Programmable topographical surface enabled by the controllable formation of instability pattern

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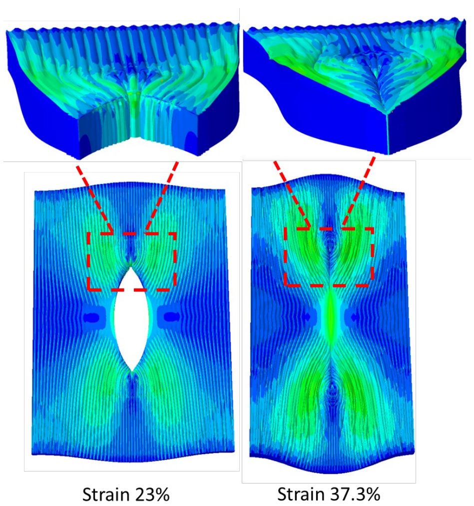
Abstract. By manually planting micropatterns on the surface of an elastic bilayer system or swelling induced multilayer mechanism, the surface topology of elastic instabilities is obviously influenced by the localization of stress with specific structure. The buckles occurred and are gradually transformed into crease and folds and observed in experiment. Furthermore, we utilized the Neo-Hookean hyperelastic model and finite element method to demonstrate the morphogenesis under uniaxial compression for elastic bilayer structure and the buckling phenomenon of hydrogel with free swelling.

Introduction

In various industries, bilayer or multilayer structures containing different elasticity layers are commonly employed [1-4]. The phenomenon of wrinkles was first observed and documented during the compression process of sandwich panel construction [5]. The elastic instability of the bilayer system, which includes stretching and bending energy of the soft substrate and stiff surface, leads to the emergence of buckling with due to the mismatch of strain at each layer when the structure is compressed beyond a critical strain determined by material properties and dimensions [6]. Previous studies have illustrated different buckling models for flat elastic bilayer structures, such as wrinkling, double wrinkling, and creasing [7]. Assuming that the layers are fully tied without any delamination or shear stress between them, the entire buckling mode's surface pattern is almost a sinusoidal curve with folded creases under further compression. The literature has sufficiently demonstrated the relationship between key material factors [8,9]. In this study, we combined experimental results with finite element method (FEM) simulations to demonstrate the morphogenetic process by elastic instabilities in PDMS bilayer structure and the multilayer configuration of hydrogel induced by swelling.

Experiment, Results and Application

In this experiment, a commercially available rubber-like elastomer with hyperelastic properties, known as PDMS, was used to fabricate the basic cuboid sample. The curing process involved using a specific mold with photolithographic circular micropatterns. The outer surface of the sample was then oxidized using plasma treatment to create a shell-core system that could be viewed as a bilayer structure in three dimensions, rather than a simple 2D bilayer system. Finally, uniaxial compressive loading was applied in the length direction of the sample for achieving the elastic instabilities. In the other multilayer system, a polyacrylamide-co-sodium acrylate hydrogel with micropatterns on the surface was synthesized using a resin mould. The multilayer configuration was generated through free swelling, resulting in a gradient layer with varying water elastic modulus due to the gradual diffusion of water, which in turn led to the emergence of stress localization and elastic instabilities.



Figures 1. Morphogenetic process of patterned PDMS bilayer by compression.

The results showed that for the PDMS shell-core system, both wrinkles and creases initially formed near the circle area perpendicular to the compressing direction. With increasing loading, folds emerged and merged into large and deep buckles. In contrast, for the hydrogel multilayer system, small creases first formed and gradually transformed into large, deep creases before eventually disappearing due to the balance of elastic instabilities.

The intrinsic mechanism of the shell-core bilayer structure with micropatterns and multilayer configuration was investigated further through the use of FEM simulation. The dynamic module with explicit solver of the commercial software ABAQUS and the PDE module of COMSOL were employed for this purpose. The simulation results obtained were found to be consistent with the experimental results and shown in Figure 1. This suggests that the process can be predicted and controlled by manipulating various parameters, making it a promising direction for combining hydrogel and paper-based multilayer configurations. Such configurations have the potential to enable the development of biomedical microfluidics [10,11], microelectronics [12-14], and other related applications.

Conclusion

In summary, our study outlines the mechanism of elastic instabilities through the use of a 3D shell-core structure incorporating customized micropatterns and multilayer configurations induced by varying moduli. The morphogenesis of the buckling phenomenon has been comprehensively elucidated through experimental observations and corresponding simulations, thereby providing a potential strategy for further regulation of surface topology resulting from elastic instability.

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