Materials Science and Engineering C 35 (2014) 441–448

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Alligator osteoderms: Mechanical behavior and hierarchical structure

Irene H. Chen [a], Wen Yang [a,*], Marc A. Meyers [a,b]

[a] Materials Science and Engineering Program, University of California, San Diego, La Jolla, CA 92093, USA
[b] Departments of Mechanical and Aerospace Engineering and Nanoengineering, University of California, San Diego, La Jolla, CA 92093, USA

ARTICLE INFO

Article history:
Received 14 June 2013
Received in revised form 17 October 2013
Accepted 16 November 2013
Available online 1 December 2013

Keywords:
Alligator
Osteoderms
Scutes
Mechanical properties
Mechanisms

ABSTRACT

Osteoderms are bony scutes embedded underneath the dermal layers of the skin acting as a protection of the alligator (Archosauria: Crocodylia) internal organs and tissues. Additionally, these scutes function as an aid in temperature regulation. The scutes are inter-linked by fibrous connective tissue. They have properties similar to bone and thus have the necessary toughness to provide protection against predators. The scutes consist of hydroxyapatite and have a porosity of approximately 12%. They have a disc-like morphology with a ridge along the middle of the plate, called the keel; the outer perimeter of the disc has depressions, grooves, and jagged edges which anchor the collagen and act as sutures. Computerized tomography reveals the pattern of elongated pores, which emanate from the keel in a radial pattern. Micro-indentation measurements along the cross-section show a zigzag behavior due to the porosity. Compression results indicate that the axial direction is the strongest (UTS ~67 MPa) and toughest (11 MJ/m^3); this is the orientation in which they undergo the largest external compression forces from predator teeth. Toughening mechanisms are identified through observation of the damage progression and interpreted in mechanistic terms. They are: flattening of pores, microcrack opening, and microcrack growth and coalescence. Collagen plays an essential role in toughening and plasticity by providing bridges that impede the opening of the cracks and prevent their growth.

1. Introduction

The existence of the crocodilians can be traced as far back as 180 million years ago, when they coexisted with dinosaurs [1]. They survived through volcanic eruptions, erratic climate changes, ice ages, and a possible asteroid collision with the earth at the Cretaceous-Tertiary boundary which occurred 65 million years ago, wiping out all but a few species. Alligators have to not only defend themselves from intra species predation but also contend with various predators. One of the important features that the alligators have evolved and developed through environmental and defensive selection is the “armored skin”. This characteristic was also found on dinosaurs and ancient fish [2]. The osteoderms on their dermis provide a protective barrier against attack, such as enemy's teeth and claws [3]. In ancient times, alligator osteoderms were used as army protective outfits; they were considered to be strong and tough enough to protect against arrows and blows from the enemy.

The alligator scutes are oriented along the back of the animal in the transverse direction with 15 rows of 6 larger plates (per row) and another 5 rows of 3 smaller plates near the posterior shown in Fig. 1a [4]. The scute (cross-sectional view in Fig. 1b and c), a round disc-like plate, has a varying diameter of 5 cm to 8 cm depending on the anatomical location along the back of the animal and on the animal's size. It has a keel, a tilted projection, in the middle of the disc. The keels arranged in rows give out the spiked characteristics in the back of the animal (Fig. 1a). The keel is assumed to provide a structure which the skin can anchor itself on [6]. Other morphological characteristics include the small nutrient bony network on the surface near the keel. Viewing from the longitudinal direction (Fig. 1b) a porous region is revealed, similar to the structure of bovine bone. The osteoderms overlap [7] and are inter-connected by collagen fibers [8,9]. The limbs are also covered by osteoderms [10]. Due to the connection mechanisms, the entire alligator skin with osteoderms is very flexible [11]; especially, the axial and paraxial locomotor apparatus is quite mobile [10].

The formation of an alligator scute begins with calcium mineralization at the center (keel region) and proceeds radially, one year after hatching; calcium is gradually deposited on the collagen fibers from the surrounding dermis layer. Before calcification, the integument has already developed into the epidermis and dermis regions. Vascularization is seen throughout the dermis region. The individual osteodermal development is a synchronized process across the body sequenced by firstly forming dorsally next to the neck region and then gradually growing by the addition of successive elements along the caudal and lateral positions [12,13]. Growth marks [9,14] are formed, comprising annuli deposited in winter and zones formed in the summer. It was proposed that under palaeoenvironmental conditions, osteoderms might have provided calcium storage [15]. The osteoderms also provide other functionalities for alligators as suggested by Seidel [6]: thermal absorption and transformation. The osteoderms absorb radiant heat efficiently during basking and can rapidly transfer and carry heat from the outside surroundings due to their vascularity. The vascular network throughout the osteoderms controls the animal's body thermoregulation

* Corresponding author.
E-mail addresses: wey005@eng.ucsd.edu, wyang8207@gmail.com (W. Yang).

0928-4931/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msec.2013.11.024

by vasoconstriction and vasodilation [6]. This helps with the body temperature regulation of the animal. The vascularization also allows the osteoderms to store calcium [16].

The osteoderms are bony plates and as such the known response of bone is essential to their understanding. Bone has an extraordinary toughness that is enabled by the toughening mechanisms that were identified by Ritchie *et al.*[17,18]. These toughening mechanisms are divided into intrinsic and extrinsic. The extrinsic toughening mechanisms act to shield the crack from the applied load and operate behind the crack front. Four extrinsic toughening mechanisms are present in bone: crack deflection, uncracked ligament bridging, collagen fibril crack bridging, and microcracking. Intrinsic mechanisms, on the other hand, typically act ahead of the crack tip and reduce stresses and strains through localized yielding and redistribution of stresses [19–22], or may even promote crack growth.

