beetle species (*Coleoptera*, approximately 3,500,000 species worldwide [57]) have remarkable capabilities of adhesion for flight at a distance and locomotion on various complex surfaces. The beetle's adhesive structures are present on the whole body from wing to tiptoe, which can be classified depending on the particular function of each adhesive system. Nanoscale observation of beetle's attachment systems has revealed unique, complex surface architectures with or without liquid secretion as shown in Fig. 1(a), demonstrating essential functions that are needed for its survival. At first, the wing-locking device in beetles (e.g., *Promethis valgipes*) is operated by bringing densely populated micro-hairs (termed microtrichia) on the cuticular surface in contact in order to fix their delicate flight wings (Fig. 1(b)) [39,58]. In contrast to other reversible binding systems (e.g., hooks or loops in commercial Velcro®), the interlocking mechanism of wing-locking device does not require any physical grasping of complicated structures [39]. Fig. 1c(i)—(iv) shows that a group of beetles have claws (e.g., *Gastrophysa viridula*) [59] and mushroom-shaped pads (e.g., *Leptinotarsa decemlineata*/*Chrysolina fastuosa*) [60] for locomotion on a ground or a tree, and oil-assisted spatula-shaped pads for walk or defense system (e.g., *Hemishpaerota cyanae*/*G. viridula*) [55,56]. In the case of mushroom-shaped setae, symmetric nano-roof structures induce conformal contacts for adhesion on rough dorsal surfaces of a female (e.g., *L. decemlineata*) [61]. Interestingly, some beetle families (e.g., *C. fastuosa*) have mushroom-tipped seta for non-slip attachment on various surfaces of plants [60]. In addition, the spatula-tipped pad of beetle's foot is covered with branched fibers, which are reminiscent of gecko's seta, and a thin liquid layer covers the surface by secretion from the basal nano-pores (e.g., *G. viridula*/*H. cyanae*) [55,56,62]. These oil-assisted asymmetric pads are actuated under dynamic situations of walking or defensive adhesion. The functional mechanisms of the attachment systems are still not fully understood, which are currently under active investigations from many research groups, aiming at a new branch of integrative beetle-inspired surfaces and systems.

Table 1 summarizes five adhesive structures in beetles along with their characteristics. Detailed explanations are as follows:

a. Time-dependent attachment: long-term or short-term attachment

Beetle attachments can be divided into two types based on time-domain functionality, which are operated in different surface conditions or situations: long-term fixation and short-term locomotion. The former includes the wing-locking device, mushroom-shaped pads, and oil-assisted spatula-shaped pads for defensive adhesion. These attaching systems are reversible with an active response to the change of circumstances in particular cases such as short traveling, mating with a female, or