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Instability/collapse of polymeric materials and their structures in stimulus-induced shape/surface morphology switching

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ABSTRACT

With the current development in 3-D printing and origami-inspired technologies, stimulus-induced shape/surface morphology switching becomes a novel approach to produce complex 2-D/3-D mechanisms/structures. This paper briefly discusses major instability/collapse phenomena in the shape change/memory effect based such switching in polymeric materials and their structures, from the beginning of fabrication and programming to the final step of shape/surface morphology switching. As shown here, stimulus-induced shape/surface morphology switching is essentially a mixture of mechanism and structure, so that on the one hand it shares many common features as in conventional mechanisms and structures, while on the other hand it has some unique characteristics; instability may happen during programming as well, and instability may be utilized as a powerful self-assembly technique for surface morphology switching. In most cases, traditional theories of mechanics may be applied directly in analysis/design to either avoid instability/collapse or purposely induce these phenomena for our intended purpose.

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1. Introduction

In general, almost every material is able to change its one or more chemical/physical properties at the presence of some particular stimuli. Among these properties, the ability of shape switching may be utilized for motion generation, force generation or other functions. If a material responses to the applied stimulus either instantly in an elastic manner or gradually in a viscous-elastic fashion, this phenomenon is called the shape change effect (SCE). On the other hand, if the deformed shape can be virtually maintained forever, unless a right external stimulus is applied as the driving force to trigger recovery back to the original shape, this phenomenon is known as the shape memory effect (SME) [1,2].

In fact, depending on the working environment and the type of stimulus, a material may have the SCE and SME separately or simultaneously. For examples, Nitinol (NiTi shape memory alloy, SMA) has the heating-responsive SME in the low temperature martensite phase, while in the high temperature austenite phase, it is superelastic (the mechano-responsive SCE) [3]; silicone/melting glue hybrid is *always* highly rubber-like in response to mechanical loading so that it is mechano-responsive shape change material (SCM), while it is also a heating-responsive shape memory material (SMM) [4]. A recent study reveals that in addition to water-responsive SCE (swelling/de-swelling), a hydrogel may be heating-responsive at a low water content or rubber-like at a relative higher water content [5]. On the other hand, ether-vinyl acetate copolymer (EVA) shows strong temperature dependent relaxation behavior [6], which reveals the similarity in the fundamentals between the SME and SCE in materials. That is to say if the energy barrier between two shapes is high, additional driving force (via applying a right stimulus) is required for shape recovery (the SME); if the energy barrier is none or small, the material shows the SCE either in an instant manner or gradually (i.e., viscous-elastic) [2,7].

In these couple of years, we started to see a number of origami-inspired technologies to produce complex three-dimensional structures and machines [8–13] and even to add in one more dimension (of time) to 3-D printing to realize so called *4-D printing* for shape

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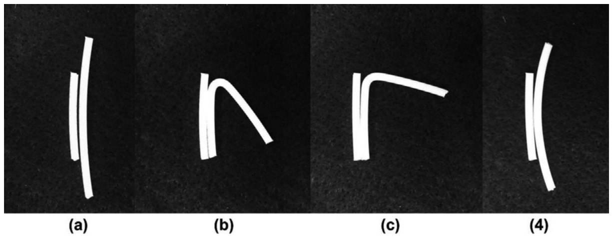

Fig. 1. The SME in 1.75 mm diameter ABS filament used in 3-D printing. (a) Original filament (left short sample is for comparison); (b) after bending at room temperature; (c) after heating in boiling water and (d) after heating to 120 °C.

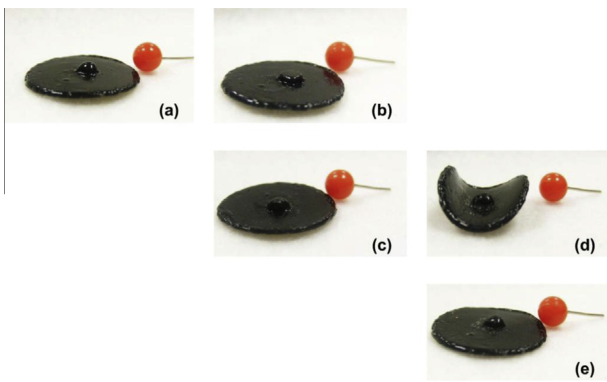

Fig. 2. Heating-responsive SME in PLA structure. (a) Original structure; (b) top of the crown shaped protrusion is flattened; (c) after heating in hot water; (d) after subsequent bending and (e) after heating in hot water.

