

Helicoidal microstructure of Scarabaei cuticle and biomimetic research

B. Chen^{a,*}, X. Peng^a, C. Cai^b, H. Niu^a, X. Wu^a

^a Department of Engineering Mechanics, Chongqing University, Chongqing 400044, PR China

^b Department of Applied Physics, Chongqing University, Chongqing 400044, PR China

Received 8 July 2005; received in revised form 30 October 2005; accepted 29 November 2005

Abstract

Insect cuticles as a natural biocomposite include many favorable microstructures which have been refined over centuries and endow the cuticles excellent mechanical and physical properties, such as light weight, high strength and toughness, etc. The various microstructures of a Scarabaei cuticle are investigated with a scanning electronic microscope and reported in this paper. It is found that the cuticle is a kind of fiber-reinforced biocomposite composed of chitin-fiber layers and sclerous protein matrixes. Different chitin-fiber layers have different orientations, composed of crossed and helicoidal structures at different location. In the helicoidal structure, each fiber layer rotates with an almost fixed angle against its neighboring layer. The maximum pullout energy of the helicoidal structure is analyzed based on the representative model of the structure. The result shows that the pullout energy of the helicoidal structure is markedly larger than that of the conventional 0°-structure. A biomimetic composite with the observed helicoidal structure is designed and fabricated. A comparative test shows that the fracture toughness of the biomimetic composite is markedly larger than that of the 0°-layer composite.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Scarabaei cuticle; Helicoidal structure; Pullout energy; Biomimetic design

1. Introduction

Insect cuticle is a typical example of natural biocomposites of light weight, high strength and toughness. The favorable mechanical and physical properties of insect cuticle, which are optimized by nature over many centuries, are closely related to its microstructures [1]. The investigation to the microstructures of insect cuticle may help people to gain insight into the mechanisms of the excellent properties and provide available information to improve the properties of current composites and to develop new composites, especially for the application in aircraft where materials are strongly required to be of light weight, high strength and toughness.

An insect cuticle can be separated into two primary parts [2]: epicuticle and procuticle (Fig. 1). Epicuticle is the outermost layer of the cuticle, consisting primarily of waxes, lipids, and proteins. It ranges between 0.1 and 3 μm in thickness and mainly acts as an environmental barrier, contributing little to the mechanical property of the cuticle. Procuticle, with the thickness from about 10 to 100 μm, is the main part of the cuticle that

enables the cuticle to keep its shape and stability under external loading [3]. It can further be separated into the exocuticle and the endocuticle, both of which are laminated materials consisting of chitin fibers and various protein matrixes. The chitin fiber is composed of a straight chain polymer of *N*-acety glucoseamine molecules. The protein matrixes are sclerotized completely or incompletely [4].

The microstructures of insect cuticle received much attention in recent years. Several models have been put forward for the specific structures of the chitin fibers in different insect cuticles and different sections in an insect cuticle. A helical model [5] describes the fiber structure as a series of thin unidirectional sheets stacked one by one with the orientation of each fiber layer rotating sequentially by a nearly constant angle. A modification to this model was suggested by Neville [6] for the helicoidal structure of Bessbug cuticle, where the fibers in each ply are curved. Another model is the dual helical model for *Odontotaenius* cuticle [4], where two alternating helicoids rotate clockwise from outside to inside of the cuticle. These works are profitable to understand the microstructures of various insect cuticles, but they are mainly limited to the observation of the microstructure of the insect cuticle they researched, i.e., less analysis on the microstructure and experimental verification were conducted. Other microstructural characteristics of

* Corresponding author.

E-mail address: bchen@cqu.edu.cn (B. Chen).

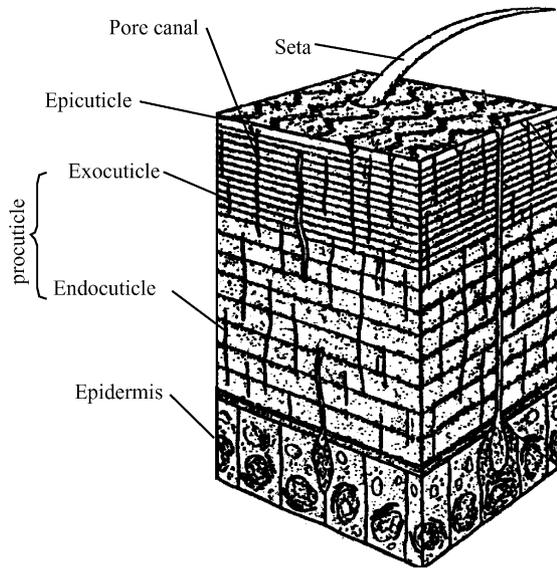


Fig. 1. A cross-section of a generic insect cuticle.

