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Research on the microstructure of insect cuticle and the strength of a biomimetic preformed hole composite

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Abstract

The insect cuticle is a typical natural composite with excellent strength, stiffness, and fracture toughness. Scanning electron microscope observation of the microstructure of Hydrophilidae (an insect) cuticle showed several unique plies and structural characteristics, which may provide available information to the design of advanced composites. The microstructure found in the vicinity of pore canals in the insect cuticle was used for the design of the composite laminate with a hole. Compared with the composite laminate with a normally drilled hole, it was found that the strength of the specially designed composite laminate increases markedly, which is of important significance to the design of high-performance composites. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Insect cuticle; Composite; Microstructure; Bionics; Preformed hole; Strength

1. Introduction

Insect cuticle is a typical example of a natural composite, the microstructure of which endows it very good mechanical properties, such as excellent strength, stiffness, and fracture toughness. Insect cuticle is, in nature, a composite of fiber-reinforced laminate. The fibers, a high-molecular weight polysaccharide called chitin, are embedded in a proteinaceous matrix (Rudall and Kenchington, 1973). Although the components of the cuticle, sugar and protein, in general, possess poor mechanical properties, the insect is able to combine them in a unique way to produce a high-performance material with highly optimized microstructures (Hepburn and Ball, 1973). The research on these microstructures and the corresponding characteristics may provide valuable information for improving current composites and developing high-performance materials.

An insect cuticle can be divided into two primary sections: epicuticle and procuticle (Hadley, 1986) (Fig. 1). Epicuticle is the outer layer, consisting mainly of wax, lipid, and protein without chitin fibers. This layer, being 0.1-0.3 |xm in thickness, acts as an environmental barrier and contributes little to the shape or the strength. The procuticle, the structural division, about 10-100 |xm in thickness, provides shape and mechanical stability. It can be further divided into the exocuticle and the endocuticle, both of which contain chitin fibers and a protein matrix. The chitin fibers, containing bundles of microfibers, are embedded in a proteinaceous matrix and arranged in a series of thin lamina with various orientations.

The fiber ply orientation in the cuticle received much attention. Several theories have been proposed for specific orientation of these fiber plies, among which the most widely accepted one is the helicoidal model proposed by Bouligand (1965). It takes the structure as a series of thin unidirectional lamellas stacked one by one with the orientations rotated by a small and nearly constant angle between lamellas. The model modified by Neville (1970) involves the same stacking sequence, but curve-fibers were assumed in each lamella. Several other models were also proposed, including the screwcarpet model by Weis-Fogh and the cross-hatch model (Hepburn, 1983), which used the form of a woven cloth or fabric. Another model receiving extensive attention is the dual helicoidal model proposed by Schiavone and Gunderson (1989), which describes the structure as two alternating helicoids rotating in a clockwise direction from the outside to the inside of the cuticle.

One of the purposes of this study is to obtain more information about the microscopic structure of insect cuticle with scanning electron microscope (SEM) techniques, and find the relation between the microscopic structures and macroscopic mechanical behavior of insect cuticle. The other purpose of this study is to explore the possible

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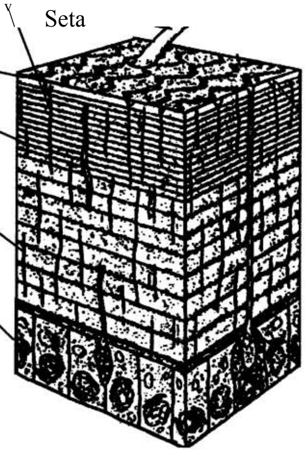

Fig. 1. A cross-section of a generic insect cuticle, showing the different layers.

applications of the unique forms of plies and structures in the insect cuticle for improving properties of advance synthetic composites and structures.

The microstructure and mechanical properties of the insect cuticle were studied with a SEM. Several unique forms of plies and structures were observed, which may provide new design methods for man-made high-performance composites. The observed unique fiber plied structure surrounding the pore canals was used in the fabrication of resin/fiber composites containing holes. Tensile tests showed that the strength of the composites containing preformed holes increases significantly compared with that with drilled holes.

