Arch-inspired super-elastic carbon materials

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Arch structures have been widely used in engineering construction due to their structural advantages, and continue to find new applications in various fields. Except for arch bridges that transform significant weight to extrusion force along the arch axis, elastic arches are another important construct. For example, leaf springs act as a kind of arch-shaped spring-type suspension system in vehicles (Fig. 1a). A bow transforms the elastic potential energy of the flexed rod into the velocity of an arrow when the string is released. Another example is in the human foot, where the arches

Figure 1. Elastic carbon monolith based on a micro-arch structural design. (a) A typical example of an elastic macro-arch. (b) Schematic showing the fabrication process of the carbon elastomer. (c) SEM image showing the lamellar multi-arch microstructure of the carbon elastomer. (d) High-resolution TEM image showing that the lamella is composed of an amorphous carbon and graphene composite. (e) Real-time images from a high-speed camera showing that a steel ball rebounds from the carbon elastomer at a large speed, in a spring-like fashion. (f) Stress–strain curves of the carbon elastomers at 20% strain for $1 \times 10^6$ cycles, at 50% strain for $2.5 \times 10^6$ cycles and at 80% strain for $1 \times 10^6$ cycles. (g) The true material strain (von Mises total strain) profiles of the cylindrical shell model under a large geometrical deformation. Reprinted with permission from Ref. [2] with permission from Copyright 2016 Nature Publishing Group.
act as elastic arch-shaped springs that support the weight of the body in the erect posture and facilitate body motion [1]. These macro-arch structures are notable for combining elastic and fatigue-resistant properties, and provide material scientists with conceptual inspiration for microstructural solutions in structural materials design.

In a latest report co-authored by Yu and Wu’s groups from the University of Science and Technology of China (USTC), the researchers, inspired by these macro-arches, reported the fabrication of a new low-density carbon material with micro-arches as its structural unit [2]. It is amazing that this material consists of a brittle carbon skeleton yet displays brilliant mechanical performance, including super-elasticity, high compressibility and superior fatigue resistance. It is an important breakthrough because low-density structural materials are of great significance in various fields [3–9], while they often suffer from fatigue-induced failure or poor elasticity due to the inevitable microstructure damage when they undergo cyclic high-strain processes.

This carbon monolith contains numerous micro-arches aligned along a preferred direction in a staggered stacking manner, which has been achieved by an ingenious combination of bidirectional freezing and subsequent annealing (Fig. 1b–d). The bidirectional freezing process is used to first obtain a monolithic chitosan-graphene oxide composite (CS-GO) scaffold with a parallel, aligned and thin lamellar structure. Then, these thin lamellas are crumpled into a wavy micro-arch morphology in an annealing process that benefits from the different degrees of local volume decrease of the CS matrix and the embedded GO sheets when they are carbonized.

By designing such a unique microstructure, the final monolithic carbon material has an elastic behavior with, typically, very little energy loss (∼0.2) even when a high compressive strain of 90% is applied. A steel ball rebounds from it in a spring-like fashion with a fast recovery speed (∼580 mm/s) (Fig. 1e). In particular, it can undergo more than $1.0 \times 10^6$ compression cycles at 20% strain, $2.5 \times 10^5$ cycles at 50% strain and $1.0 \times 10^4$ cycles at 80% strain, yet still retain its structural integrity (Fig. 1f). These exceptional mechanical properties appear to be far superior to those of current state-of-the-art compressible structural materials made from stronger and more robust solid constituents. Mechanical simulations and further in situ SEM observations prove that the origin of the brilliant mechanical performance is the essential structural superiority of the micro-arch unit (Fig. 1g). Distinct from the irregular cellular walls or struts in traditional open-cell foams, these thin-shell micro-arches can undergo large and elastic out-of-plane deformation while undergoing very small in-plane material strain. Therefore, the monolithic material is more elastic and robust against compression. Moreover, because buckling and/or fracture is infrequent, sliding friction between opposing arch-shells is identified as the main reason for the small energy dissipation in each compression cycle, which is confirmed by mechanical simulation.

In short, this innovative microstructural design, which is motivated by elastic macrostructures encountered in daily life, should guide the fabrication of other microstructural super-materials based on accepted theories in the structural mechanics of macrostructures.

Conflict of interest statement. None declared.

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