insect cuticles were also investigated by many researchers. Vincent and Wegst [7] reviewed the formation and microstructure of arthropod cuticle, then analyzed the remarkable mechanical performance of the cuticle and compare it with that of other materials using material properties charts and material indices generated for this propose. Tong et al. [8] investigated the geometrical features and the wetting behavior of the pronotum cuticle surface of dung beetle *Copris ochus* Motschulsky. It was concluded that the beetle has embossed textured surfaces on its pronotum, clypeus and elytra surfaces. Some practical applications of the geometrical features and the wetting behavior of the cuticle surfaces were discussed. Chen et al. [9] investigated the microstructure of *Dichotoma* cuticle, proposed a three dimensional honeycomb-columniation model and discussed several design concepts for further development on three dimensional composite structure. However the above work does not involve the design or fabricated of biomimetic composite. Chen et al. [10] observed the microstructures of Rutelidae cuticle. A kind of spiry structure was found. The maximum pullout force of the structure was analyzed and compared with 0° -structure. In this work, the microstructure of *Scarabaei* cuticle was observed with SEM. A kind of helicoidal structure was found. The maximum pullout energy of the structure is analyzed and compared with that of the 0° -structure. The result shows that the maximum pullout energy of the structure is markedly larger than that of the 0° -structure. A biomimetic composite with the helicoidal structure is fabricated. A comparative test shows that the fracture toughness of the biomimetic composite is markedly larger than that of the 0° -structure composite.

2. SEM observation on *Scarabaei* cuticle

The structural characteristics of insect cuticles are different between the different kinds of insect cuticles [4,5]. In this paper, the microstructures of the cuticle of *Scarabaei* (an insect) are firstly investigated. The insect cuticle should have some dif-

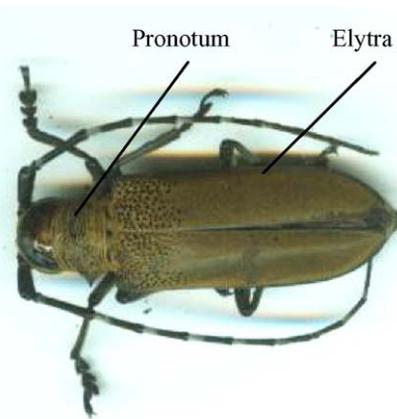


Fig. 2. Two different sections of a *Scarabaei* used for observation.

ferent microstructures from that of the other insect cuticles [4,5,10].

Scarabaei (Fig. 2) distribute in southern China and can be easily captured during summer. The color of the *Scarabaei* cuticle is brown, the length and the width of its body are about 40 and 15 mm, respectively. The cuticle of *Scarabaei* is strong, stiff and tough to protect its body against external attacks, but it keeps very light for the insect to fly rapidly and easily. The excellent mechanical and physical properties of the cuticle come from its excellent microstructures, which are refined by nature over many centuries.

The microstructures of *Scarabaei* cuticle was investigated with an Amray KYKY-1000B scanning electron microscope. The main sections for observation are the elytra (a pair of hard outer “wings” which protect the inner wings and the body of the insect) and the pronotum (a protective cover for the prothorax) (see Fig. 2). The samples were prepared by separating the elytra and the pronotum from *Scarabaei*, cleaning them with a little brush and alcohol, having them dried in a drier and then cutting them into samples with a scalpel along upright and transverse directions. For scanning electron microscopy, the samples were fixed on a little metal pedestal with an adhesive fabric, a coat of gold-powder, which is about 10 nm in thickness, was spurted on its surface. The maximum voltage used for the observation is 25 kV and magnifications ranges from $50\times$ to $15,000\times$.

