Macro-/Micro-structures and mechanical properties of elytra in beetles--Balance of lightweight and high-strength*

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1 Introduction

Beetles are one of the few insects which possess multiple locomotive capabilities and have developed multi-functional macro- and micro-structure. Some elytra have a non-smooth surface texture with scattered micro-concavities, which have inspired engineers to develop tools with lower soil adhesion and frictional resistance[1-4]. The other possess a honeycomb-trabecula structure to increase the peeling resistance greatly[5,6], or braided by branched fibers to produce much greater pull-out force than that of straight fibers [7]. There exist four different easy and effective locking-mechanisms for beetle to lock its elytra to the abdomen, wings and scutellum tightly[8-10]. The elytra couple each other with a symmetrical concave-convex structure[11,12]. The geometry of elytra opening and closing in some beetles are a planar rotation around a single axis across the scutellum[13] .

To meet the requirement of developing lightweight structures, we studied the elytra from surface textures, macro- /micro-structures, topology of mechanical properties, as well as the coupling mechanism point of view. The purpose of the paper is to further our studies in the direction[14] and to set up several much general ideas for biomimetics on designing and developing lightweight structures.

2 Experimental details

Four species of beetles (Cybister, A.dichotoma, P.brevitarsis, Serrognothus titanus) were studied. Samples were washed in an ultrasonic machine for five minutes and air dried for about thirty minutes, then put under the microscope to observe the surface texture. Mechanical properties were measured by a Nano-Indenter (SA2, MTS, USA) and the tensile stress of the elytra and the coupling force were tested using a multifunctional test machine.

3 Result

3.1 Surface texture of elytra

The surface textures of beetles' elytra are composed of furrow stripes and concavo-convex texture. The former is corresponds to Big cybister, Agrilus nakanei, etc. and the latter is corresponds to A.dichotoma, P. brevitarsis, Serrognothus titanus, etc. The surface of Cybister's elytra is very smooth for macroscopic view.

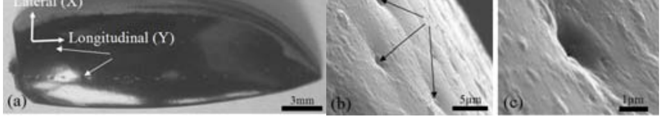

Figure 1 Surface morphology of Cybister elytra (a) a single elytron (white arrow marked two pit lines) (b) SEM photo of the elytra (the black arrow) (c) microstructure of a single pit

There are two distinct punctures apart from 3~4mm each other along the longitudinal direction of elytra (Figure 1(a)arrows). They are non-smooth for microscopic view, on which distribute many micro-concavities with diameter 1-2μm (Figure 1(b) and (c)). Figure 2 shows the surface morphology of three beetles (Potosia brevitarsis, Serrognothus titanus, Big cybister).

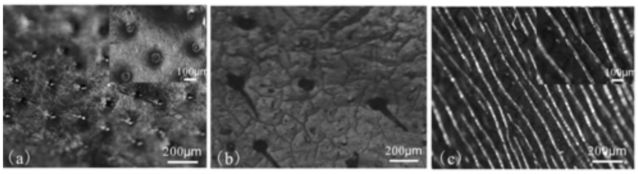

Figure 2 Surface morphology of three beetles elytra
(a) *Potosia brevitarsis* (b) *Serrognothus titanus* (c) *Big cybister*

P. brevitarsis (Figure 2(a)) and S. titanus (Figure 2(b)) have similar surface morphology with that of Cybister, but the microstructure and the density of the micro-concavities are different. The surface texture of elytra of Big cybister is also non-smooth, but microstructure is furrow stripes (Figure 2(c)), that is quiet different.

3.2 Microstructure on cross-section

The microstructures of cross-sections of three beetles' elytra. It indicates that the beetles elytra have s similar structure topology, namely a lightweight and hollow structure, in which the fiber bundles connect the exocuticle to the endodermis act as a bridge pier. The thickness of the Cybister elytra, the black epicuticle and a single fiber layer in exocuticle is 220.78±37.67 μm, 11.84±1.99 μm and 5.04±1.68 μm (Number of samples N=7, number of measurements n=21), respectively. Inside the elytra sections are some circular cavities around which are several twisted parallel fiber layers. The elytra are spanned by 25~35 cavities with average diameters of 81.57 ± 12.83 μm (N=3, n=15) in lateral direction. In the longitudinal direction the values are 70~80 and 100.83 ± 16.60 μm (N=4, n=22), respectively. The fiber bundles, act as a bridge pier, are braided with the fiber layers in helix, positive-negative way. The duty ratio (the cavity areas to the elytra areas) of Cybister elytra is about 22%. The specific gravity of Cybister elytra is 0.89 g/cm3. The geometric structural parameters, duty ratio and density of elytra of three beetles are list in Table 1.

The elytra consist of several layers: a black dense epicuticle, followed an exocuticle braided by several chitin fiber layers in a helix structure, and then bridge piers formed by the fiber bundles connecting the exocuticle and endodermis. Lots of setae, micro-spikes or micro-concavities are grown in the ventral side of

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the elytra which depends on the species of beetles.