2. SEM observation of the microstructure of insect cuticle

The insect used in this study was Hydrophilidae beetle (Fig. 2). It was selected due to its larger size (about 35 mm in length) and the availability in this district. Different sections of the insect were selected for analysis: the pronotum (a protective cover for the prothoractic, or upper section

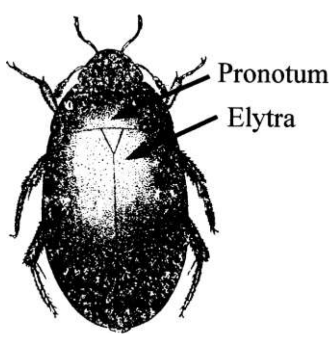

Fig. 2. The Hydrophilidae, showing the two different areas examined in the study.

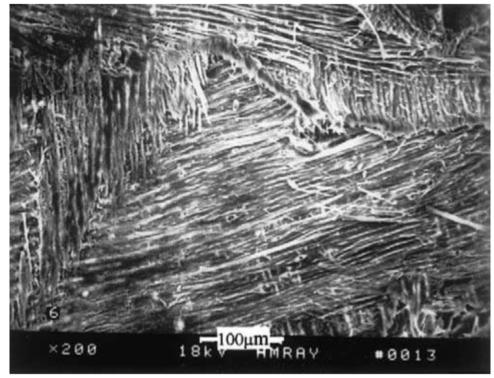

Fig. 3. The fiber-reinforced laminates of plies.

of the body); and the elytra (a pair of hard outer 'wings', which protect the inner wings and the body of the insect). Both sections are shown in Fig. 2, each of which was examined with the SEM and light microscope.

The SEM specimens were prepared (Schiavone and Gunderson, 1989) by cutting the selected section from the insect, dipping it in liquid nitrogen for about 1 min, and then cutting the section transversely with a scalpel. The specimens were then placed on aluminum plugs using low-resistance contact cement as an adhesive. A 10 nm coating of gold-palladium was made using a sputter coater. These specimens were then observed using an Amray KYKY-1000B SEM with the voltage of about 20 kV and with magnifications ranged from 20 X to 11,000 X. Linear distances were measured directly from the SEM micrographs with a micron marker bar for calibration.

Besides the results similar to that obtained by Bouligand (1965), Schiavone and Gunderson (1989), some new structural characteristics were found. The SEM observation showed that the microstructure of the insect cuticle resembles the man-made fiber-reinforced resin matrix composites. The elytra and pronotum are composed of highly orderly unidirectional plies of fibers embedded in a protein matrix (Fig. 3). These plies are arranged in various orientations, but parallel with the cuticle surface. Several regular forms of ply were found in this insect cuticle, such as helicoidal and dual helicoidal forms, as shown in Figs. 3 and 4, which appears to depend on their location in the cuticle. For instance, more dual helicoidal sheet plies were found in the elytra of the beetle cuticle. Especially, the dual helicoid plies are approximately the combination of cross-hatch fiber fabric sheets. The difference of angles between neighboring helcoidal plies is, on average, about 25°, and that between successive plies is about 85°. Many setas and holes (or pore canals) in the insect cuticle were also found (Fig. 5), which serve as receptors and transport channels for external excretion, nourishment, and reconstruction/repair, respectively (Locke, 1961). A phenomenon observed is that the fibers near the holes round these holes continuously (see Fig. 6), which is more reasonable compared with the broken fibers in man-made composites with drilled or punched holes

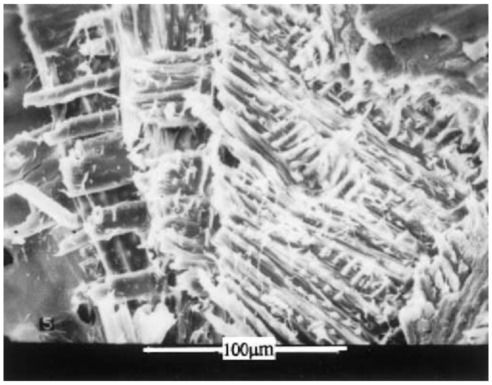

Fig. 4. The dual helicoidal arrangement of plies.