The SEM observation shows that the insect cuticle is a kind of natural composite consisted of chitin fibers and protein matrixes that is completely or incompletely sclerotized (Figs. 3 and 4), similar to that of the other observed insect cuticles [4,5,10]. The chitin fibers are embedded in protein matrix with layered form and approximately parallel with the surface of the cuticle. The direction of the chitin-fiber coincides with that of maximum principal stress and provides the maximum load-bearing-capability to the cuticle when it suffers from external loading on its surface. The observation also reveals that the chitin fibers in a layer have identical orientation, but the fibers in different layers have different orientation, which forms different fiber structures. The fiber structure achieved depends strongly on the location of the structure in the cuticle, and necessary strength



Fig. 3. The cross structure of fibers.

and toughness required. Fig. 3 shows a kind of cross fiber structure which is often observed in the endocuticle. In this fiber structure, the orientation between two neighboring fiber layers is about 90°, which can be called as a crossed fiber structure. The endocuticle is close to the center of the cuticle where higher strength is required, and crossed structure can meet the requirement [11]. Fig. 4 shows another kind of fiber structure which often appears in the exocuticle of the cuticle. In the structure, the fibers in an arbitrary fiber layer rotate by a variational angle (from 22° to 28°) against the fibers in its neighboring layer, which can be regarded as a variational helicoidal structure. There are also some other differences between the structure and that in other cuticle. For example, the fibers in the Scarabaei cuticle are thinner and more circular, while the fibers in Refs. [4,10] are thicker and elliptical. The exocuticle is close to the fringe of the cuticle where high fracture toughness is required, it will be shown that the helicoidal structure can meet the requirement.

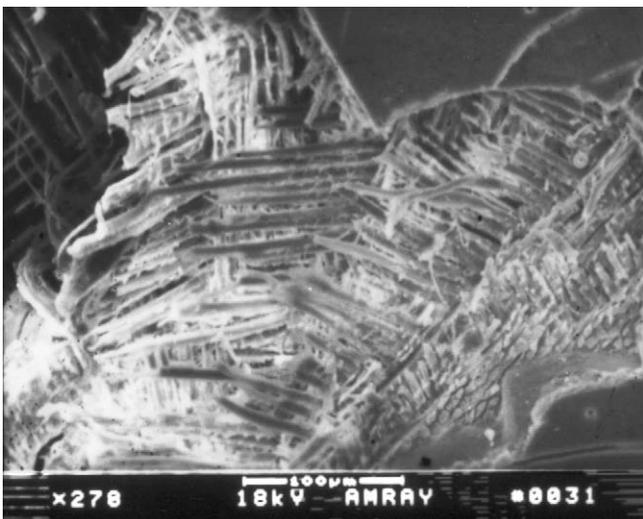


Fig. 4. The helicoidal structure of fibers.

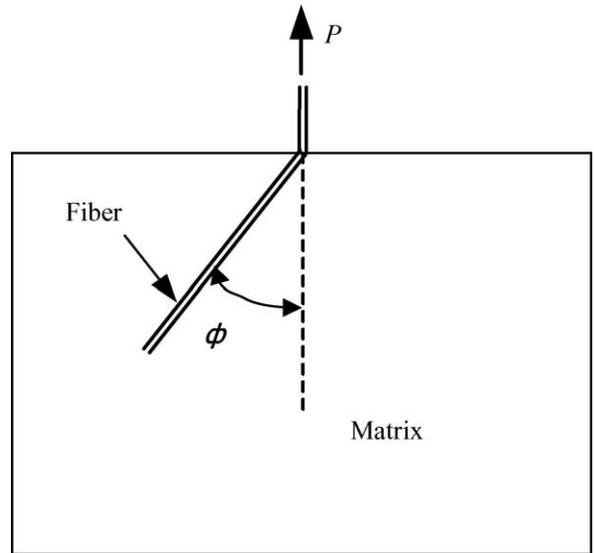


Fig. 5. Pullout of a fiber at an angle ϕ .

3. Model analysis for maximum pullout energy

It is more rational using the concept of pullout energy to analyze the fracture toughness of a fiber-reinforced composite than using the concept of pullout force. In this section, the maximum pullout energy of a helicoidal structure is analyzed, based on the analysis of a representative model of the helicoidal structure.

