Microstructure of round-hole-fiber distribution in insect cuticle and biomimetic research

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Summary

Insect cuticle possesses excellent mechanical properties, such as strength, stiffness and fracture toughness, which are closely related to its elaborate microstructures optimized through millions of years' evolution. SEM observation to the insect cuticle shows a particular distribution of fibers surrounding a hole in the insect cuticle, which is quite different from that in conventional man-made composites. In this paper the mechanism of such microstructure is analyzed. Making use of such microstructure, fiber-reinforcing laminate specimens containing preformed holes are designed and fabricated, the ultimate strength of which is investigated experimentally. For comparison, the ultimate strength of the fiber-reinforcing laminate specimens containing drilled holes is also tested. It shows that the ultimate strength of the laminates with preformed holes is distinctly higher than that with drilled-holes, and the difference increases as the hole diameter increases.

Introduction

Insect cuticle is a complex hierarchical microstructure composed of biologic fibers and matrixes. The biologic fibers, a high-molecular weight polysaccharide called chitin, are embedded in biologic proteinaceous matrixes [1]. The laminate is a closely similar to synthetic advanced composites [2]. Although the components of insect cuticle, sugar and protein, in general, possesses poor mechanical properties, the insect is able to combine these materials in a unique way to produce a high performance material with highly optimized microstructures [3]. The research on the microstructures and the corresponding mechanical properties may provide beneficial information for improving the qualities of current composites and developing new high-performance composites.

Fiber-ply direction plays an important role in the mechanical properties of insect cuticle. Several models describing fiber-ply directions have been proposed. The model on helicoidal ply was firstly proposed by Y. Bouligand [4] and has been extensively confirmed. In addition, dual-helicoidal model, which was presented by Schiavone and Gunderson [2], has also received especial attention.

The holes and pores in insect cuticle also received attention, which are used as transport channels for excretion, nourishment and reconstruction/repair [5]. These holes or pores are visually described in Figure 1 [6]. Schiavone and Gunderson [2] found that the holes in the Bessbug's cuticle aid the transportation of wax from the epidermal cells to the epicuticle surface through the thickness of the cuticle, and believed that cracks travel around the these holes instead of penetrating through them.

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Inspired by these researches, preformed holes were made with carbon/epoxy unidirectional tape [7].

In the work of this paper, scanning electron microscope (SEM) was used for the observation of the microstructures of Hydrophilidae cuticle, the observation concentrates mainly on the characteristics of the microholes in the cuticle, and the round-hole fiber distribution. It shows that the fibers near holes pass deviously and continuously round the holes. Based on the SEM observation a set of laminates with preformed holes was fabricated. The ultimate strengthes of the biomimetic laminate were tested and compared with those containing ordinarily drilled holes. The results show that the strengths of the composite laminates with preformed holes are markedly larger than that of the drilled holes.

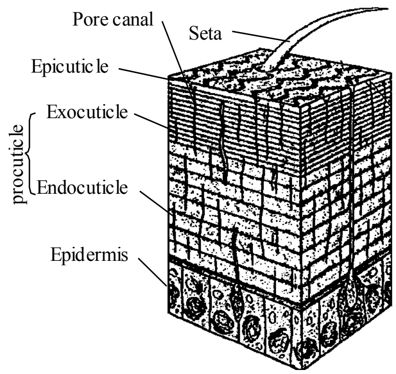

Fig. 1. A cross section of a generic insect cuticle, showing the many pore canals (holes)

SEM Observation of hole microstructure of the insect cuticle

The insect used in this study was the Hydrophilidae (Figure 2). Two parts of the insect (see Figure 2) were observed with scanning electron microscope (SEM). One is the pronotum (the protective cover for the prothoractic, or upper body section), the other is elytra (a pair of hard outer "wings" which protect the inner wings and the body of the insect). The samples were prepared by the following three steps: abstracting the selected cuticle from the insect, cleaning their surfaces with 95% alcohol, and then cutting the cuticle into samples with a scalpel. In order to investigate the destruct characteristics and mechanism of the cuticle, a devastating method, cracking the cuticle with little forceps, was also adopted. The samples were then stuck to a smell metal plate using a gummy fabric, and coated with a 10nm film of gold powder with a spraying method. These samples were then observed using an

