Extreme Mechanics Letters 6 (2016) 1–9

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Phase-transforming and switchable metamaterials

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ARTICLE INFO

Article history:
Received 20 September 2015
Accepted 18 November 2015
Available online 1 December 2015

Keywords:
Phase transition
State switching
Metamaterial
Material science
Soft matter

ABSTRACT

This paper demonstrates a new soft structure that uses a meso- or macro-scale elastic instability to generate a shape-memory effect similar to that exhibited by a ferroelastic material. It demonstrates the phase transitions, state switching, and shape-memory effects in this system, both in experiment and in simulation. The new class of materials described in the paper is potentially useful, since it comprises what are effectively "shape-memory alloys" of arbitrarily low modulus and arbitrarily large remnant strain. The reproduction of properties of materials usually associated with atomic- or molecular-level changes in structure using meso-scale structural opens the door to development of new, soft materials with new properties and functions.

1. Introduction

Many forms of matter – atoms, ions, molecules, and materials – can exist in multiple forms (phases), having different structures at the atomic and molecular scale, and different properties. The interconversions of these phases are a central concern in materials science and engineering, and can be classified as follows: transformations that exhibit discontinuity in the first derivative of the free energy with respect to some thermodynamic variable are characterized by large changes in thermodynamic properties (e.g. melting of a solid [1], smectic-A to nematic transition in liquid crystals [2], etc.), and are called first-order phase transitions. Transformations that exhibit continuity in the first derivatives of the free energy but discontinuity in the second derivative are called second-order phase transitions. Examples of materials exhibiting second-order phase transitions are ferroelectric [3–5] and ferromagnetic materials [6], shape memory alloys [7], ferroelastic materials [8–10], superconductors [11], and superfluids [12]. A similar definition could be applied to higher-order phase transitions.

Although most examples of phase transitions involve structural rearrangements at the atomic/molecular scale, the underlying concept of a phase as a form of matter with defined structure can be applied at larger scales. Examples of phase transitions at the meso- and macro-scale include colloidal suspensions [13,14], 2D arrays of polymeric spheres [15], heat-shrinkable polymer patterns [16], meso-scale silicon rods embedded in a hydrogel [17–19], and slabs of elastomer with an array of holes [20–23]. In broad terms, an emerging opportunity in materials science and engineering is to create phase-transforming materials by integrating materials – elastomers, liquids, metals, and even open spaces and voids filled with gas or liquids

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http://dx.doi.org/10.1016/j.eml.2015.11.004
2352-4316/

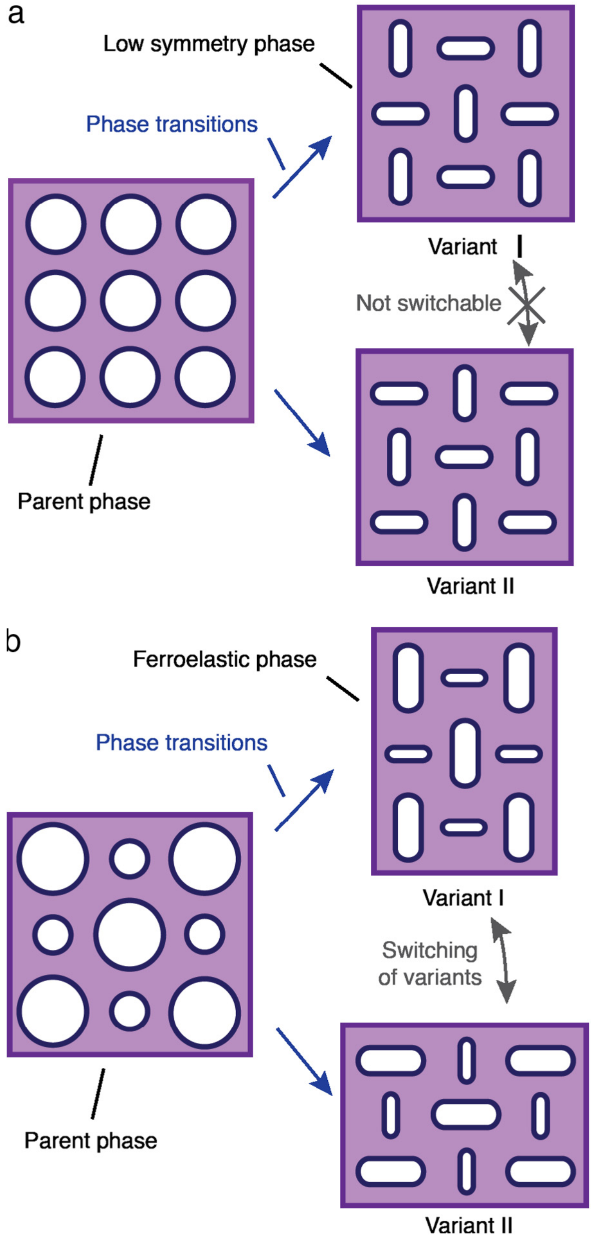

Fig. 1. Change of phases and switching between variants. (a) For an elastomeric block containing holes of the same size, the parent phase transforms to a low-symmetry phase. In the low-symmetry phase, the structure has two variants of the same state of spontaneous strain, so that one variant cannot be switched to the other under external force. (b) For an elastomeric block containing holes of different sizes, the parent phase transforms to a ferroelectric phase. In the ferroelectric phase, the structure has two variants of different states of spontaneous strain, so that one variant can be switched to the other variant by an external mechanical force.

– through geometry and mechanics, at meso- or macro-scale. This letter describes a new soft structure that uses a meso- or macro-scale elastic instability to generate a shape-memory effect similar to that of a ferroelastic material.

Ferroelasticity is the mechanical analogue of ferroelectricity and ferromagnetism, and it is the mechanism that underlies the characteristics of shape-memory alloys [24]. When cooled below a certain temperature – the "Curie temperature" – a ferroelastic material undergoes a phase transition, develops spontaneous strains, and is said to be in a "ferroelastic phase". These microscopic states of spontaneous strain – also known as "variants" – are equivalent crystal structures in different orientations (e.g. a tetragonal unit cell where the long axis points at different directions). A macroscopic external stress can induce "switching" between these variants throughout the material. As a result, the bulk material can be molded into different macroscopic shapes depending on its history of loading, while maintaining a memory of its grain arrangements. When heated above the Curie temperature, the spontaneous strain disappears, and the material is said to be in a "paraelastic"