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Research paper

Structure and mechanical behaviors of protective armored pangolin scales and effects of hydration and orientation

Z.Q. Liu*, D. Jiao, Z.Y. Weng, Z.F. Zhang*

Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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ABSTRACT

As natural flexible dermal armor, pangolin scales provide effective protection against predatory threats and possess other notable properties such as anti-adhesion and wear-resistance. In this study, the structure, mechanical properties, deformation and damage behaviors of pangolin scales were systematically investigated with the effects of hydration and orientation evaluated. The scales are divided into three macro-layers constituted by overlapping keratin tiles with distinct lamellar arrangements which are further composed of lower-ordered lamellae. Both hardness and strength are significantly decreased by hydration; while the plasticity is markedly improved concomitantly, and as such, the mechanical damages are mitigated. The tensile strength invariably approximates to one third of hardness in value. The tensile deformation is dominated by lamellae stretching and pulling out under wet condition, which is distinct from the trans-lamellar fracture in dry samples. The compressive behaviors are featured by pronounced plasticity in both dry and wet scales; and notable strain-hardening capacity is introduced by hydration, especially along the thickness direction wherein kinking occurs. Inter-lamellar cracking is effectively alleviated in wet samples compared with the dry ones and both of them deform by macroscopic buckling. This study may help stimulate possible inspiration for the design of high-performance synthetic armor materials by mimicking pangolin scales.

1. Introduction

Biomimetic design has attracted increasing attention because it may provide innovative approaches for developing new types of high-performance materials and components (Chen et al., 2012; Fratzl, 2007; Greiner and Schäfer, 2015; Liu and Jiang, 2011; Wegst et al., 2015). The derivation of useful designing strategies relies fundamentally on a broad understanding about natural biological materials. The materials synthesized by living organisms generally possess notable properties far exceeding those of their components and synthetic counterparts (Chen et al., 2012; Meyers et al., 2013;

*Corresponding authors. Tel.: +86 24 23971043; fax: +86 24 23891320.
E-mail addresses: liuzq@imr.ac.cn (Z.Q. Liu), zhfzhang@imr.ac.cn (Z.F. Zhang).

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Wegst et al., 2015; Weiner et al., 2000). Such superiority can be exemplified by the natural dermal armors evolved in many animals, such as the scales of fishes and osteoderms of reptiles (Wang et al., 2016; Yang et al., 2013). The armors provide effective protection against predatory threats while maintaining sufficient flexibility; and many of them also participate in multiple other functions, such as waterproofing and temperature regulation. The study on natural armors has important implications as it may stimulate valuable inspiration for designing new synthetic armor materials in terms of biomimicking. So far, the scales of a variety of fishes have been investigated by combining experimental and computational methods (Bruet et al., 2008; Han et al., 2011; Ikoma et al., 2008; Torres et al., 2015; Yang et al., 2014; Zimmermann et al., 2013). Different design principles have been revealed accordingly and proposed for strengthening and toughening synthetic materials. Besides, the structure and mechanical properties of other biological armors, including the osteoderms of alligators and armadillos as well as the turtle carapaces, have also been clarified (Achrai et al., 2015; Achrai and Wagner, 2013; Balani et al., 2011; Damiens et al., 2012; Rhee et al., 2011; Sun and Chen, 2013).

The pangolins, also referred to as scaly anteaters, are a unique type of armored mammal inhabiting the tropical and subtropical regions throughout Africa and Asia. They are featured by their overlapping scales covering the majority of skin (Fig. 1(a)), which may account for ~20% of the body by weight. Such scaly armored manner, which has been suggested to favor higher flexibility, is quite different from the cases in most reptiles and other terrestrial animals that tend to have juxtaposed plates connected by collagen fibers (Achrai et al., 2015; Achrai and Wagner, 2013; Balani et al., 2011; Chen et al., 2011; Sun and Chen, 2013; Yang et al., 2013). The pangolins curl up when threatened to project their scales outwards as in half-opened fir cones and expose the sharp scale edges, giving rise to effective defense and even injury to the predators. Moreover, the scales of burrowing pangolins possess other outstanding functions of anti-adhesion and wear-resistance against soil and even rock. The chemical constituents and histological characters of pangolin scales have been analyzed in pioneering studies (Spearman, 1967; Tong et al., 1995, 2000, 2007). The scales were determined to be composed of both α- and β-type keratins and suggested to be homologous with the primate nails (Spearman, 1967; Tong et al., 1995). In addition, the tribological behaviors have been paid much attention to explore possible guidelines for the design of soil-engaging components (Sun et al., 2012; Tong et al., 1995, 2000, 2007). Nonetheless, despite the potential inspiration for synthetic armor materials, the structure and mechanical behaviors of pangolin scales have rarely been reported to date. The objective of this study is to clarify the mechanical properties, deformation and fracture behaviors of pangolin scales and correlate them to the structure. Different testing methods of indentation, tension and compression

