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ScienceDirect
Journal of Bionic Engineering 13 (2016) 124–131

Structure and Roles of the Various Layers in the Shells of Conch *Conus litteratus*

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Abstract

Mollusc shells are renowned for their mechanical strength and toughness. To better understand the mineralization process of the shell, structure of the body whorl and base of *Conus litteratus* (Conus shell) were in detail investigated by using scanning electron microscopy. Three-point bending tests were taken to demonstrate that each layer of crossed-lamellar structures is indispensable to enhance the whole strength of the shells. The results show that the conch shell is composed of hierarchical structure from nano scale to macro scale, and the basic constituent is long rod-shaped aragonite. Different positions of the shell have varied structures, and the base is more complicated than the body whorl. The mechanical properties of Conus are highly anisotropic and the arrangement of middle layer has a great influence on the bending strength. The outer and inner layers are very thin but play a protective role for the middle layer.

Keywords: crossed-lamellar, mechanical properties, aragonite, mollusc shell

doi: 10.1016/S1672-6529(14)60166-9

Nomenclature

TP	Transverse sample, loading on the P plane
LP	Longitudinal sample, loading on the P plane
TP-M	Middle layer of TP
LP-M	Middle layer of LP
TP-OM	Transverse sample that machined off the inner layer
TP-MI	Transverse sample that machined off the outer layer

1 Introduction

The shell material has attracted increasing attention of many scientists due to its high-toughness and intermediate-strength, which can surpass man-made ceramics[1–6]. Shells are ceramic/polymer laminated composites consisting of aligned, anisometric, calcium ($CaCO_3$) grains separated by extremely thin protein matrix[7,8]. Structure is essentially crucial to the mechanical properties when the components are consistent. The design principles found in these natural materials inspires scientists to synthesize composite materials owing optimized properties.

The novel structure and mechanical property of the nacre have become a new research trend during the past few decades[9–12]. Nacre is composed of a brick-and-mortar like structure and is considered to be stronger than the other structures in the shells[13]. However, another typical structure—crossed-lamellar is less strong but more widely exists in nature[14,15]. Crossed-lamellar has the property of fast growth and low content protein (less than 1%), and its repair processes are quicker than nacre when the shell is damaged[16]. Crossed-lamellar also has excellent mechanical properties that even surpass those of nacre in some respects. The researches of conch shell have provided clear evidence that the crossed-lamellar structure is the hardest[17] and its rupture work can reach 10 times as high as that of nacre[1,3]. Conus shells generally are made of three crossed layers on the macro[18]. Current researches of Conus mainly focus on the partial structure and mechanical properties, trying to explain why these mollusc shells have high fracture work. The main mechanisms of high toughness have been summarized: extensive crack deflection, fiber pull out and mineral bridges[15,19,20].

As is known to all, the great mass of the shell pro-

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vides stability against upheaval by tidal forces or predatory attackers, as well as protection from crab attacks that may involve forces as great as 800 N[7]. But scars are found in the body whorl in a number of conus shells (Fig. 1). To better understand the design of mollusc shells, the holistic structure of conus shells and mechanical properties that over different directions have been conducted in this paper. It proposes the possibility that the source of the scars in the shells.

2 Materials and methods

Conus litteratus was studied herein and the appearance is shown in Fig. 1. The sampling section is the body whorl of the conch shell, where symbols L, T and P represent longitudinal section, transverse section and stratification plane, respectively.

2.1 Scanning Electron Microscopy(SEM)

The intact longitudinal section of the body whorl and cross section of the base were prepared. The samples were polished by abrasive papers and etched by 1% HCl for 15 s. Subsequently, the structures of *Conus litteratus* on different positions were observed by SEM (S4800) after spray silver treatment. Fracture morphologies of some areas were also taken by SEM.

2.2 Three-point bending tests

These tests were desired to declare the role of each layer on promoting the whole strength of the shell. To minimize varying test results caused by the influence of age and environment, all longitudinal and transverse samples on each contrast experiments were cut out of one shell. Hacksaw with an abrasive blade were used to obtain rectangles with approximate sizes firstly. Successively, these precut specimens were divided into three groups and machined by raw abrasive papers to get the desired size for the following experiments. The length of 8 mm and different sizes of cross sectional areas were kept, considering the rectangular samples of transverse were too hard to take. The span was 6 mm for all the tests and the samples herein were tested by a head speed of 0.1 mm·min^{-1}. The results can only give comparison within group because of the samples are not standard.

Integrated samples, which have the full thickness of the shell with the sectional areas about 2 mm × 2.5 mm, were tested on different planes in the first group. The loading was on P plane for the transverse and longitudinal samples (TP, LP). Fig. 5a gives an overview of the different test configurations. In the second group, all samples were machined off the inner layer and outer layer to remain the middle layer with cross sectional areas about 1 mm × 1 mm. The loading was applied on P plane for the transverse specimens (TP-M) and longitudinal specimens (LP-M). In the third group, the transverse samples were tested on P plane (TP). A part of them were removed the inner layer (TP-OM) or outer layer (TP-MI).

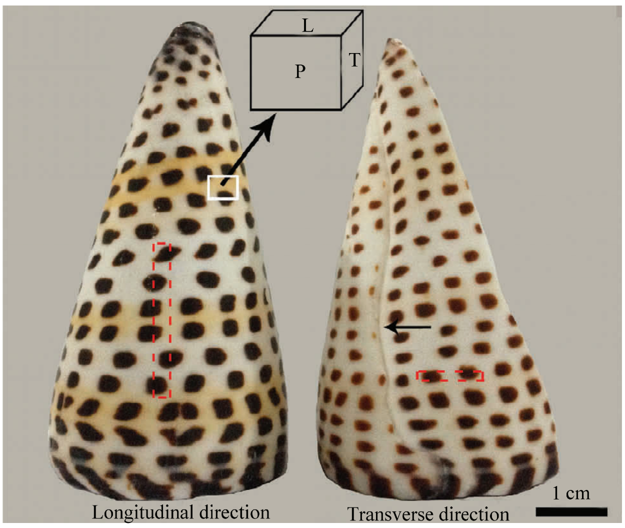

Fig. 1 The appearance of *Conus litteratus*, showing the cutting directions and positions of the test pieces; Scar is shown in the right one. L: longitudinal section, T: transverse section, P: stratification plane.

3 Results and discussion

3.1 Structure of the body whorl

3.1.1 Macrostructure

A mature conch *Conus litteratus* has a cone-like shell of proximate 60 mm – 70 mm high and of 30 mm – 40 mm diameter base, as shown in Fig. 1. The longitudinal section of the shell (Fig. 2a) indicates that the shell consists of several whorls growing from inside to outside. The most outside whorl is quite uniform in thickness and is also the thickest, and the middle position is about 2.0 mm – 3.0 mm. Due to this reason, we used the shell of this whorl as sample to measure the mechanical properties of the shell.

The uniform area of the shell is constituted of three layers along the thickness direction: outer layer (O), middle layer (M) and inner layer (I) (Fig. 2d). The middle layer is the thickest, about 1.5 mm, while the inner