Table 1 Geometric structural parameters of three beetles' elytra

Beetle	TEL(μm)	TE(μm)	TFL (μm)	N	DR	D (g/cm^3)
Cybister	220.78±37.67	11.84±1.99	5.04±1.68	10	22%	0.89
AD	99.77±12.44	10.06±1.35	2.67±1.02	6	31%	0.88
PB	110.34±14.31	23.45±2.14	3.55±1.16	6	36%	0.80

TEL—Thickness of elytra; TE-- Thickness of epicuticle; TFL--Thickness of fiber layer; N-- Numbers of fiber layers; DR—Duty ratio; D—Density; AD-- *Allomyrin dichotoma;* PB--*Potosia brevitarsis*

3.3 Tensile tests

Table 2 shows that the fracture to strain of fresh samples is smaller than that of dry samples either lateral or longitudinal direction. Considering the influence of error, there is no apparent difference among them and the average value of fracture to strain is 12.46%. As far as modulus is concerned, the results of fresh elytra are twice larger than that of dry elytra either at lateral or at longitudinal direction. The maximal value is 1,412 MPa for fresh elytra at longitudinal direction. The change tendency of limit stress is similar to that of modulus. The maximal value is 194.5 MPa for fresh elytra at longitudinal direction while it is 90 MPa for dry elytra. The specific gravity of beetles elytra is 0.8~0.9 g/cm^3. So the specific strength is 190~218 $MPa/g\bullet cm^{-3}$.

Table 2 Results of tensile tests in Cybister elytra

Elytra Samples		SAF (%)	YM (MPa)	SSF (MPa)
Fresh	lateral	12.22±1.97	1192±129	169.2±22.5
	longitudinal	12.21±0.95	1412±159	194.5±23.4
Dried	lateral	12.75±1.53	564±79	85.4±13.7
	longitudinal	12.74±0.53	593±160	90.9±18.7

SAF--Strain to fracture; YM--Young's modulus; SSF--Stress to fracture

3.4 Coupling strength

The mean coupling force between the elytra of P. (Liocola) brevitarsis are 1,014 mN (tests n=23 and animals N=16); the force is 623, 552 and 160 mN for the beetles of the species C. molossus, dichotoma, and S. titanus, respectively. The larger deviation of the coupling forces may result from the individual variation of beetles, or from the artificial reformation of the elytra, or even from the possible difference of the glued point of wire on the elytron. To evaluate the coupling forces more objectively and to avoid the influence of body size, a coupling force per length was defined by way of measuring the coupling length and dividing the coupling force by the length of the sutural edge, which was measured using a wire along the sutural edge. The results show that the unified coupling force of P. (Liocola) brevitarsis is much higher than that of others. Furthermore, dividing the result by the body weight (BW), the coupling force per BW for P. (Liocola) brevitarsis (0.64±0.06 g, N=22) is 160, which is the highest of all species, while that of S. titanus (2.76±0.98g, N=10) is only 6.5, which corresponds to the lowest of all species. It could be concluded out that geometric structure or the shape of suture plays a key role in the coupling strength.

4. Discussions and conclusions

4.1 Structure topology and microstructure

Surface texture heavily affect the wettability of elytra in beetle[15]. Elytra consist of chitin fiber which are tough and resist tension well[16].The structures of fiber layers, braided in parallel and twisted manner, may reduce the shear stress of the composite, enhance resistance to shearing and peeling. Similar with traditional honeycomb structure and folded structure, beetles' elytra are hollow and lightweight biomaterial. What different is the cavities in the elytra are not transfixed with each other. The advantage of biomaterial can eliminate the problems existing in the traditional materials (honeycomb, folded and metal foam structure),where discontinuous interface between lightweight material and outer panel skin may be insufficient strength and unreliable. Morphological observations reveal that the multilayer structure within the exocuticle differs little among the different color morphs but the layers within the epicuticle have characteristic thicknesses that correspond to the observed color. The reflectors consisting of five layers within the epicuticle are responsible for all the different colors observed in P. sericea[17].

4.2 Mechanical properties

Research shows only slight differences on the elytra, which indicates that elytra have an optimized structural design. Hence the mechanical properties of high stress regions are more density than the lower stress region. These considerations in the structural design help to significantly reduce the weight and to enhance the strength of elytra.

4.3 Tensile tests

The experiments suggest that the modulus has a similar change tendency with the limit stress of elytra. The results of fresh elytra are twice times that of dry elytra as well as the values of longitudinal samples are larger than that of lateral samples at both condition. The average strain to fracture of Cybister elytra is 12.46±0.34%. Compared with other biomaterials (strain to fracture for a crab claw is 6.4±1.0% [18] ; for a lobster cuticle, it is 1.8±0.3%[19]), the Cybister elytra have much better flexibility.

4.4 Coupling strength

The measurements revealed that the coupling forces are 6.5~160 times that of the beetle's body weight, which suggests that the coupling structure may have a very high connecting strength, while that an ingenious controlling mechanism must be available to ensure the opening and closing of the elytra occurs. The experiments revealed that the scutellum, which is located in the two elytra, and the ospresternum are essential parts of the controlling structure for unfolding of the elytra, when a very small force is exerted on the scutellum, the elytra can be unlocked easily.

References(omitted)

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