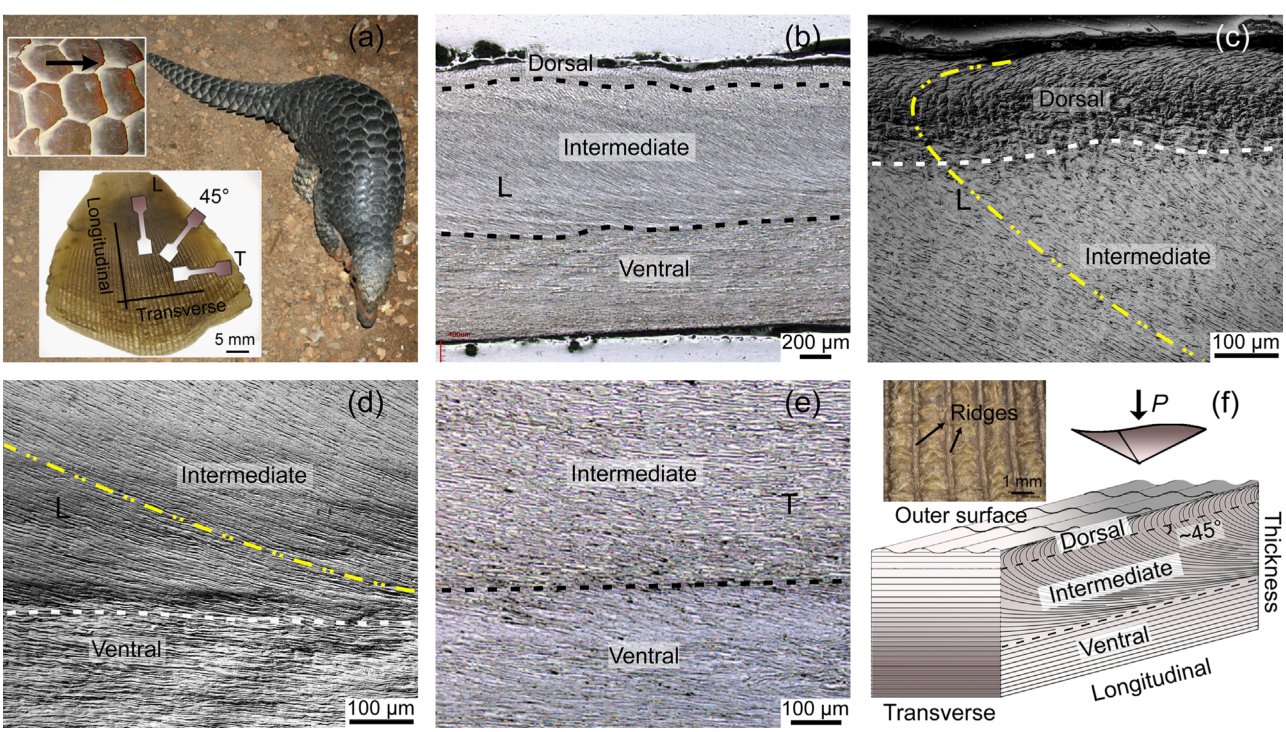

Fig. 1 – (a) Macroscopic image of pangolin. The arrangement of scales on the back and the top-view appearance of one scale are shown in the insets. The orientations of tensile samples are indicated. The growth direction is denoted by the arrow. (b) Morphology of the longitudinal section from the central part of pangolin scale. The boundaries between adjacent layers are denoted by dashed curves. Magnified views of (c) the upper region in longitudinal section and middle region in (d) longitudinal and (e) transverse sections. The orientations of keratinous lamellae are indicated by the dash–dotted curves. (f) Schematic illustrations of the structure of pangolin scale and indentation procedure along the thickness direction. The morphology of outer surface is shown in the inset.