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Indentation-triggered pattern transformation in hyperelastic soft cellular solids

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ABSTRACT

This paper explores indentation-triggered microstructural instability in hyperelastic cellular solids through combined experimental, numerical, and theoretical efforts. The results demonstrate that when the indentation depth is greater than a critical value, local instability occurs and further propagates into a rectangular region beneath the indenter. The width of the rectangular region scales with the contact width, and we propose a simple scaling relation to estimate the maximum depth to which the instability can propagate based on the elastic contact theory. The results reported here may find such applications as in the integrity evaluation of soft cellular materials and structures and the development of advanced functional materials with unique optical, acoustic and wetting properties.

1. Introduction

Soft materials with small-scale periodic cellular structures have a wide variety of technologically important applications, ranging from photonic or phononic band-gap materials, microfluid networks, self-healing materials to scaffolds in tissue engineering [1–6]. Due to their low elastic moduli and large deformation ability, elastic instability of microstructures may occur in the soft hyperelastic cellular materials under loading. Understanding the microstructure instability is of great importance. For instance, in the use of soft cellular materials as components of microdevices, stable microstructure is usually required to guarantee their desired performance and functions. The occurrence and propagation of the instability (e.g., caused by the contact with other harder components) may represent the failure of the system. On the other hand, microstructural instability can be utilized in some other circumstances. For example, a recent interesting study of Mullin et al. [7] found that uniaxial compression can trigger dramatic pattern transformations in certain classes of simple periodic structures, foreseeing a route for creating metamaterials with transformative photonic/phononic or hydrophobic/hydrophilic attributes [7]. Although historically numerous studies have been carried out on the deformation behavior of cellular solids [8–11], investigation on the microstructural instability of hyperelastic cellular solids with the focus on the development of metamaterials is only recently pursued [7,12]. Different from simple compression, deformation induced by local contact pressure (e.g., under contact or indentation load) varies along the depth according to elastic contact theory [7]. Thus it is expected that indentation may trigger pattern transformation with controllable spatial gradient in a periodic cellular hyperelastic material. This method could be particularly useful for the development of some photonic crystals, surface patterns with unique wetting properties, and scaffolds for tissue engineering [14].

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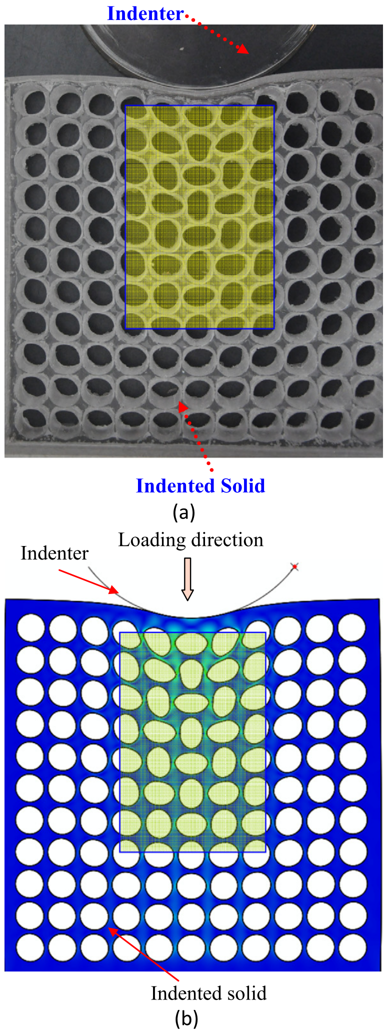

Fig. 1. (Color online.) Indentation-triggered microstructural instability in an elastomeric cellular solid. (a) A desktop experiment; (b) the result of post-buckling analysis.

Based on the above considerations, we here explore the indentation problem of hyperelastic materials with periodic cellular structures. Indentation has been widely adopted in material characterizations and nano-imprinting in recent years [15,16], which currently can be easily performed with commercial equipments at different length scales. In the literature, a number of authors have investigated the indentation of cellular solids [17,18], where the matrix material is assumed to be elastoplastic. However, indentation-induced microstructural instability and its propagation in **hyperelastic** cellular solids has not been investigated. In this study, our attention is paid to two interesting issues, i.e., how the local instability of microstructures occurs under contact load imposed by indentation and how it propagates in the material. To this end, we performed a desktop-scaled indentation experiment of a soft material consisting of circular holes using a cylindrical indenter and carried out nonlinear finite-element analysis to simulate the plane-strain indentation. A model is further devised to understand the underlying physics based on the elastic contact theory [13].

2. Experiments

In our desktop experiment, a mold consisting of a square array of 11×11 identical cylinders was prepared. Polydimethylsiloxane (PDMS) was prepared by mixing a degassed elastomer base and a crosslinker in a ratio of 10:1 w/w. The pre-polymerized mixture was filled in the mold and cured at 60 °C for 8 h. When the PDMS had become a solid state, the cylinders were taken out and a specimen consisting of 11×11 circular holes was obtained. The sample was 190 mm long, 190 mm wide, and 20 mm thick. All holes had the same diameter of 14 mm, and the center-to-center spacing was 16 mm. The indentation test was performed by using a glass cylinder with the diameter of 128 mm, which is sufficiently hard to be considered as rigid. Fig. 1a shows the deformation in the indented sample when the indentation depth was around 10 mm. Indentation-induced local microstructural instability could be evidenced, which further triggered distinct