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# Enhanced protective role in materials with gradient structural orientations: Lessons from Nature

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ABSTRACT

Living organisms are adept at resisting contact deformation and damage by assembling protective surfaces with spatially varied mechanical properties, *i.e.*, by creating functionally graded materials. Such gradients, together with multiple length-scale hierarchical structures, represent the two prime characteristics of many biological materials to be translated into engineering design. Here, we examine one design motif from a variety of biological tissues and materials where site-specific mechanical properties are generated for enhanced protection by adopting gradients in structural orientation over multiple length-scales, without manipulation of composition or microstructural dimension. Quantitative correlations are established between the structural orientations and local mechanical properties, such as stiffness, strength and fracture resistance; based on such gradients, the underlying mechanisms for the enhanced protective role of these materials are clarified. Theoretical analysis is presented and corroborated through numerical simulations of the indentation behavior of composites with distinct orientations. The design strategy of such bioinspired gradients is outlined in terms of the geometry of constituents. This study may offer a feasible approach towards generating functionally graded mechanical properties in synthetic materials for improved contact damage resistance.

**Statement of Significance**

Living organisms are adept at resisting contact damage by assembling protective surfaces with spatially varied mechanical properties, *i.e.*, by creating functionally-graded materials. Such gradients, together with multiple length-scale hierarchical structures, represent the prime characteristics of many biological materials. Here, we examine one design motif from a variety of biological tissues where site-specific mechanical properties are generated for enhanced protection by adopting gradients in structural orientation at multiple length-scales, without changes in composition or microstructural dimension. The design strategy of such bioinspired gradients is outlined in terms of the geometry of constituents. This study may offer a feasible approach towards generating functionally-graded mechanical properties in synthetic materials for improved damage resistance.



## 1. Introduction

The increasingly stringent requirement for the enhanced performance of materials has stimulated the concept of functionally graded materials (FGMs) which encompass spatial gradients of composition or/and structural characteristics in continuous or fine discrete manner. Compared to the traditional materials that are usually homogeneous or possess abrupt changes of composition/structure, the overall properties of FGMs benefit from their gradients in a range of aspects [1–4]. A prime example is the graded metal-ceramic composites designed for thermal barrier applications [1,2]. The thermal stress and resultant damage can be effectively mitigated by introducing a smooth compositional transition over the volume by manipulating the spatial dispersions of constituents [4,5]. Another advantage of FGMs is their enhanced resistance to contact deformation and damage [6,7]. A customary motif is to utilize relatively harder materials, generally at a surface that experiences a high stress, to resist wear and/or penetration, and to employ relatively tougher materials, generally at the subsurface region, to accommodate deformation, dissipate mechanical energy and arrest the propagation of cracks.

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The processing and properties of FGMs have attracted considerable research interest over the past two decades [1–4,6]. A common strategy that has been most frequently adopted is to control the spatial distribution of compositions or constituents [3]. For example, a ceramic-glass FGM with improved indentation toughness can be generated by infiltrating an oxynitride glass into a silicon nitride matrix [7]. Alternatively, the characteristic dimension of the structural units can be manipulated; a prime example is the gradient nano-grained metals fabricated by surface mechanical grinding treatment [8]. Additionally, elastic gradients can be created in laminated composites via a stepwise variation of the in-plane alignment of fibers between adjacent laminates [9].

Although the idea of FGMs is relatively new in the engineering field (the concept was first proposed in 1980s in Japan [1,2]), the design principle has long been utilized in Nature by optimizing the performance of numerous biological materials [10–19]. For example, bamboo, as a naturally-occurring FGM, features a composite structure reinforced by vascular bundles that comprise mainly cellulose fibers aligned along the long axis of stem [12]. These bundles are distributed in a graded fashion with decreasing density from the outermost periphery inwards, leading to graded mechanical properties that endow the bamboo with enhanced flexural rigidity [13]. An important class of natural FGMs are biological armors, such as fish scales [14–16], mollusk shells [17,18] and alligator osteoderms [19], wherein distinct layers are usually assembled to generate site-specific properties for enhanced protection to penetration, *e.g.*, caused by the biting attack from predators. Although it is doubtful whether the primitive idea for early graded materials, such as the blades of Samurai or ancient Chinese bronze swords [20], originated from Nature, biological materials may offer fruitful inspiration for the development of such high-performance synthetic FGMs.

