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Multi-Functional Insect Cuticles: Informative Designs for Man-Made Surfaces

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Abstract—Biomimicry has many potential benefits as many technologies found in nature are superior to their man-made counterparts. As technological device components approach the micro and nanoscale, surface properties such as surface adhesion and friction may need to be taken into account. Lowering surface adhesion by manipulating chemistry alone might no longer be sufficient for such components and thus physical manipulation may be required. Adhesion reduction is only one of the many surface functions displayed by micro/nano-structured cuticles of insects. Here, we present a mini review of our understanding of insect cuticle structures and the relationship between the structure dimensions and the corresponding functional mechanisms. It may be possible to introduce additional properties to material surfaces (indeed multi-functional properties) based on the design of natural surfaces.

Keywords—Biomimicry, micro/nanostructures, self-cleaning surfaces, superhydrophobicity

I. Introduction

For a long time insects have employed micro/nanostructures on their cuticles, especially their wings, to serve extraordinary functions. Developed through evolution the surface asperities often reduce the insect cuticle adhesiveness beyond many man-made flat surfaces and greatly enhance the insect's survival in harsh environments. It also helps them to escape from accidental contact with water or sticky surfaces (e.g., spider webs). As well as reducing surface adhesion, the surface structures depending on their dimensions and shapes can also aid in other functions that co-exist on the cuticle membrane. These include camouflage (colour patterns or anti-reflection) [1]-[3], thermal regulation [1], communication [1], [2] and friction/wear reduction [3]. Surfaces with low adhesion to water droplets resulting in a self-cleaning function are common amongst many of these insect cuticles.

Since Wenzel's publication on the wettability of textile fabrics and the resistance of solid surfaces to wetting by water [4], altering surface energies with surface roughness has been widely researched. Roughness induced low energy surfaces have been widely applied in micro and nano-electro-mechanical systems. As devices become smaller, their components start to encounter more problems associated with surface effects such as surface adhesion and friction leading to device malfunction and difficulty in production [5]. Apart from reducing surface energies other 'technologies' from insect cuticles could potentially be incorporated onto/into a range of products including textiles for a multitude of purposes [3], [6-9].

It may be possible in the near future to combine various insect cuticle structuring and create a single surface with multiple desired functions. Specific functions could also be enhanced by altering the surface structure shapes and dimensions. In this paper we explore some of these attributes found on insect species that could extend the potential applications of man made surfaces/devices.

II. Low Adhesive and Self-Cleaning Surfaces

To maintain sufficient mobility and high functional efficiency of their wings, many insects (particular those with a high ratio of wing surface area-to-body mass) have the ability to reduce/remove surface contamination.

Altering surface chemistry to further reduce surface adhesion may have reached an evolutionary stage where it is more difficult than employing micro/nano scale surface roughness which reduces the contact adhesion between component surfaces.

The micro/nano-scale asperities on insect cuticles lower the surface adhesiveness by reducing contact area with foreign contacting surfaces. Solid and liquid particles will roll or fall off the low adhesive surface at slight inclinations. Water drops are restricted from entering the small spacings between the surface structures (Fig. 1) and results in a higher apparent contact angle θ_c. The Cassie-Baxter expression [10] provides a good approximation for this wetting behaviour and is given by:

$$\cos\theta_C = R_f f_{SL} \cos\theta + f_{SL} - 1 \qquad (1)$$

where R_f is the roughness factor defined by the solid-liquid area to its projection on a flat plane (the roughness factor of the wetted area) and f_{SL} is the fraction of the solid/water interface (the area fraction of the projected wet area). θ represents the contact angle which would occur on a smooth surface with the identical chemistry and can be expressed by the Young's relation $\cos\theta = (\gamma_{SV} - \gamma_{SL}) / \gamma_{LV}$ where the γ_{ij} terms correspond to the solid-vapor, solid-liquid and liquid-vapor interfacial energies/tensions, respectively.

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Fig. 1 Interaction of a water drop with structured surface according to the Cassie-Baxter model

The surface roughness of the wing may allow insects to shed water off their wings quickly reducing the flying weight of the insect. Moreover droplets will also pick up contaminant particles along the way hence produce a self-cleaning effect.

