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Structure and mechanical properties of naturally occurring lightweight foam-filled cylinder – The peacock's tail coverts shaft and its components

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ABSTRACT

Feather shaft, which is primarily featured by a cylinder filled with foam, possesses a unique combination of mechanical robustness and flexibility with a low density through natural evolution and selection. Here the hierarchical structures of peacock's tail coverts shaft and its components are systematically characterized from millimeter to nanometer length scales. The variations in constituent and geometry along the length are examined. The mechanical properties under both dry and wet conditions are investigated. The deformation and failure behaviors and involved strengthening, stiffening and toughening mechanisms are analyzed qualitatively and quantitatively and correlated to the structures. It is revealed that the properties of feather shaft and its components have been optimized through various structural adaptations. Synergetic strengthening and stiffening effects can be achieved in overall rachis owing to increased failure resistance. This study is expected to aid in deeper understandings on the ingenious structure–property design strategies developed by nature, and accordingly, provide useful inspiration for the development of high-performance synthetic foams and foam-filled materials.

1. Introduction

Lightweight cellular solids or foams and foam-filled structures have attracted great attention owing to their unique properties, such as outstanding kinetic energy absorption efficiency from impacts, high strength-to-density ratio, and good insulation ability [1]. So far, a huge number of synthetic foams and foam-filled materials have been exploited and widely applied in various fields, e.g., buildings, transport systems and biomedical implants. Besides the composition, structure plays a dominant role in determining the properties of cellular materials [1,2]. Accordingly, the structural design and control have invariably been a central focus for property optimization. In this respect, nature has achieved great successes and may serve as a fruitful source of insights and inspiration. There are numerous biological materials with cellular structures in nature, such as wood, bone, porcupine quill, avian beak and feather rachis [1–10]. Through long-period natural evolution and selection, the structures and properties of these materials have been optimized for their particular functions, despite the fact that most of them are synthesized using weak elements at ambient conditions [9]. For instance, the bending resistance of avian beaks can be improved by three to six times without significantly increasing the density through incorporating closed-cell foam into exterior shell [10]. Owing to the notable properties and plentiful resources, some naturally occurring cellular materials, e.g., wood, have found widespread engineering applications [1,8]. Moreover, valuable inspiration may be generated for exploiting synthetic foams and foam-filled materials by mimicking the ingenious structures [3,5,11], e.g., titanium foams for bone substitutes and porous polymer scaffolds for tissue engineering [12,13]. Therefore, it has broad implications to elucidate the structure and mechanical properties, especially their relationships, in natural biological cellular materials.

As one of the most complex integumentary appendages in vertebrates, feathers possess a hierarchically branched construction based on a central shaft and fused with a series of barbs [14,15]. As the primary mechanical supporter, feather shaft can be divided into two parts along its length. The most proximal section, termed calamus, is anchored into follicle and featured as a hollow tube. In comparison, the majority of shaft, the feather rachis, is manifested by a near cylindrical cortex shell filled with medullary foam. Feathers have evolved to be robust and flexible enough to withstand the aerodynamic forces during flight, yet still maintaining a low density

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[14–16]. They also aid in the thermal insulation, waterproofing, camouflage, and even courtship [17]. Owing to these attributes and their potential inspiration, feathers are drawing an increasing attention and research interest [14,15,18–29]. It is reported that feathers are composed of feather keratin which can be classified as the so-called β-keratin made of β-sheets [28–30]. The arrangement of β-sheets at the molecular level has been elucidated through experiments [18–21]. The mechanical properties of feather shaft as well as cortex and foam have also been preliminarily evaluated [22–29]. Nevertheless, a systematic understanding is still far from being achieved on the structures, mechanical properties, deformation and failure behaviors of feather shaft and its components, especially from a viewpoint of materials science. Meanwhile, the mechanical behaviors have rarely been correlated to the structures so far [15]. As a result, it still remains unclear about the involved mechanisms that make feathers strong and tough.

The peacock, or the male peafowl in the pheasant family, is primarily featured by its extravagant tail coverts which are normally used for sexual displaying, frightening predators and fighting with rivals. Though contributing little to flying, the tail coverts do bear substantial stresses from both their own weight and external loads during above processes [28]. Meanwhile, they are long and thick among various avian feathers and thus may provide samples in sufficient size for experiments. In this study, the structures of peacock's tail coverts shaft and its components are systematically characterized. The mechanical properties, deformation and failure behaviors are analyzed. The strengthening, stiffening and toughening mechanisms are investigated.

