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Investigation of fiber configurations of chafer cuticle by SEM, mechanical modeling and test of pullout forces

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Abstract

Insect cuticle as a natural biocomposite includes many favored microstructures which have been refined over centuries and endow the cuticle eminent mechanical properties. This paper first studies the microstructures of chafer cuticle through SEM observations. Several peculiar fiber configurations and fiber-ply arrangements such as branched fiber, acanth-fiber and helicoid plies are observed. These microstructures are useful for man-made fiber-reinforced composites to improve their mechanical properties. Then, a special configuration of the branched fiber found in chafer cuticle is in details analyzed through a mechanical model and experimental verification. The pullout force of fibers as an index is firstly studied through parameter study. The factors, which can improve the pullout forces, are identified. Finally, the maximal pullout force of the branched fiber is experimentally tested and compared with that of plain straight fiber. It is proved that the maximal pullout force of branched fibers is obviously greater than that of the plain straight fibers.

Keywords: Biocomposite; Fiber configuration; Branched fiber; Pullout force

1. Introduction

Insect cuticle is a typical natural biomaterial which is composed of chitin fiber (a high-molecular weight polysaccharide, called as bio-fiber) and proteinaceous matrix (called as bio-matrix) [1,2]. The bio-fibers embed in the bio-matrix to reinforce the cuticle in layer forms. Study on the microstructures of insect cuticle can provide beneficial information to composite material design, thus improving the mechanical properties of man-made fiber-reinforced composites.

As shown in Fig. 1, the insect cuticle can be divided into two primary sections [1]: epicuticle and procuticle. Epicuticle is the outermost layer of the cuticle and consists primarily of waxes, lipids, and proteins without chitin fibers. This layer is

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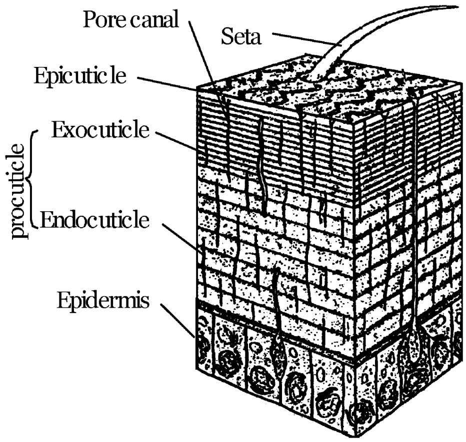

Fig. 1. A cross-section of a generic insect cuticle.

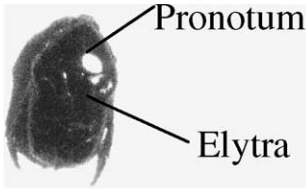

Fig. 2. Two different sections in a chafer used for observation.

about 0.1–3 μm thick and contributes little to shape or strength, but acts as an environmental barrier. Procuticle, the largest structural division of the cuticle, with thickness about 10–100 μm, enables the cuticle shape and mechanical stability [2]. The procuticle can be divided into exocuticle and endocuticle, both contain chitin fibers and protein matrix [3].

In this paper, the microstructures of chafer cuticle are observed with scanning electron microscope (SEM). Several peculiar fiber configurations and fiber-ply arrangements such as branched fiber, acanth-fiber and helicoid plies were discovered. Based on this microscopic observation, the branched fiber structure is theoretically and experimentally studied for its maximum pullout force. It is found that the pullout force of the branched fiber is greater than that of the plain straight fiber.

2. SEM observation

Chafer beetle as shown Fig. 2 is studied in this paper. Their different structural sections were selected for observation and analysis. These sections include the pronotum (a protective covering for the prothoractic, or upper body section) and the elytra (a pair of hard outer "wings" which protect the inner wings and body of the insect). Each section is examined with SEM and light microscope.

The SEM specimens are prepared as follows: Remove the cuticle from the chafer, clean it with 95% alcohol, and cut or crack the cuticle along different directions and sections with a scalpel or forceps. The specimens are then fixed on a little metal tray using gummy fabric. A coating of gold-powder about 12 nm is put on the specimens using a sputter coater. The specimens are then observed using an Amray KYKY-1000B scanning electron microscope. A voltage of 25 kV is applied. Magnifications ranged from 20 to 12,000×. The SEM photomicrographs are taken to analyze the various microstructures in the cuticle.

