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Design of a bionic aviation material based on the microstructure of beetle's elytra

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ABSTRACT

Because almost all adult insects can fly, their cuticles must have a low mass and high efficiency that is enabled by a delicate and complicated micro-/nanostructure. These structures provide useful bionic design templates for new, advanced composite materials. We implemented this idea in the present research to design bionic aviation materials. Here, we propose a bionic columnar and laminate (BCL) model for aircraft skin. For a comparative study, equal-quality (EQ) and equal-thickness (ET) models were established. Mechanics, heat transfer, and thermal-structure coupling analyses and optimization designs for these models were performed using ANSYS Workbench. The mechanical analysis included compression, shear and three-point bending studies. The heat transfer analysis included two types of working conditions, cruising and landing, and optimization parameters for the material design were determined: the extension length of the columnar structure was 6.26 mm, the chamfer radius was 3.08 mm, the number of columnar structures was 6, and the diameter of the columnar structures was 17.90 mm. The results of this research will provide guidance for developing advanced bionic composite aviation materials.

1. Introduction

The ongoing development of material technologies is important for ensuring continued progress and achievements in aviation and aerospace, and the development and application of these technologies also reflect the engineering capabilities and technology level of a country. Composite materials with high strength, fatigue resistance and flexibility are in high demand in modern aircraft manufacturing [1].

To adapt to the natural environment, biological materials in nature have evolved complex microstructures. Natural biological materials have several unique performance advantages compared to traditional materials [2]. In nature, the structures of biomaterials and correlations between their properties or functions are the basis of bionic materials [3]. There are more than 600,000 insect species on Earth [4], and almost all adult insects can fly. Hence, the cuticle must be a lightweight and efficient exoskeleton [5], and the design of innovative bionic composite materials can be inspired by this unique and delicate structure [6]. Bionic studies on the structure of insect cuticles can be traced back to the beginning of the last century, with Thompson's paper published in 1917 considered to be the earliest article in this field [7]. Beetle cuticles have a structure that can be adapted to their unique living environment, and these cuticles have excellent properties [8] that enable beetles to fly in the air, burrow underground and swim in water. Among these physical mechanisms, fluidic transportation and heat transfer in micro/nanofluidic systems have attracted wide scientific attention [9]. As cuticles are an important bionic reference material in aviation and aerospace, shipbuilding and architectural design and other fields, it is helpful to study the structural characteristics and structural model of the beetle cuticle in depth to aid in the systematic design of new types of high-strength and high-reliability aviation materials.

The surface of the beetle elytron exhibits two main forms: a concavo-convex structure, as found in *Cybister tripunctatus* (mainly concave pits), *Cybister japonicus* Sharp (mainly slightly convex pits) and other species; and a convex structure, as found in *C. japonicus* (diving beetles) [2]. The internal microstructure of the elytron has three main types: stacking, columnar and honeycomb-columnar.

The cuticles of beetles are composed of keratinized protein and chitin fibers. The chitin fibers in the protein matrix form the cuticle, which is stacked in a parallel cuticle and layered form. The direction of the chitin fibers in each layer is consistent, whereas the chitin fibers in adjacent layers are angled [10]. Composite laminates have been tested during bionic studies of the elytron structures of beetles [11,12]. The results showed that the fracture

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toughness of bionic composite laminates with fibers arranged in a spiral array was 12 times that of laminate materials; additionally, the bending strength and strength of the bionic composite laminates were excellent. Moreover, the fracture toughness of biomimetic laminate materials with a double-helix laminate structure was found to be 1.37 times greater than that of traditional materials [13]. Beetle cuticles also have a columnar structure that is composed of an upper layer, a hollow layer and a lower layer [14]. The hollow layers of elytra are laminated composite structures supported by a column, and the fibers in the small columnar and upper and lower layers lie at obtuse angles and are continuously connected to each other [15]. Because of the different locations of elytra, the shapes and sizes of the small columns are different and can be divided into linear and curved types; however, most elytron small columns are linear. The middle part is the smallest, but the root is relatively thick. Overall, the size and density of small columns in differ among species [14]. Another experiment showed that the existence of columnar structures can improve the stripping performance of elytra by an average of threefold, and some positions can even increase performance by dozens-fold [14]. Therefore, the columnar structures in elytra can greatly enhance their stripping performance [15]. It is also believed that elytron columnar structures are similar to a honeycomb arrangement [14,16,17]. The best compressive strength is provided by the short-cylinder model, followed by the elongated-cylinder model, and, finally, the round table model [18]. The nanomechanical properties of beetle elytra also vary by species [19], and the nanohardness of elytra within the same species varies with its location; thus, elytra exhibit anisotropy [20].