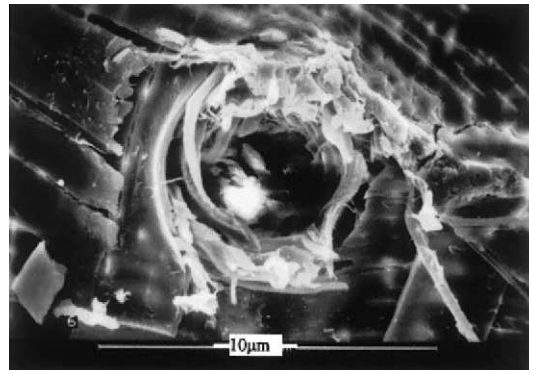

Fig. 6. Hole used as transport channel and fibers remained continuous.

(Gunderson and Lute, 1992). In Fig. 7, it can be seen that there are small spaces and perpendicularly arranged pillars between the plies of fibers, which may contribute to the improvement of fracture roughness and lightweight.

3. Fabricating and strength test of biomimetic preformed hole composite

The unique fiber ply structure and near-hole fiber distributions observed in the insect cuticle (Fig. 6) were used for the design of biomimetic ply structure. Gunderson and Lute (1992) ever made preformed holes by laying carbon/epoxy unidirectional tape into a caul plate containing circular pins. In this research, the preformed hole was produced using glass/epoxy fabric weaved with 0/90° fibers instead of unidirectional tape. This material was selected due to the extensive use of glass fabric and epoxies in civil and industrial structures. The strength of the specimens with preformed holes was compared with that with drilled holes, and the effect of hole-diameter was also investigated.

A pair of special moulds was fabricated. The moulds include a bottom board containing four circular pins of diameters $d = 4, 8, 11, 14$ mm with proportional spacing (Fig. 8(a)), and an upper board containing four holes matched the pins on the bottom board (Fig. 8(b)). The working area in the mould was separated into two identical sections: one for processing specimens with preformed holes and the other for processing specimens with drilled holes (see Fig. 8). Eight-layer glass fabrics weaved with 0/90° fibers soaked with epoxy resin were laid sequentially on the bottom board, and preformed holes were made by carefully letting the plies be penetrated by the circular pins. As a result, the fibers of the glass fabric curved gently round the pins. Then, the upper board was put on it, letting the protruding portion of the pins get into the holes in the upper board. The whole mould was placed in a hot-press and cured at 230 °C and 120 MPa for 16 h, when the composite laminate was solidified. At the place of the composite laminate set aside for drilling hole a set of holes (d = 4,8,11,14 mm) were drilled. Finally, the composite laminate was cut and the tensile specimens, each containing a hole in the middle, were made. The advantage of the mould is that it can provide specimens with the same quality and with preformed and drilled holes simultaneously, which is important for the comparison between the mechanical properties of the specimens with drilled or preformed holes.

Tensile tests of the specimens with drilled and preformed holes were performed. The average strength can be calculated with:

$$\sigma = \frac{}{ab}$$

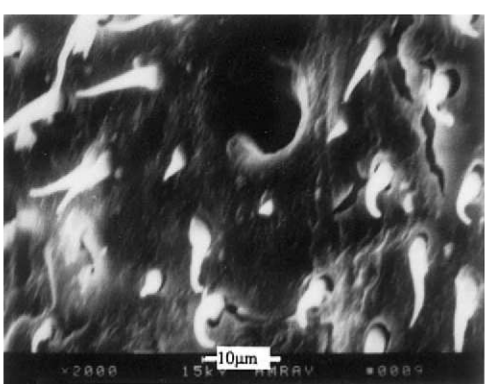

Fig. 5. The setas and holes called pore canals in the insect cuticle.