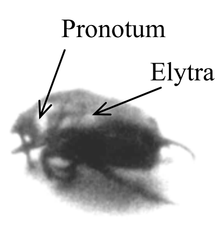

Fig. 2. A Hydrophilidae and its uticle

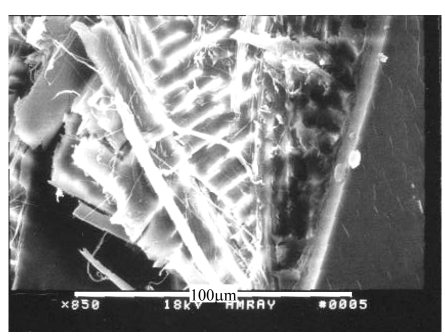

Fig.3. A helicoidal ply in elytra

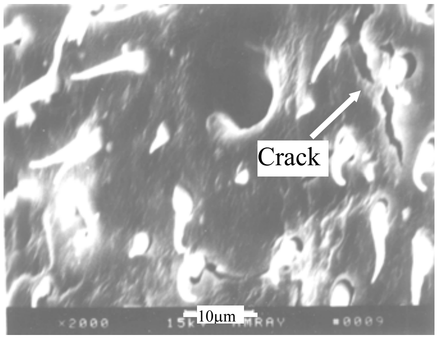

Fig. 4. Hole and the setas on the surface of the insect cuticle

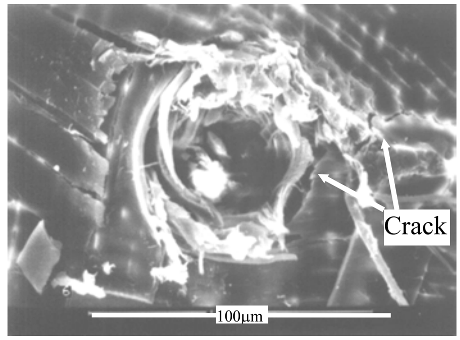

Fig. 5. Hole and circuitous fibers in the insect cuticle

Amray KYKY-1000B SEM at about 20 kV voltage, and with magnifications ranged from 20 to 12000×.

The SEM observation showed that the basic microstructure of the insect cuticle is similar with the man-made fiber-reinforced resin matrix composites. It is composed of highly ordered unidirectional plies of fibers embedded in a sclerotized-protein matrix. These plies are parallel with the surface of the cuticle and the fiber orientation is a helicoids arrangement. Figure 3 shows a representative presentation of the helicoidal plies found in elytra when the cuticle was peeled off. The characteristics and advantages of the helicoidal plies were analyzed elsewhere. Beside the observed basic microstructure of the cuticle, many holes (or pore canals) and its neighboring microstructure were also investigated. Figure 4 shows a larger hole and many setas on the surface of the cuticle. In this Figure, a little crack near the hole can also be found. An interesting phenomenon is that the progress of the crack is not very close to the hole. The reason of the phenomenon can be made clear from the inner-microstructure mechanism of the cuticle. Figure 5 is the SEM photograph of the inner of the cuticle, it was clearly shown in which that the fibers near the hole surrounding the hole in a curving, flexural and continuous form. A similar interesting phenomenon can also be found in figure 5, i.e., the crack near the hole changes its progressive direction when it meets the fibers at the margin of the hole. The crack was shielded by the continuous curving fibers at the fringe of the hole. It can be concluded that the form of fiber structure near the hole improves the strength at the margin of the hole and reasonably matches the high-stress field in the vicinity of the hole. Compared with man-made composites, in which most holes required for the purpose of joining are usually fabricated with the method of drilling or punching, which may sever fibers and cause discontinuity or reduction of fibers. It is harmful for composites because it is known that a larger stress concentration may appear in near-hole region. But in the cuticle of the insect, fibers pass round a hole continuously, which coincides with the stress concentration in the corresponding region and is beneficial for stress to distribute more reasonably between fibers and matrix.