Thus adoption of similar chemistry and topography to micro/nano scale cuticle structuring may lead to low energy surfaces with self-cleaning properties. The micro/nano-structures are not limited to sophisticated technological devices. Applying self-cleaning structures on everyday surfaces like windows, cars and bathroom tiles may help reduce maintenance and extend material lifetimes [3], [11].

III. Waterproofing Hairs

Setae (hairs) on many insect cuticles (lacewing [12], termite [13], cranefly [14], and water strider [15]) have been shown to prevent wetting to the underlying cuticle membrane by holding water droplets on their tips (Fig. 2). Dense nano-patterned hairs found on the legs of water striders can withstand high hydrodynamic pressure experienced during leg strokes while traversing across the water surface [16]. Water drops with kinetic energy falling onto the surface of the wings of the lacewing can be repelled away with the aid of the hairs acting as a layer of microsprings that resist penetration and dispersal of drops. The drops can also partially wet the underlying membrane surface and collect contaminants in the wetted region (Fig. 3) and remove them.

These types of setae have potential applications as liquid-stain-proofing for textiles such as clothes and carpets.

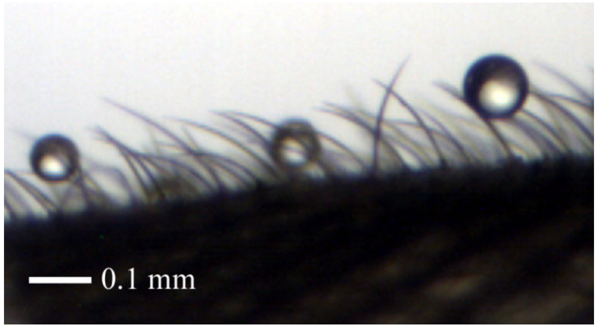

Fig. 2 Optical microscope image of microdroplets of water from a mist sprayer supported by hairs on the lacewing *Nymphes myrmeleonides*

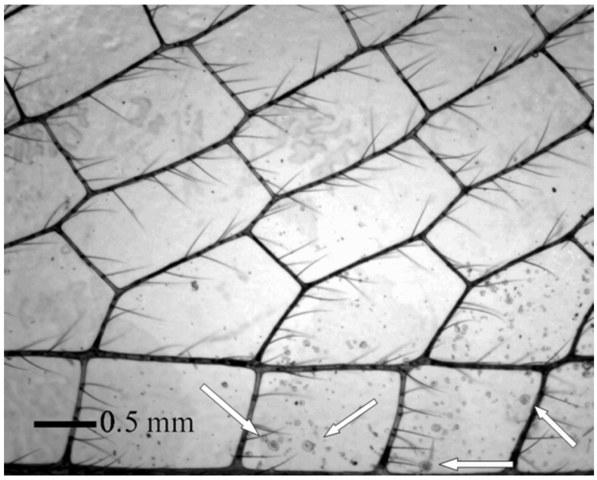

Fig. 3 Optical microscope image of the lacewing contaminated with silica beads and cleaned by water drops dropped from a pipette 10cm above. The bottom right corner of the image was not wetted and remained fairly contaminated. Four of the larger beads remaining are indicated by arrows

IV. High Optical Transmitting Surfaces

Ordered hexagonally packed structures with a spacing and height of ca. 200 nm are found on the surfaces of moth eyes [17] and the transparent wing membranes of a number of cicada species (e.g., *Tamasa tristigma, Macrotristria angularis*, *Thopha saccata Psaltoda claripennis*, and *Cicadetta oldfieldi*) [17-20] (Fig. 4). The surface with the structures can be thought of as a homogeneous surface with a smooth transitional increase in refractive index to improve transmittance and thus lower reflectance [17] of light and improving camouflage. These anti-reflective, surfaces can be easily replicated on polymers such as PDMS (Poly-Di-Methyl-Siloxane) [19] and may find applications for other transparent surfaces where low contamination and high light transmission is desired such as display monitors and shop windows. A 10% increase in energy capturing of solar panels have been reported [3], [21].