Here we extract one salient natural design motif of FGMs used to enhance offense and/or defense against predators from a multitude of biological materials and components where functionally graded mechanical properties can be achieved by tuning the structural orientations. Variations in local mechanical properties with structural orientation, including stiffness, strength and fracture resistance, are quantitatively elucidated and the mechanisms for improved protection clarified and further visualized by numerical simulation.

## 2. Gradient structural orientations in Nature

Biological materials are generally composites comprising relatively hard and soft components and have evolved complex hierarchical architectures that have been ingeniously optimized from nano to macro length-scales for their specific functions [21–24]. This is particularly true for tissues or materials serving as offensive weapons and/or defensive armors; both are vital for most living organisms. Such biological design has developed through the long-period "evolutionary arms race", in particular using continuously varying structural orientations, with mechanical efficiency as the central concern [15,25]. Notable examples of macro tissues in this type are the horns of yak and antelope [26], tusks of wild boar, walrus and elephant [27], claws of lobster and crab [28,29], scorpion stingers [30], spider fangs [31,32], and worm jaws [33,34], as shown in Fig. 1. The long axes of these tissues change gradually towards their apexes to approach the direction of external force experienced therein (the external force is generally nearly tangent to the centerline [30–32]), so that the overall orientation continuously deviates from the external force with increasing distance from the loading site.

In addition to the macroscopic geometry, a number of biological materials possess graded structural orientations at the micro/nano length-scales. For example, in nacreous shell materials, the first-order constituent layers along the thickness are gradually tilted from being parallel to the surface in the interior to being oblique

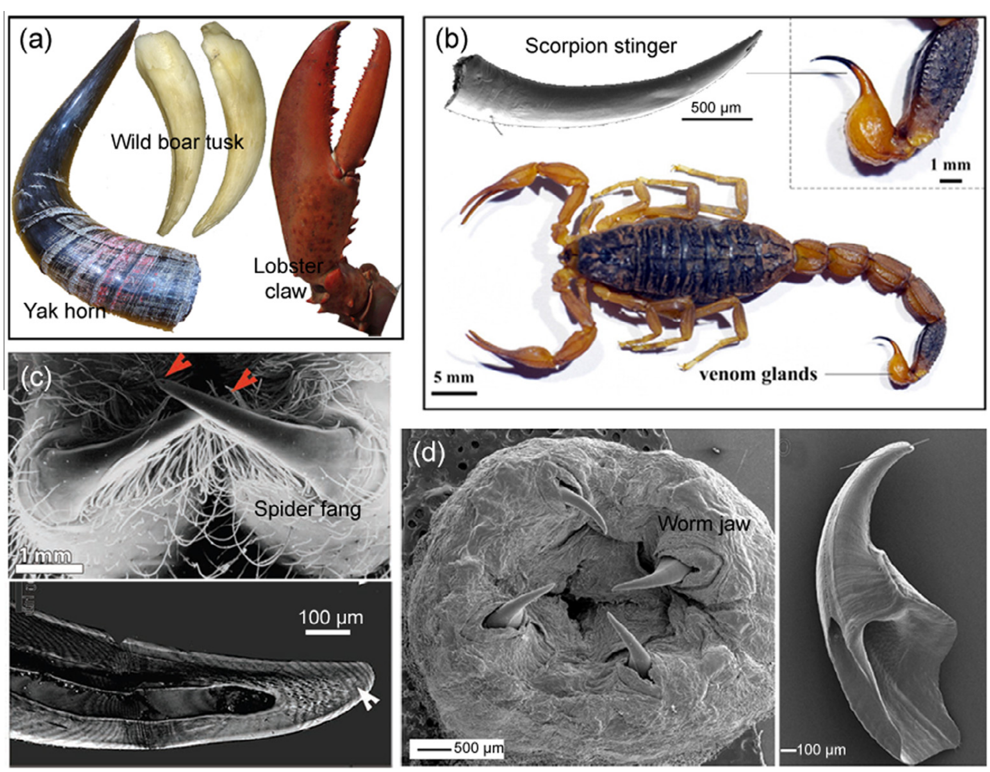


**Fig. 1.** Continuously curving shapes in representative biological tissues of yak horn, wild boar tooth, lobster claw (a), scorpion stinger (b), spider fang (c), and worm jaw (d). (b-d) are adapted with permission from Refs. [30,31,34].