Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 7 (2010) 6–12

Macro-/Micro-Structures of Elytra, Mechanical Properties of the Biomaterial and the Coupling Strength Between Elytra in Beetles

Zhendong Dai, Zhixiang Yang

Institute of Bio-Inspired Structure and Surface Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, *P. R. China*

Abstract

Macro-/Micro-structures and mechanical properties of the elytra of beetles were studied. The Scan Electron Microscope (SEM) and optical microscopy were employed to observe the macro-/micro-structure of the surface texture and cross-section structure of elytra. Nano-indentation was carried out to measure the elastic modulus and the hardness of elytra. Tensile strengths of elytra in lateral and longitudinal directions were measured by a multifunctional testing machine. The coupling force between elytra was also measured and the clocking mechanism was studied. SEM images show the similar geometric structure in transverse and longitudinal sections and multilayer – dense epicuticle and exocuticle, followed by bridge piers with a helix structured fibers, which connect the exocuticle to the endodermis, and form an ellipse empty to reduce the structure weight. The elastic modulus and the hardness are topologically distributed and the mechanical parameters of fresh elytra are much higher than those of dried elytra. The tensile strength of the fresh biological material is twice that of dried samples, but there is no clear difference between the data in lateral and longitudinal directions. Coupling forces measured are 6.5 to 160 times of beetles' bodyweight, which makes the scutellum very important in controlling the open and close of the elytra. The results provide a biological template to inspire lightweight structure design for aerospace engineering.

Keywords: beetle, elytra, mechanical properties of biomaterial, coupling force

doi: 10.1016/S1672-6529(09)60187-6

1 Introduction

Beetles can fly, walk or climb on surfaces at any orientation, dig holes and swim. During millions of years of evolution and adaptation, beetles have developed multi-functional macro- and micro-structures. The elytra of *Catharsius molossus* have a non-smooth surface texture with scattered micro-concavities. This morphology has inspired scientists to develop tools with lower soil adhesion and friction[1–4]. The elytra of *Allomyrina dichotoma* possess a honeycomb-trabecular structure, which can greatly increases the peeling resistance[5,6]. The elytra of *Potosia brevitarsis* are braided by branched fibers, which can endure much greater pull-out force than straight fibers[7]. Moreover, there are four different simple and effective locking mechanisms which lock the elytra to the abdomen, wings and scutellum tightly[8–10]. The elytra are centrally joined with a symmetrical concave-convex structure[11,12]. The geometry of elytra opening and closing in some beetles is a planar rotation around a single axis across the scutellum[13]. The beetle wings that only make up 0.5% to 5% of body weight, can produce 75% of the lift force[14–16]. The wings are composed of veins and membrane and the Young's modulus ranges from 0.3 GPa to 13.7 GPa, where the modulus of vein is apparently higher than that of vannus[17,18].

To meet the requirement of developing lightweight structures, which is always demanded in aerospace engineering, we studied the elytra from the viewpoints of surface textures, macro-/micro-structures, relationship between topography and mechanical properties, and the coupling mechanism. The purpose of this paper is to further our studies in the direction[19] and to propose some general ideas for biomimetics in designing and developing lightweight structures.

Corresponding author: Zhendong Dai
E-mail: zddai@nuaa.edu.cn

2 Materials and methods

2.1 Materials

Four species of beetles (*Cybister japonicus*, *Allomyrina dichotoma*, *Potosia brevitarsis*, *Serrognothus titanus*) were used in mechanical properties study. The samples of *C. japonicus* were bought from the Guangzhou aquaculture market and the other beetles were collected at Zijin Mountain in Nanjing. Five beetles from each species were killed and soaked in 70% alcohol solution immediately. Before testing, they were dehydrated and air dried as dry samples. Other beetles were bred in laboratory and killed in an hour before testing as fresh samples.

2.2 Microscopy examination

Before observation, elytra were cleaned in pure water by an ultrasonic machine for five minutes and air dried for about thirty minutes. To observe the microstructure of the cross-section, the cleaned elytra were dehydrated in 70% alcohol for thirty minutes, air dried and frozen in liquid nitrogen for over an hour. Then, elytra were broken with a nipper along the lateral and longitudinal directions. Samples were sputter-coated with gold-palladium (50 nm ~ 100 nm) and observed with a SEM (QUANTA200, FEI, UK) at 20 kV.

2.3 Measurements of mechanical properties

Some mechanical properties, namely elastic modulus and hardness, were measure with a Nano-Indenter (SA2, MTS, USA). The samples were cut from the different zone of the elytra (sample size: 2 mm×2 mm; number of samples: 8 for each zone). The measurements were repeated 6 to 10 times under experimental parameters as following: depth of the indentation, 500 nm; the thermal drift rate, 0.15; the Poisson ratio, 0.3; the temperature around, 25 ˚C and the humidity, 65%.

2.4 Measurements of ultimate tensile stress and strain of elytra

Ten fresh elytra and ten dried elytra, taken along either the lateral or longitudinal direction (Fig. 1a), were prepared for measuring the ultimate tensile stress and corresponding strain. The tensile tests were performed using a multifunctional testing machine. One end of the specimen was clamped by a screw on a sample holder, and the other was clamped to the sensor and kept vertical with the pulling force (sample size: width 1.5 mm and length 3 mm centre zone for measuring, two 4 mm width ends for clamping)[19]. When testing, the sensor was lifted by a motor until the specimen was broken. The limited forces measured by the sensor were digitally recorded and the tensile stresses were calculated. The corresponding displacements from the motor were digitally obtained and the tensile strains were also calculated[20].

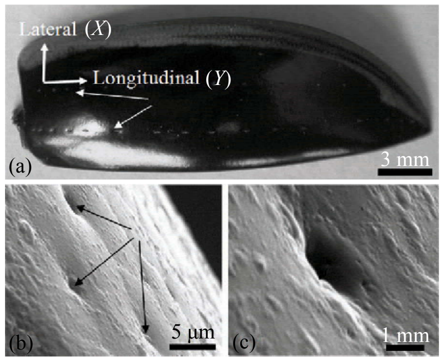

Fig. 1 Surface morphology of *C. japonicus* elytra: (a) a single elytron (two pit lines followed by the white arrows); (b) SEM photo of the elytra (the black arrows point to the pit); (c) microstructure of a single pit.

2.5 Measurements of coupling forces between elytra

Four species of beetles (*Catharsius molossus*, *Allomyrina dichotoma*, *Potosia brevitarsis* and *Serrognothus titanus*was) were used in coupling forces tests. The tests were performed using a multifunctional testing machine[21]. The elytra were extracted from the beetle and artificially reassembled in their natural coupling status. The left part of the coupled elytra was glued onto a sample holder and the right part was glued onto a wire midway along its length in order to make sure the applied force was perpendicular to the coupling zone. The other end of the wire was connected to a 2D sensor, which was moved vertically so that the wire was at a tangent to the coupled elytra, and then moved horizontally until the elytra were separated. The forces measured by the sensor were recorded using a computer and the force at which the coupling was broken was set as coupling force.

3 Results

3.1 Surface texture of elytra

The textures of elytra of beetles are composed of furrow strip and concavo-convex. The former corresponds to *C. japonicus*, *A. nakanei*, *etc.* and the latter is corresponds to *A. dichotoma*, *P. brevitarsis*, *S. titanus*,