Experimental investigations to the ultimate load of the laminates with round-hole fiber-distributions

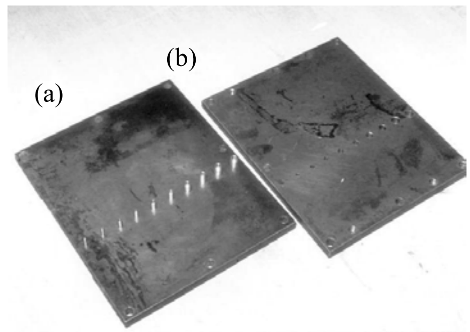

Fig. 6. (a). The bottom mould board containing circular pins of different diameter; (b). The upper mould board with matched holes

Experiment was made to explore the possibility of applying the fiber distribution shown in Fig. 8 in practice. The composite laminate samples with round-hole fiber-distribution shown in Fig. 6 were fabricated, and the ultimate load of these composite laminate samples was tested and compared with that of samples with drilled or punched holes. The material used was glass-fiber fabric reinforced epoxy resin composite, which was selected due to the extensive use of glass fabric and epoxy resin in civil and industrial structures. Firstly, a special mould (see Figure 6) was made which includes an upper and a bottom board. The bottom board contains the circular pillars with different diameters (d = 4, 6, 8, 10, 12, 14 mm), and the upper board includes the same number of holes with the same diameters so that those pillars on the bottom board can insert them. Then twelve layers glass-fiber fabric with cross-shaped form were dipped with epoxy resins and laid on the bottom board sequentially. In this course, it is necessary to make the plies be penetrated by the circular pillars reliably. When this process was finished, put the upper board was on the top of the fabrics, letting the protruding portion of the pillars get into the holes in the upper board. The whole mould was placed in a hot-press and cured at 210℃ and under vertical pressure of 120 MPa for 13 hours when the composite laminate was solidified. Finally, the composite laminate was cut into the tensile specimens, each containing a hole in the middle. Because these holes are preformed, the fibers at the neighborhood of the holes remain continuously round the holes. On the other hand, the other set of specimens used for comparison also was designed and fabricated with ordinary mould at the same time. They have the completely identical geometry with that of the first set of specimens, but with the holes drilled, and the fibers passing though the holes had to be severed.

The ultimate tensile loads of the two sets of the specimens were tested on an Instron 1342 Material Testing System. The average ultimate strength can be calculated with:

$$\sigma = \frac{P}{ab}, \tag{1}$$

where P is the failure load, a and b are the width and thickness of the specimen, respectively. The testing results of the two kinds of specimens are shown in Figure 7, it can be seen from which that the average ultimate strength of the composite laminates with preformed hole are obviously larger than that the holes drilled. Another fact found is that the difference between the average ultimate strengths of the composite laminates respectively with preformed and drilled holes increases with the increase of the hole diameter. And it shows the composite laminate with preformed hole has a better load-bearing-capability than that with hole drilled or punched, especially in the case when a larger hole is required.

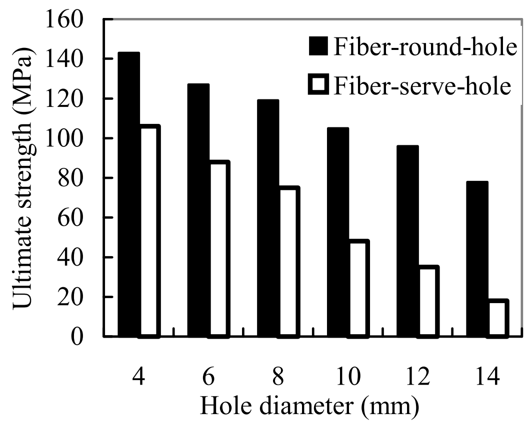

Fig. 7. The ultimate strength of the specimens with preformed and drilled holes

Conclusions

Microscopic observation shows that the Hydrophilidae cuticle has the similar basic structural characteristics to that in the conventional fiber-reinforced laminated composites. It consists of helicoidal plies of chitin fibers and sclerotized-protein matrixes. Observation also shows that there are many tiny holes in the cuticle that are used as ventholes or for transportation. SEM observation shows that the fibers near the holes pass round the holes continuously and deviously. The distribution of fibers near the hole coincides with the stress concentration in this region. The ultimate loads were analyzed for the composite laminates with holes and the observed round-hole fiber-distribution, and compared with that corresponding to the composite laminates with drilled or punched holes, where the fibers passing though the holes are severed. The results show that in the former case the ultimate load is distinctly larger than that in the latter case. This conclusion was verified in experiment, where a set of composite laminates with preformed holes fabricated, with the round-hole fiber distribution similar to that observed in the Hydrophilidae cuticle. The experimental average ultimate strength is found to be distinctly larger than that of the specimens with the same material and geometry but with the holes drilled. This difference increases with the increase of the hole diameter.

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