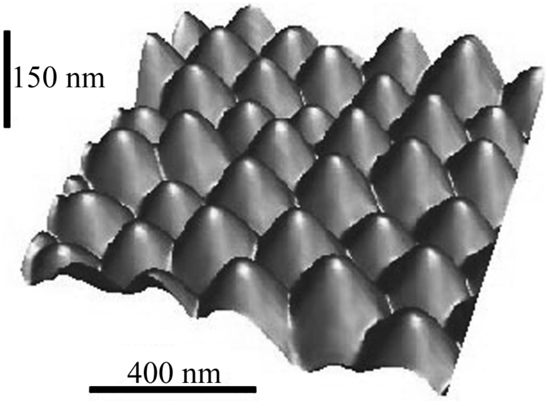

Fig. 4 Atomic Force Microscope generated 3D image of a cicada wing array

V. Optical Properties of Lepidoptera Scales

Many butterflies and moths (Lepidoptera) possess a structuring on their wings comprised of many scales organized in a tile-like arrangement. The colour of the butterfly is enhanced due to the arrangement of the surface asperities of the scale [22], [23]. Depending on the scale size, curvature and arrangements, these insect wings can display a range of optical functions such as iridescence and/or selective wavelength absorption/reflection which serves the purpose of camouflage, signaling, and thermoregulation [1].

Scale alignments that absorb light can be mimicked to produce a solar thermal collecting surface to be applied on winter clothes and outdoor surfaces where heat absorption and self-cleaning functions are desired. The iridescence of the butterfly may also function as a distracting camouflage to avoid predation while in flight [1]. The technology could be also utilised to discourage animals such as on a scarecrow.

Reflecting a specific range of wavelength of light using their wings as a form of communication is common amongst butterflies [1] and dragonflies [2]. This technology has potential for ultra-violet reflective glass to prevent harmful UV passing through windows of cars and buildings. Physical colouration of textiles using surface structure to scatter, diffract or create interference has been reported [3], [23] and commercially produced [6].

VI. Weight And Material Minimisation

Some insects present surface asperities designed to minimise weight and material usage [12-14]. Insect surfaces like butterfly and moth wings show hierarchical levels of structuring where the surfaces of the primary structure (scales) are also covered with asperities (holes and crisscrossing ridges). As well as further reducing the solid-liquid contact, weight and material of the energetically expensive chitin (the basic material make-up of many insect cuticles) [17] is reduced.

In the case of some termite species (e.g., *Microcerotermes sp*) the wings present microstructuring in the form of small clusters, (called micrasters) (Fig. 5). These structures serve as an anti-wetting protection layer and have an open form of structuring to minimise weight and material. If this form of structuring was not of an open arrangement but of a solid architecture then the wings would become five times heavier [13] and excess weight may inhibit the ability to fly.

Various grooves on setae of many insects (Fig. 6) may possibly enhance the stiffness and promote direct wetting [14], [24]. Hydrophobicity is greatly reduced when the surface grooves are eliminated [12-15], [25]. In the case of various termite species (e.g., *Nasutitermes sp*), the grooves on the hairs may reduce the weight of each hair by as much as 10%.

Protrusions on some cicada wings due to their shape (e.g., *Gudanga sp)* have a small region of attachment at the base (Fig. 7) allowing a larger air pocket and giving additional air pressure that may help to repel falling drops off the surface. The narrower base reduces the volume of each protrusion by more than 30% [26].

Fig. 5 SEM images of termite wing membrane surface showing star-shaped micrasters and a hair