2. Materials and experimental procedures

2.1. Materials

Naturally shed tail coverts in length of ~105 cm of healthy adult peacocks (*Pavo cristatus*) were purchased from a local farm. Feather shafts were obtained by cutting off the vanes. The apparent densities of shaft and its components were obtained by dividing their weights using volumes determined by optical observation. The mean moisture content was measured to be ~7.9 wt.% through adequately drying the shafts at 105 °C for 5 h. The dried shafts were then ashed at 560 °C for 40 h. The mineral content (or ash content) was quantified as the ratio between weight of ash and that of original dried sample [31].

2.2. Structural characterization

Different types of specimens have been adopted for structural analysis. A feather shaft was transversely sectioned using a low speed diamond saw at different positions along its length with intervals of 1 cm near the proximal and 7 cm for the majority of rachis. The proximal part of another shaft was sectioned in the longitudinal direction. These samples were then mounted in epoxy, ground and polished to mirror finish. Fractured shafts were also prepared by manually tearing for examination. The structure was characterized by laser scanning confocal microscopy (LSCM) using an Olympus LEXT OLS 4000 3D-measuring microscope and field emission scanning electron microscopy (SEM) on an LEO Supra 35 instrument. Samples were sputter-coated with a film of gold prior to SEM observation. The surface roughness was measured according to LSCM using the accessory software. At least 90 foam cells from random regions were analyzed for each position to determine the cell sizes. X-ray computed micro-tomography (XCT) was employed to visualize the three-dimensional morphologies of foam by an Xradia-Versa XRM 500 scanner with a voxel size of 0.68 μm. The phase constituents of both cortex and ash of shaft were examined by X-ray diffraction (XRD) using a D/MAX-2500PC diffractometer. The ash was further characterized by transmission electron microscopy (TEM) using an FEI Tecnai G2 F20 system.

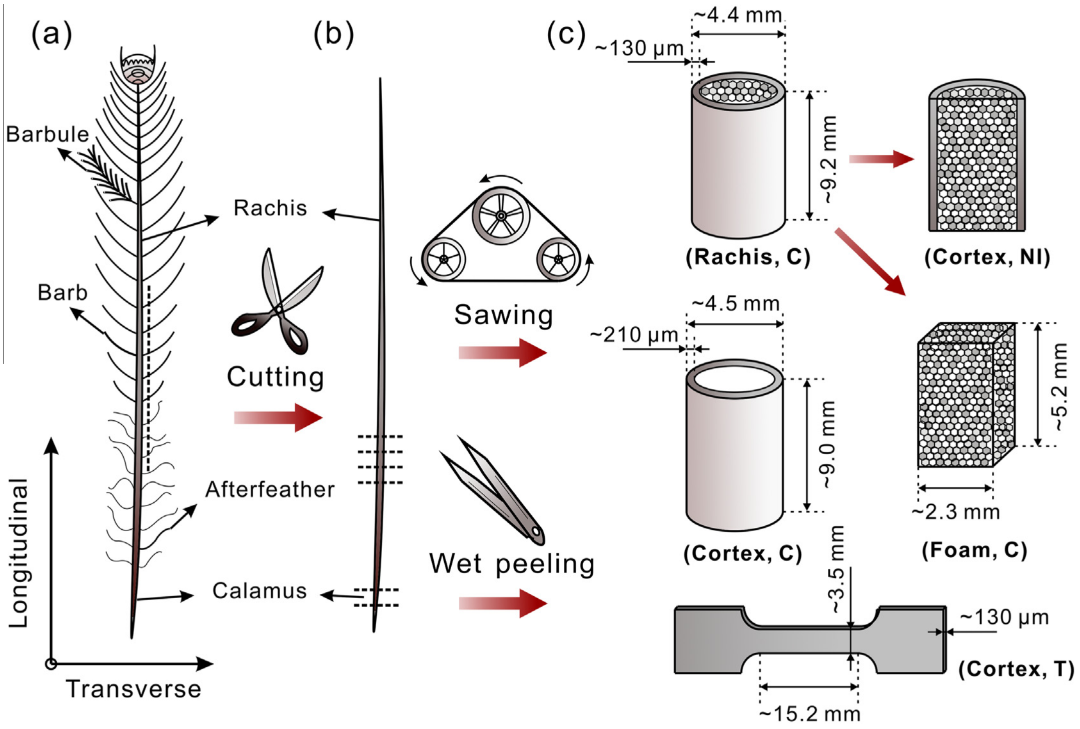

Fig. 1. Schematic illustrations for preparation procedures of the mechanical testing samples and their nominal dimensions. NI, C and T represent the testing methods of nanoindentation, compression and tension, respectively.