The SEM observations reveal several typical microstructures of the insect cuticle as shown in Fig. 3. They are similar to man-made advanced composites. The elytra and pronotum are comprised of highly ordered unidirectional plies of fibers embedded in sclerotized proteinaceous matrixes. These plies are arranged parallel to the cuticle surface in various orientations. There is still some difference from man-made advanced composite. For example, there are some particular layups, each layer in the layup is in different directions as shown in Fig. 3(a), and any two contiguous layers of fibers keep almost changeless angle (helicoidal angle), which can be called as helicoidal layup [4]. In Fig. 3(a) the helicoidal angle is about 20°. These fiber layers along different directions can increase their pullout forces which are favorable to the improvement of the fracture toughness of the cuticle. The fiber plies in the cuticle are discontinuous and interruptive in some place, namely, the fiber plies in the insect cuticle do not always spread whole layer. Some queer micrograins were also found in the matrix of

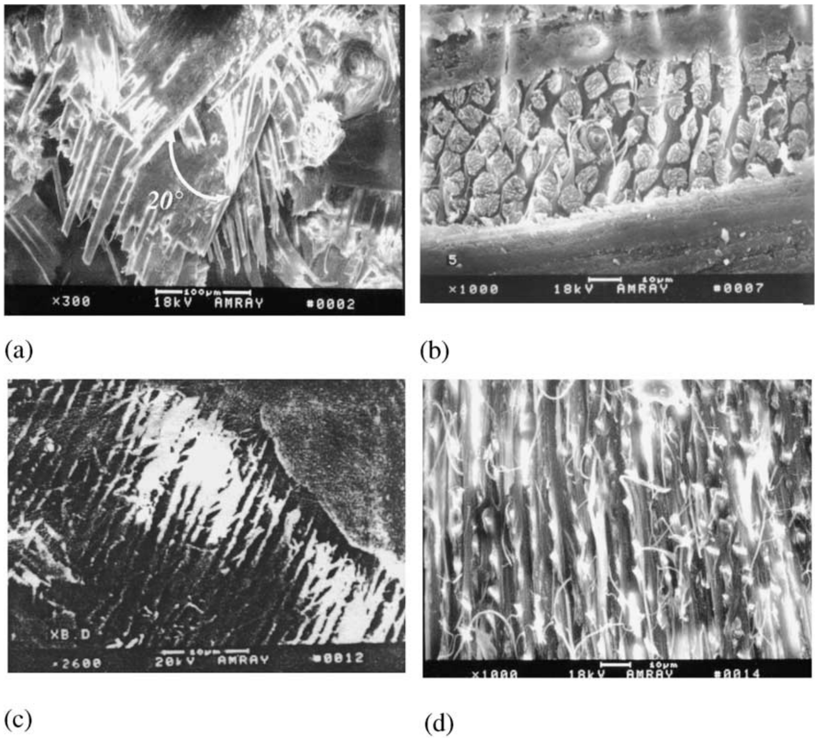

Fig. 3. Microstructures in chafer cuticle: (a) fiber plies, (b) micrograins, (c) branched fibers, (d) spinous fiber.

the insect cuticle as shown in Fig. 3(b). More careful observation shows that these micrograins' surfaces are not slick but look like pinecones. The functions and mechanisms of these micrograins will not be explored here. In the exocuticle of the elytra some particular fibers are also found, some of which looks like branch as shown in Fig. 3(c). These branched fibers are regularly arranged and the branched micro-fibers join the adjacent fibers as indicated in Fig. 3(c). These branched fibers may be useful to increase the pullout forces of the fibers and improve the fracture roughness of the cuticle. The fibers joined each other may enhance the capability of the load transfer of material. Another kind of particular fiber, acanth fiber as shown in Fig. 3(d), is also found in the cuticle. The stem of the fibers grows many times, which increase the interface between fibers and matrix. We will study the pullout force of branched fibers from mechanical model and experimental test in next section.

3. Maximal pullout force of branched fiber

3.1. Mechanical model

The branched fiber in Fig. 3(c) is not common in man-made fiber-reinforced composites. This section proposes a mechanical model as shown in Fig. 4 for the pullout force analysis of branched fiber. The maximal pullout force is analyzed as follows. The branched fiber includes main-stem

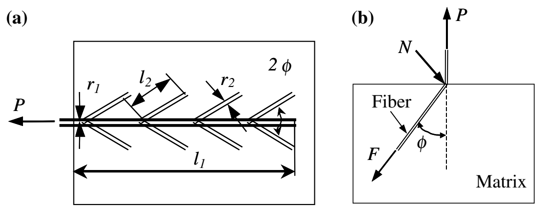

Fig. 4. Branched fiber and inclined fiber models: (a) model for branched fiber, (b) model for inclined fiber.