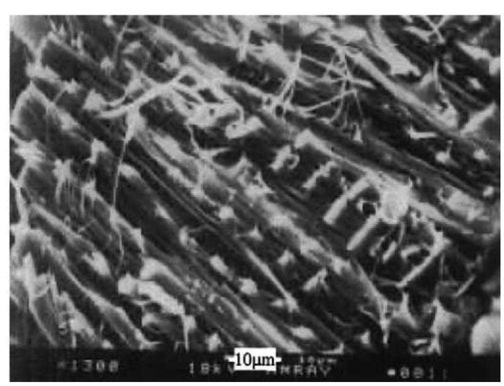

Fig. 7. Spaces and pillars between plies of fiber.

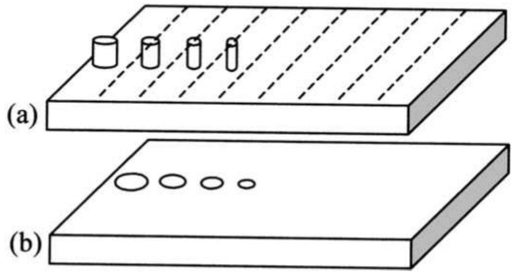

Fig. 8. (a) The bottom mould board containing different diameter circular pins, (b) The upper mould board with matched holes.

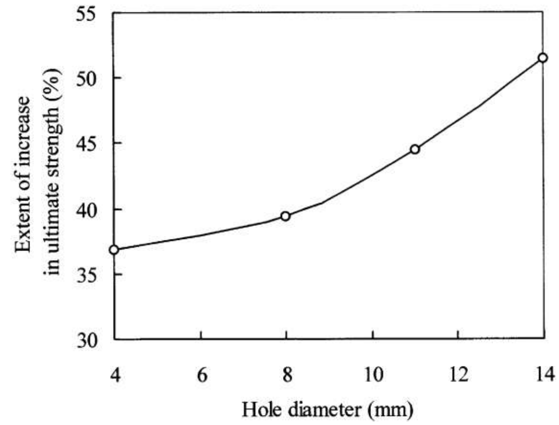

Fig. 9. Extent of the increase in the ultimate strength of the specimens with preformed holes of different hole-diameters.

where P is the failure load, a and b are the width and thickness of the specimen, respectively.

The results related to the specimens with preformed and drilled holes are shown in Table 1. It can be seen that the strength of the specimen with a preformed hole gains a remarkable increase compared with that with a drilled hole. On the other hand, the strengths of the specimens with preformed holes of diameter 4, 8, 11, and 14 mm were 36.9, 39.4, 44.5, and 51.5% greater than that of the specimens with drilled holes of the same diameters, respectively. Fig. 9 shows the extent of the increase in the ultimate strength of the specimens with preformed holes of different hole-diameters. It can be seen that, compared with the specimens with drilled holes, the larger the diameters of the hole, the greater the increase in the ultimate strength will be achieved for the specimens with preformed holes.

4. Conclusions

The microstructure of insect cuticle, a natural fiber-reinforced laminated composite, consisting of unidirectional plies of fibers embedded in a matrix, is very similar to the structure of man-made polymeric composite. Microscopic investigation to the cuticle of a Hydrophilidae indicates several unique forms of plies and structures, which provides novel concepts for the design of joint, fiber orientation, and laminated structure of man-made composite.

A set of specimens with preformed holes of different diameters were made and tested. These preformed holes were accomplished during the composite processing with a special technology making the fibers remain continuous around the hole. Tensile tests showed that, compared with those containing drilled holes, the strength of specimens containing preformed holes significantly increases. The larger the hole-diameters, the larger the increase in the average strength of the specimens with preformed holes. It can be attributed to the less damage in the specimens with preformed holes due to the continuity of fibers around the holes.

Table 1
Tension test results, showing a remarkable increase in the ultimate strength of the specimens with preformed holes compared with that of the specimens with drilled holes

Diameter of hole (mm)	Strength of drilled holes (MPa)	Strength of preformed holes (MPa)	Extent of increase in ultimate strength (%)
4	103.3	141.4	36.9
8	92.6	129.1	39.4
11	78.2	115.2	44.5
14	52.4	103.5	51.5

Acknowledgements

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