In this paper, a new type of bionic composite material model is designed based on beetle elytra. Finite element analysis software is used to study the mechanics, heat transfer, and thermal-structure coupling and optimization design. Finally, this model is analyzed and compared with two other models.

2. Materials and methods

2.1. Development of the geometric model

Fig. 1 presents a cross-sectional view of the elytron of two beetles. Field emission scanning electron microscopy (FESEM, JEOL JSM-6700F) was used to examine the microstructures of the elytron cross-sections (Fig. 1A), with Fig. 1A showing that of the dung beetle *Copris ochus* Motschulsky and Fig. 1B that of *Prosopocoilus inclinatus* [21]. Fig. 1B shows that the elytron is composed of an epicuticle, exocuticle and endocuticle. The middle layer is composed of a combination of columnar structures. The columnar structure in the middle varies with the species of the beetle and the different parts of the elytra, but the cross-section of the columnar structure is more similar to a circle.

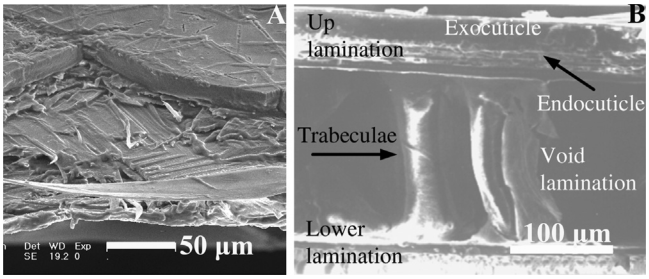

Fig. 1. (A) The laminated structure of a dung beetle, *Copris ochus* Motschulsky; (B) the trabecular structure of *Prosopocoilus inclinatus* (longitudinal section) [20].

A bionic columnar and laminates (BCL) model was developed (Fig. 2A) based on the observed lamellar fiber structure of the surface of the beetle elytron and the columnar structure of the beetle elytron in Fig. 1B. The model consists of five layers of materials. The first, third and fifth layers are 7075 aluminum alloys that are commonly used in the aviation industry; the second and fourth layers are anisotropic materials with embedded fibers. To better understand the characteristics of the model in terms of achieving a light mass and high strength, we developed two other comparative models: the equal-quality model (EQ, Fig. 2B) and the equal-thickness model (ET, Fig. 2C). The structural parameters are shown in Fig. 2.

The material parameters for each layer of the model were chosen based on the literature [17] (Table 1).

EX, EY and EZ are Young's moduli in the X-direction, Y-direction and Z-direction, respectively; GXY, GYZ and GXZ are the *xy*, *yz* and *xz* shear moduli, respectively; PBXY, PBYZ and PBXZ are *xy*, *yz* and *xz* Poisson's ratios, respectively; ρ is the mass density; k_x, k_y and k_z are the thermal conductivities in the x-direction, y-direction and z-direction, respectively; and α_T is the coefficient of thermal expansion.

For the BCL model, because of the existence of the chamfer and cryptographic network, the software automatically adopts a tetrahedral element (solid187 grid) to better adapt to the model (Fig. 3A), but the EQ (Fig. 3B) and ET (Fig. 3C) models are regular cuboid. Therefore, the software achieves a relatively high calculation accuracy using hexahedral elements (solid186).

2.2. Thermal analysis

As a very common natural phenomenon, heat transfer involves interactions between the environment, energy, structures and other fields. Engine-cooling systems, spacecraft man–machine thermal environment systems, spacecraft return-cabin insulation systems and even computer-chip cooling systems form the core of the entire system in which they participate [22].

2.2.1. The working conditions of high-altitude cruising

Based on the literature [23], when aircraft cruise at an altitude of 11 km, the ambient air temperature is −56.5 °C. The aircraft fuselage heat is mainly generated from friction between the aircraft and air and solar radiation, and the total flux of solar radiation at 40° north latitude in mid-July at noon is approximately 5128 W/m^2. Therefore, the thermal load on the models is as follows:

(1) The top surface is 5128 W/m^2.
(2) The bottom and all side surfaces are the default fully adiabatic state.

After the boundary conditions are added to the model, the results are as follows:

(1) The top ambient temperature is set at −56.5 °C, and the convective heat transfer coefficient is 178 W/(m^2 K).
(2) The middle columnar structure and its two planes in contact with the top and bottom surfaces set at the heat radiation rate are 0.55; the ambient temperature is set at −50 °C.
(3) The ambient pressure is P = 22,700 Pa, and the air flow angle of attack is 0 degrees.

2.2.2. The working conditions of low-altitude landing

Based on the literature [23], when the plane lands at low altitude, the ambient air temperature of 40° north latitude in mid-July is approximately 34 °C, and the aircraft fuselage heat is mainly due to the friction of the aircraft and air and solar radiation. At low altitude, the air density is much higher than at high altitude; thus,