fiber and many sub-stem fibers. The perimeter of the main-stem fiber is r_1, and the length is l_1. The radius of the sub-stem fiber is r_2, and the length is l_2. The branched number and angle of the sub-stem fiber are n and ϕ, respectively. The branched fiber is embedded in a matrix, and a pullout force P acts at the end of the fiber. The maximal pullout force of the branched fiber can be obtained from the maximal pullout force of the main-stem fiber $(P_{b1})_{max}$ and that of all sub-stem fibers $(P_{b2})_{max}$. The interfacial shear stress on the fiber is assumed to be uniform along the embedded part of the fiber and increase continuously with the applied load. The maximum pullout force is achieved when the interfacial shear stress reaches its interfacial shear strength, τ_s. Therefore, the maximal pullout force of the main-stem fiber can be expressed as:

$$(P_{b1})_{max} = 2\pi r_1 l_1 \tau_s \tag{1}$$

Each sub-stem fiber is an inclined fiber embedded in the matrix as indicated in Fig. 4(b). When the fiber is pulled out from the matrix at an angle ϕ, the matrix wedge at the fiber exit point exerts a normal force, N, on the fiber to allow the axial force in the fiber to change its direction. A frictional force, F, contributing to the load increase is caused by this normal force and the relative movement between the fiber and the matrix [5]. These N and F are calculated as follows, respectively:

$$N = F\,\mathrm{tg}\,\phi = 2\pi r_2 l_2 \tau_s\,\mathrm{tg}\,\phi \tag{2}$$

$$F = 2\pi r_2 l_2 \tau_s \tag{3}$$

The maximal pullout force of each sub-stem fiber can be obtained:

$$(P_{b2})_{max} = \sqrt{F^2 + N^2} = \sqrt{(1 + \mathrm{tg}^2\,\phi)F^2} = 2\pi r_2 l_2 \tau_s \sec\phi \tag{4}$$

If the branched fiber has n sub-stems, its maximal pullout force can be expressed as:

$$(P_b)_{max} = (P_{b1})_{max} + n(P_{b2})_{max} = 2\pi r_1 l_1 \tau_s + 2\pi n r_2 l_2 \tau_s \sec\phi \tag{5}$$

If a straight fiber with the same perimeter and length as the main-stem of the branched fiber is embedded in the same matrix, the maximal pullout force along the fiber direction can be expressed as follows:

$$(P_s)_{max} = 2\pi r_1 l_1 \tau_s \tag{6}$$

A change ratio is defined as follows to express the relationship of pullout forces between the branched fiber and the plain straight fiber:

$$\hat{P} = (P_b)_{max}/(P_s)_{max} \tag{7}$$

From Eqs. (5) and (6) we have:

$$\hat{P} = (P_b)_{max}/(P_s)_{max} = 1 + n\alpha\beta\sec\phi \tag{8}$$

where $\alpha = r_2/r_1$, $\beta = l_2/l_1$.

3.2. Parameter study

Let $\alpha = 0.5$ and $\beta = 0.1$. Fig. 5 gives the effects of parameter changes on the pullout forces of the branched fiber. Fig. 5(a) shows the $\hat{P}$ with branched angle ϕ. It shows that the larger the branched angle ϕ is, the larger of the pullout force is. Fig. 5(b) shows the effect of branched number n on the $\hat{P}$. It shows that the more the branched number n, the larger of the pullout force. Fig. 5(c) and (d) show the variations of the $\hat{P}$ with length l_2 and radius r_2 of sub-stem fiber, respectively. The pullout forces increase with the length and radius of the sub-stem fiber.

3.3. Experimental test

An experiment test is conducted to verify the findings from above mechanical model. The maximal pullout forces of the branched fiber are compared with those of plain straight fibers. As shown in Fig. 6, branched fibers with different numbers of branches are fabricated by welding some short steel threads (10 mm in length) with long steel thread (110 mm in length). The steel thread is 0.8 mm in diameter. The plain straight fiber is also fabricated for comparison. These fibers are embedded in the matrix of ethoxyline. One end of these fibers remains outside the matrix for pullout experiments. The experimental ratio is given in Fig. 7 and the pullout force and the increase ratio are given in Table 1. It can be seen that considerable increase is observed