Firstly, considering a single fiber embedded vertically in a matrix (the fiber can be called as vertical fiber) and suppose the radius and the length of the fiber are r and l , respectively. Applying a pullout load along the direction of the fiber to the end of the fiber an interfacial shear stress $\tau(x)$ will appear on the surface of the fiber. The pullout force contributed by the section dx can be expressed as

$$df = 2\pi r\tau(x)dx, \tag{1}$$

the corresponding pullout energy is

$$dw = 2\pi r\tau(x)x dx. \tag{2}$$

The energy to pull out the whole fiber can be determined with

$$W = 2\pi \int_0^l r\tau(x)x dx, \tag{3}$$

furthermore, if the fiber is aslant embedded in matrix (the fiber can be called as inclined fiber, see Fig. 5), when the fiber is pulled out from matrix, the pullout force can be obtained with a model of a string passing over a small frictional pulley, and the pullout force contributed by the section dx of the fiber can be expressed as [12]:

$$df_\phi = 2\pi r\tau(x)\exp(\phi f)dx, \tag{4}$$

where ϕ is the inclined angle of the fiber and f is the frictional coefficient. Correspondingly, the pullout energy of the section dx of the fiber is

$$dw_\phi = 2\pi r\tau(x)\exp(\phi f)x dx. \tag{5}$$

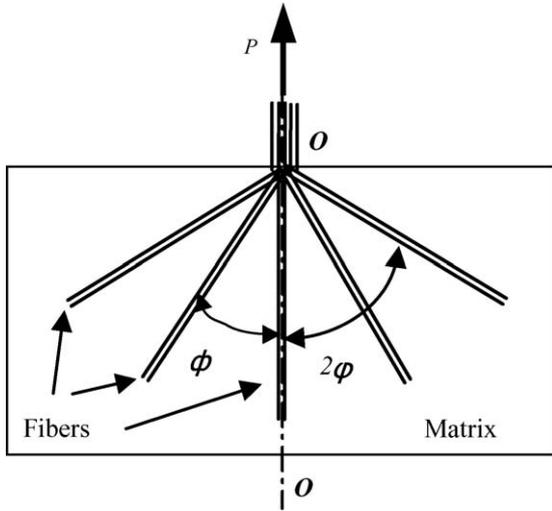


Fig. 6. Model of helicoidal structure.

The total energy pulled the whole aslant fiber out of the matrix is

$$W_\phi = 2\pi \int_0^l r\tau(x)\exp(\phi f)x dx. \quad (6)$$

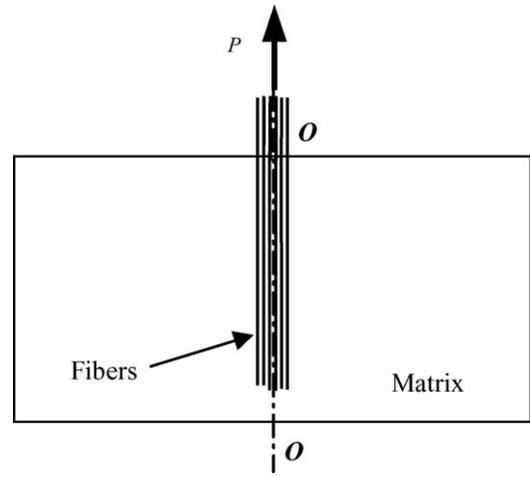
A representative model of a helicoidal structure found is shown in Fig. 6. In which, the change of the helicoidal angle and the thickness of the fiber layers are neglected. Suppose the helicoidal angle is ϕ , it is easily seen in Fig. 6 that each fiber in the helicoidal structure can be taken as an inclined fiber embedded in matrix with different angle. These fibers in the helicoidal structure will dissipate different pullout energy to resist the pull-out of the helicoidal structure. The total pullout energy of the helicoidal structure is the summation of the contribution of all the fibers. Because the helicoidal structure is laterally symmetric, from Eqs. (1) and (4), the pullout energy of the helicoidal structure can be obtained as

$$W_{\text{hel}} = 2\pi \int_0^l r\tau(x)x dx + 4\pi \int_0^l r\tau(x) \sum_{k=1}^n \exp(k\phi f)x dx \quad (k\phi \leq 90^\circ), \quad (7)$$

where n is the number of the fibers in one side of the structure, $n = (m - 1)/2$, and m is the number of the fibers in the structure. For comparison, the pullout energy of a 0° -structure (see Fig. 7), which consists of the fibers of the same the length, diameter and the number of fibers as the helicoidal structure, but all the fibers are embedded in the same matrix uprightly, was analyzed. Let the helicoidal angle ϕ (Eq. (7)) equal 0, the pullout energy for the 0° -structure can be obtained as follows:

$$W_0 = 2\pi m \int_0^l r\tau(x)x dx, \quad (8)$$

where m is the number of the fibers in the 0° -structure. Suppose the interfacial shear stress of the fibers increases with the applied load and reaches τ_s when the pullout force reaches maximum, and the maximum pullout energy of the helicoidal structure can