There is almost no information in the literature on the mechanical response of alligator osteoderms. An important goal of the research whose results are presented here was to establish the principal toughening mechanisms in the osteoderm. Since the osteoderm acts as a protection for the alligator, it is proposed that this study can inspire novel material designs, such as flexible armor.

2. Experimental procedure

The scutes in the present work are from American Alligators with age 8–10 years old. The water content of scutes was measured by drying them in a furnace for 4 h at 100 °C and weighing them before and after the treatment. The protein content was measured by heating the scute in furnace for 24 h at 400 °C. The alligator scutes were characterized using X-ray diffraction, optical microscopy, and scanning electron microscopy (SEM, Phillips XL30 SEM, Hillsboro, Oregon, USA). The mechanical behavior including the micro-hardness and compression response was examined to establish the fracture mechanisms and the relationship between the microstructure and mechanical behavior. The samples were kept in water because the osteoderm has a vascular network in the structure which indicates that blood flows through it when the alligator is alive. All the samples were coated with iridium prior to SEM observation.

2.1. X-ray diffraction

X-ray diffraction (XRD) was performed on the powder collected from the alligator's osteoderm using a bench top XRD system (MiniFlex TM II, Rigaku Company, Austin, Texas). The scan was performed continuously from $2\theta = 0$ to 60°, with a step size of 0.01° at a rate of 1°/min. The radiation source was CuKα1 with a wavelength of 0.154 nm.

2.2. Micro-indentation

The alligator scutes were cut longitudinally and transversely to determine the Vickers hardness variation through the thickness. They were ground using 180#-2500# silicon carbide paper and then polished with 0.3 μm and 0.05 μm alumina powder to ensure smooth surfaces. Hardness tests were performed in dry condition under a relative humidity of ~78% using an indentation load of 100 g (holding time:10s) with a LECOM-400-H1 hardness testing machine (LECO M-400-HI, Leco Co., Michigan, USA).

2.3. Compression tests

Due to the dimensional constraints on the alligator scutes, 30 samples were cut into cubes with approximately 5 mm × 5 mm × 5 mm. Before testing, they were immersed in fresh water for more than 24 h. Compression tests were conducted using a 30 kN load cell equipped universal testing system (Instron 3342, Norwood, MA) at a strain rate of 10^{-3} s^{-1}. Three loading orientations were adopted as shown in Fig. 1b and c; the axial direction (orientation A in Fig. 1b and c) is along the thickness of the scute, the longitudinal (orientation B in Fig. 1b and c) is along the keel of the scute, while the transverse (orientation C in Fig. 1b and c) is perpendicular to the keel. The compression samples were tested immediately after removal from the water. All

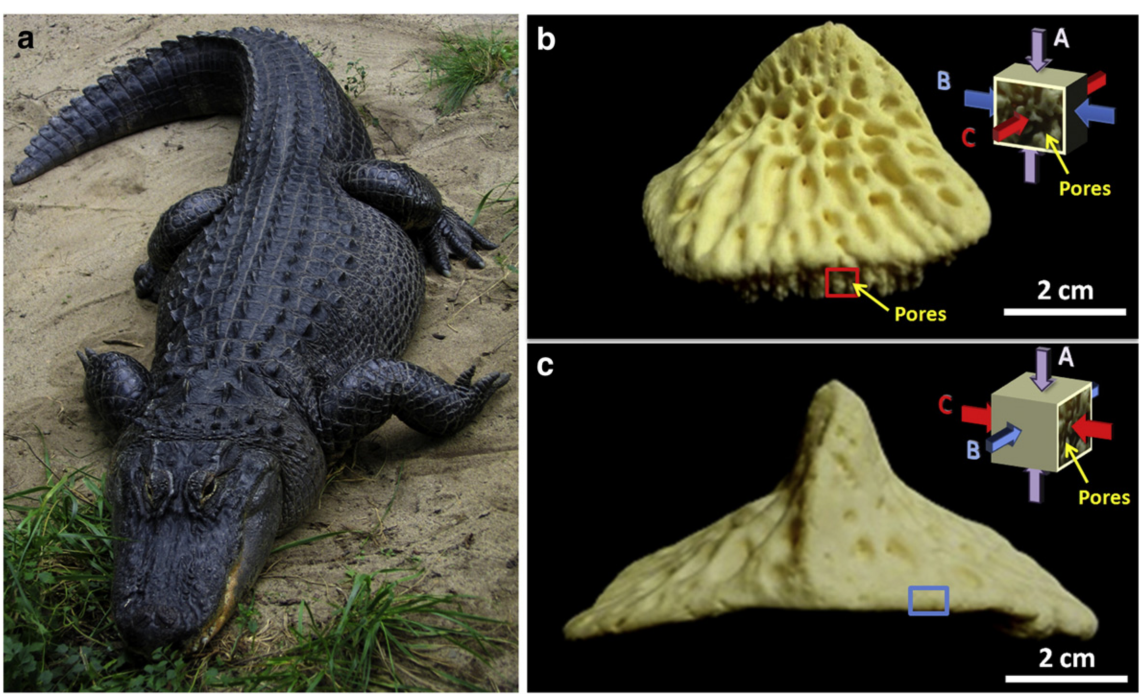

Fig. 1. (a) Alligator showing protrusions on back, each one corresponding to a scute [5], (b) longitudinal view of a scute, (c) transverse view of a scute; the schematics on the top right corners of (b) and (c) show the loading orientations of compression samples.