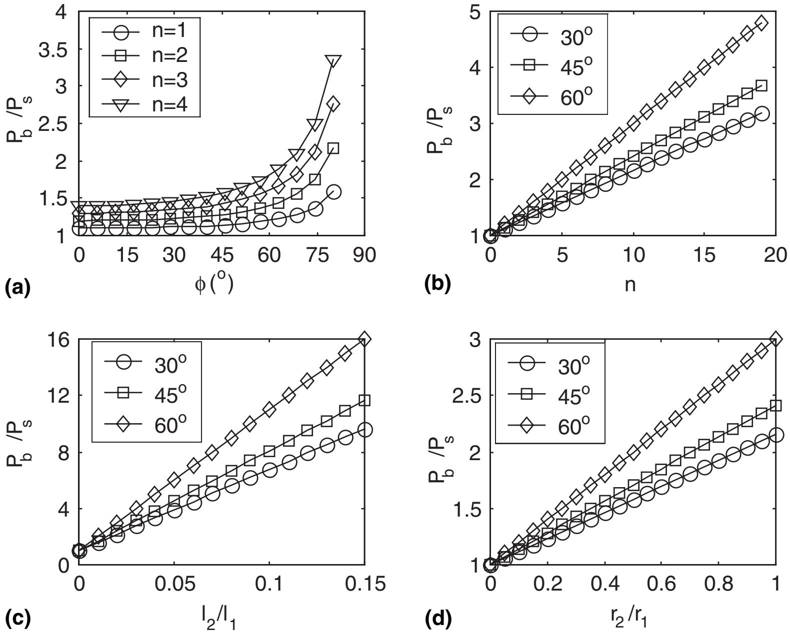

Fig. 5. Model analysis and parameter study on pullout force: (a) influence of ϕ on P_b/P_s ($\alpha\beta = 0.05$), (b) influence of n on P_b/P_s ($\alpha\beta = 0.05$), (c) effect of l_2/l_1 on P_b/P_s ($n = 50$, $\alpha = 0.5$), (d) effect of r_2/r_1 on P_b/P_s ($n = 50$, $\beta = 0.01$).

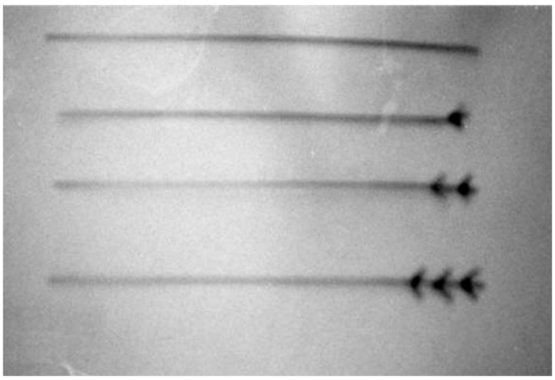

Fig. 6. Specimens of the straight and branched fibers.

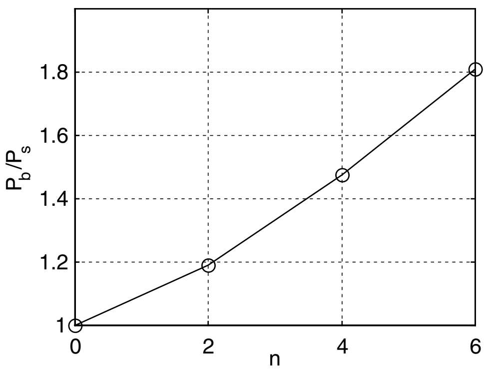

Fig. 7. The relationship between P_b/P_s and n.

compared with plain straight fiber specimens. These results also show that the more number of the branched fiber in the branched fiber specimens, the greater the increase value of the pullout force of the branched fibers specimens. This is in good agreement with the result obtained from the foregoing analysis of mechanical model.

Table 1
Experimental results for the increase of pullout forces with branch number

Number of branch n	Maximal pullout force (kN)	Increase of maximal pullout force (%)
0	0.42	1.0
2	0.51	21.4
4	0.64	52.3
6	0.73	73.8

4. Conclusion

The insect cuticle is a natural composite which is composed of unidirectional plies of chitin fibers embedded in a protein matrix. Their microstructures are very similar to man-made advanced composites. The SEM observation reveals several unique microstructures of the chafer cuticle, which include particular helicoidal plies, micrograins, branched fiber and spinous fiber. These microstructures can provide some new idea for the manufacture methods of man-made composites, fiber orientation and fiber structural design.

The maximal pullout force of branched fibers was theoretically analyzed, and experiment was conducted to verify the increase when compared with plain straight fiber. Several pullout specimens with different branched fiber and the plain straight fiber was fabricated and investigated for the maximal pullout force of fibers, which is related to the fracture roughness of the composite reinforced by fiber. The experimental results indicate that significant increases in maximal pullout force for specimens of the branched fiber, and the more the numbers of the branched fiber of the branched fiber specimen, the greater the increase value of the maximal pullout force of the branched fiber specimen than the plain straight fiber specimen. These results are in good agreement with that of the model analysis.

Acknowledgements

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References

[1] N.F. Hadley, The Arthropod cuticle, Sci. Am. (July) (1986) 104.

[2] H.R. Hepburn, A. Ball, On the structure and mechanical properties of beetle shells, J. Mater. Sci. 8 (1973) 618.

[3] R. Schiavone, S. Gunderson, The components and structure of insect exoskeleton compared to man-made advanced composites, Proc. Amer. Soc. Comp. (1989) 876.

[4] Y. Bouligand, Sur une architecture torsadee repandue dans denombreses cuticles d' arthropods, C. R. Acad. Sci., Paris 261 (1965) 3665.

[5] V.C. Li, Y. Wang, S. Backer, Effect of inkling angle bundling and surface treatment on synthetic fiber pull-out from a cement matrix, Composites 21 (1990) 132.