Fig. 7. Model of 0° -structure.

be expressed as

$$W_s = (W_{\text{hel}})_{\text{max}} = \pi r l^2 \tau_s + 2\pi r l^2 \tau_s \sum_{k=1}^n \exp(k\phi f) \quad (k\phi \leq 90^\circ). \quad (9)$$

It is easily known that the maximum pullout energy W_0 of a conventional 0° -structure can also be obtained under the same supposition from Eq. (8):

$$(W_0)_{\text{max}} = \pi m l^2 \tau_s. \quad (10)$$

In order to investigate the advantage of the helicoidal structure compared with the conventional fiber structure, the following ratio of the maximum pullout energy of the helicoidal structure to that of the conventional 0° -structure is defined:

$$\hat{W} = \frac{W_s}{W_0}. \quad (11)$$

The larger \hat{W} is, the more the pullout energy of the helicoidal structure will increase compared with that of the conventional 0° -structure. Introducing Eqs. (9) and (10) into Eq. (11) gives:

$$\hat{W} = \frac{\pi r l^2 \tau_s + 2\pi r l^2 \tau_s \sum_{k=1}^n \exp(k\phi f)}{\pi m l^2 \tau_s} = \frac{1 + 2 \sum_{k=0}^n \exp(k\phi f)}{m}, \quad (12)$$

Eq. (12) reflects the change of the maximum pullout energy of the helicoidal structure with respect to 0° -structure. Fig. 8 shows the variation of the ratio of the maximum pull-out energy \hat{W} against the number of fibers m , from which it can be seen that the larger the m , the more the maximum pullout energy of the helicoidal structure increases compared with the 0° -structure.

4. Biomimetic design

The helicoidal structure can be applied to the design of man-made fiber-reinforced composite to improve the fracture toughness of the composite. In this section a biomimetic composite

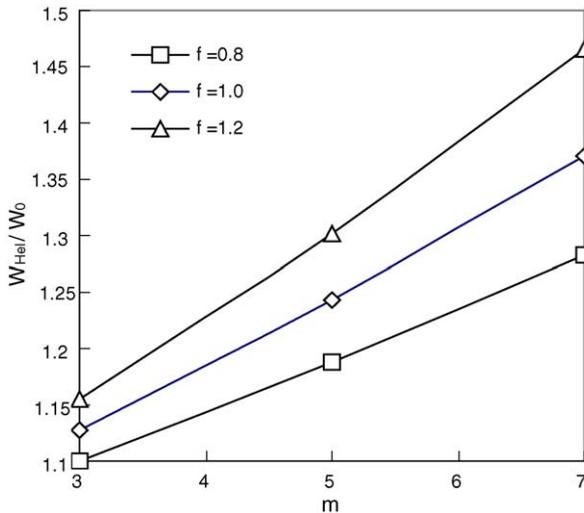


Fig. 8. The relationship between $(W_{hel})_{max}/(W_0)_{max}$ and fiber number m .

with helicoidal structure was designed and fabricated according to the pattern of the helicoidal structure found in the insect cuticle. In order to verify the advantage of the helicoidal structure in improving the fracture toughness of the composite, the fracture toughness of the biomimetic composite was tested and compared with that of conventional 0° -composite. The components used for the biomimetic fabrication are glass–fiber fabric (EW160B) and epoxy resin (E-44), which were selected due to their extensive application in civil and industrial structures. The composite with the helicoidal structure was fabricated by the following steps: dipping the fabrics of the glass fibers in epoxy resins, laying the fabric in a mould in the direction about 25° against the previous one, repeating the above two steps until all the layers designed were laid. Fifteen fiber fabrics were used altogether. After this helicoidal structure was finished, the structure was hot-pressed at curing temperature 210°C and pressure 120 MPa for 12 h. After the biomimetic composite was obtained, the conventional composite with 0° -structure was also fabricated with the same components and techniques but all the fabric layers were in the same direction. Then the two kinds of composites were cut into the specimens with the geometry as shown in Fig. 9, in which a crack was cut at the center of the specimen with a wire saw. The fracture toughness of the two kinds of the composite specimens was tested using an Instron 1342 Material Testing System, five specimens for each composite. In the test, the specimen was first aligned in the grips and tightened in place, and was then loaded monotonically at a rate of 0.02 cm/min until fracture. With the average of the obtained failure stress from the five specimens, the stress intensity factor of both the composites can be calculated with [13]:

$$K_{IC} = F\sigma\sqrt{\pi a}, \quad (13)$$

where the correction coefficient F can be expressed as

$$F = \left[1 + 0.128 \left(\frac{a}{b} \right) - 0.288 \left(\frac{a}{b} \right)^2 + 1.525 \left(\frac{a}{b} \right)^3 \right]. \quad (14)$$