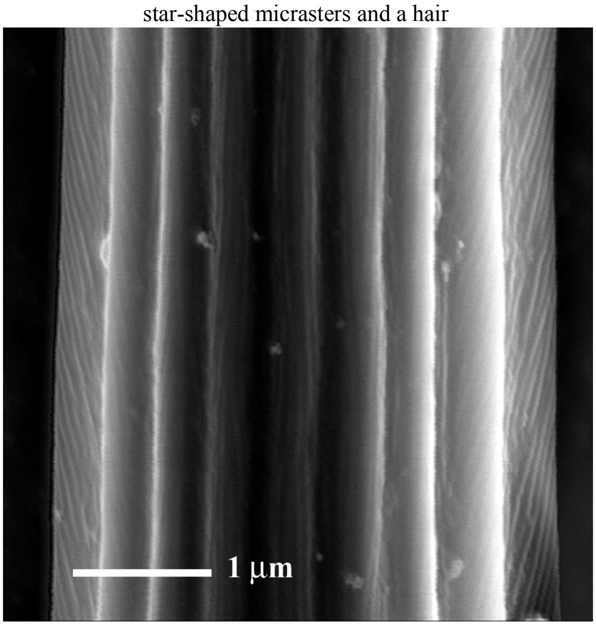

Fig. 6 SEM image of the hair of lacewing showing surface grooves and ultra fine channels at about 45 deg that meet at the top and bottom of the larger grooves

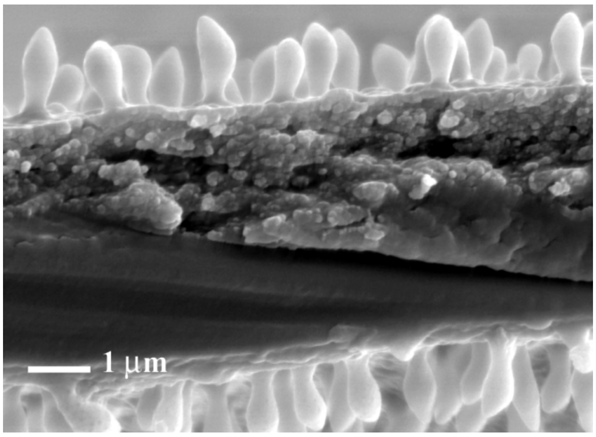

Fig. 7 SEM image of the side view of the cicada wing of *Gudanga sp.* showing the thinner base of the surface structures

Weight restrictions need to be taken into account for improving the efficiency of small unmanned miniature aerial vehicles of similar dimensions to insects. Micro Air Vehicles (MAV) defined as small, portable flying vehicles can be used for reconnaissance missions that may be unsafe or inaccessible to humans [27]. The combined advantage of weight reduction and low contaminability may allow them to fly into a range of inhospitable environments such as dusty gravels of collapsed buildings (collapse of the world trade centres [27]) and tropical storms. Water walking devices [28] could also benefit from optimised weight reduction.

VII. Introducing Multifunctionality onto One Surface

It may be possible to create surfaces with multiple micro and nano shapes as an alternative path to accommodate more functions onto one surface. Some insects incorporate varied chemistry and/or cuticle architecture for this purpose. For example desert beetles have alternating hydrophobic and hydrophilic regions on their elytron (hard protective forewing) which they use to collect drinking water from the early morning fog [29]. Wing setae on many insect wings which may contribute to aerodynamic factors [30] also have superhydrophobic structures to further reduce wetting at different length scales [13].

The idea of combining various bulk material properties (thermal, optical, mechanical) into a hybrid material is not uncommon [3], [6], [9], [31]. By understanding the relationship between the shape of surface structures and their functional mechanisms, it may become a future trend in man-made technology to introduce new functions and multiple functions onto a surface. This can be achieved by adding new layers of structuring amongst pre-existing architectures. For instance combining the water collecting technology on the desert beetle with anisotropic wetting arrangements (e.g., scales on the butterflies [32] or micro/nanogrooves [14], [24], [33], [34]) to direct the collected moisture to the desired location may result in faster water collection and reduce water loss. Implementing shallow surface roughness on the hydrophilic regions increases the area of the seeding points for water adsorption and may increase the water collecting efficiency. Adopting hierarchical arrangements on the surfaces such that one structure covers the surface of another could improve functional efficiency of the surface and may reduce the functional interferences.

VIII. Conclusion

Many of the ‘free technologies’ found on insect cuticles have intriguing functions. Functional-efficiencies of man-made surfaces are improving as surface replication, manipulation, and lithographic techniques improve. At the present time the main application of surface roughness is to reduce surface adhesion and friction. In the near future, these man-made surfaces could possibly start to be implemented with a variety and mixture of multi-functional surface structures to further improve man-made technologies/devices.

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