The computed results (based on the fracture-toughness experiments) showed that the average fracture toughness of the com-

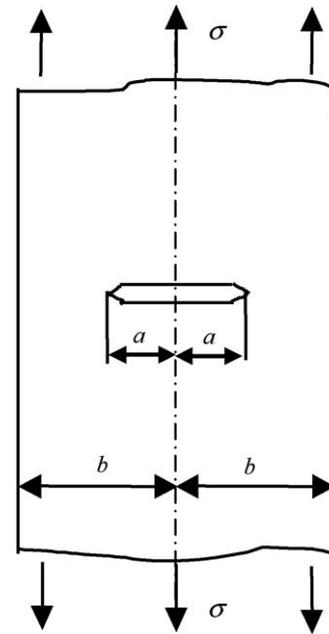


Fig. 9. Testing specimen for fracture toughness.

posites with helicoidal structure and the 0° -structure are 23.7 and $14.6\text{ MPa}\sqrt{m}$, with the standard deviations 2.54 and $1.32\text{ MPa}\sqrt{m}$, respectively. From these results it can be seen that the fracture toughness of the biomimetic composite with the helicoidal structure markedly increases compared with that of the conventional composite with 0° -structure.

5. Conclusions

The SEM observation shows that the insect cuticle is a kind of fiber-reinforced composite consisting of chitin fibers and sclerotized protein matrix. The chitin fibers are embedded in protein matrix in layered form and approximately parallel with the surface of the cuticle. The observation also reveals that the fibers in a layer have an identical orientation, and the fibers in different layers have different orientation. At different location of the cuticle the fiber structure may be different to meet different requirement of strength or toughness. The advantage of the helicoidal structure in fracture toughness is analyzed based on the analysis of the maximum pullout energy. The analytical result shows that the maximum pullout energy of the helicoidal structure is distinctly larger than that of 0° -structure. Based on the observation and analysis of the microstructure of the cuticle, a biomimetic composite with helicoidal structure is designed and fabricated. A comparative test also shows that the fracture toughness of the biomimetic composite is markedly higher than that of conventional 0° -structure composite.

Acknowledgement

The authors gratefully acknowledge the financial supports to this work from the Natural Science Foundations of China (grant Nos. 10572157, 10272120) and Chongqing (2005BB4119).

References

- [1] K.M. Rudall, W. Kenchington, *Biol. Rev.* 49 (1973) 597.
- [2] N.F. Hadley, *Sci. Am.* 7 (1986) 98.
- [3] H.R. Hepburn, A. Ball, *J. Mater. Sci.* 8 (1973) 618.
- [4] R. Schiavone, S. Gunderson, *Proc. Am. Soc. Comp.* (1989) 876.
- [5] Y. Bouligand, *Acad. Sci.* 261 (1965) 3665.
- [6] A.C. Neville, *Insect Ultra* 5 (1970) 57.
- [7] J.F.V. Vincent, U.G.K. Weget, *Arth. Struct. Dev.* 33 (2004) 187.
- [8] J. Tong, J. Sun, D. Chen, S. Zhang, *Soil Tillage Res.* 80 (2005) 1.
- [9] J. Chen, Q. Ni, Q. Li, Y. Xu, *Acta Mater. Comp. Sin.* 22 (2005) 103.
- [10] B. Chen, X. Peng, J. Wang, X. Wu, *Comp. Mater. Sci.* 30 (2004) 517.
- [11] J. Chen, N. Yang, F. Li, Z. Chen, *J. Mech. Strength* 25 (2003) 245.
- [12] V.C. Li, Y. Wang, S. Backer, *Composites* 21 (1990) 132.
- [13] Q. Gao, *Eng. Frac. Mech., Chongqing Univ.* 8 (1986) 230.