reconfiguration. The underlying mechanism of folding from two-dimensional structures, which are expected to be less costly to fabricate, into three-dimensional structures is either the SME or SCE of polymeric materials in a contactless manner [14,15]. Apart from traditional applications in deployable structures [16] and biomedical devices for minimally invasive surgery [7,17,18] etc, recent progress in utilizing the SME or SCE of materials for shape/surface morphology switching also includes surface patterning via self-assembly [19–24], programmed active disassembly of obsolete electrical devices [25,26], and anti-counterfeit [6,27,28].

Acrylonitrile butadiene styrene (ABS) and polylactide (PLA) are commonly used raw materials for 3-D printing at this moment. Excellent SME observed in ABS (shown in Fig. 1) reveals great potential of applying 3-D printing technology to conveniently and rapidly produce customized devices and structures, and after subsequent programming, to have the shape switching function. PLA is a well known biodegradable material [29]. Fig. 2 demonstrates a good opportunity for massively printing customized deployable/retractable and biodegradable implant devices for individual patients.

The purpose of this paper is to discuss an important mechanical issue, i.e., instability and collapse of polymeric materials and their structures, in stimulus-induced shape/surface morphology switching. Section 2 summarizes typical mechanisms for shape switching based on the SCE or SME. Section 3 discusses typical modes of instability and collapse during programming into a temporary shape. Section 4 presents typical examples of instability and collapse during shape switching. Major conclusions are summarized in Section 5 .

2. Typical mechanisms for shape switching

There are many ways to induce shape switching via either the SCE and/or SME in materials. In this paper, we mainly focus on polymeric materials, their hybrids and composites.

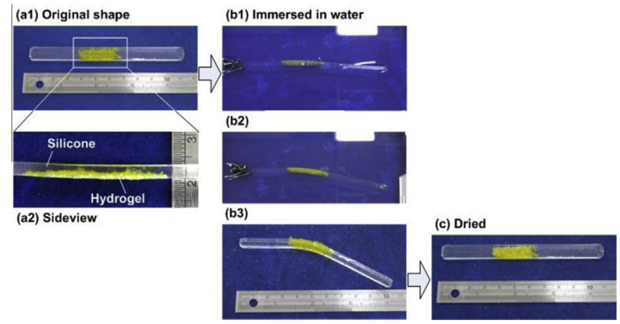

Fig. 3. Water induced SCE in a silicone strip with hydrogel embedded in part of it. (a) Original straight shape; (b) bending upon immersing into room temperature water; (c) shape recovery after drying. (Reproduced from [2] with permission).

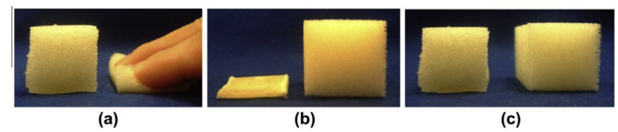

Fig. 4. Heating-responsive SME in sponge/wax hybrid (left) (right is puresponge for comparison). (a) At room temperature, sponge is elastic; (b) after compression of sponge/wax hybrid at high temperature and (c) after heating for shape recovery.

2.1 Typical stimuli and SCE/SME phenomena

Typical stimuli, which are most likely applicable to trigger shape switching in polymeric materials, include heating/cooling (thermo-responsive), light (photo-responsive), chemical/solvent (chemo-responsive), electricity (electro-responsive), and mechanical loading (mechano-responsive), etc [1,7,30–34].

According to [2,7], most polymeric materials, if not all, are heating-responsive and chemo-responsive SMM, although the actual shape memory performance varies among individual materials and may be optimized by means of selecting the right programming parameters [35]. In addition to utilizing the existing materials, we may design a material with either the SCE or SME to meet the precise requirement(s) of a particular design.

Fig. 3(a1) is a piece of strip made of silicone/hydrogel, in which small hydrogel particles are embedded within the bottom part of the middle section of the silicone beam, as shown in Fig. 3(a2). Upon immersing into water, hydrogel particles swell significantly, and thus the strip bends remarkably [Fig. 3(b)]. Upon drying in the air, hydrogel particles de-swell and finally the strip returns its original straight shape. This is a typical example of swelling/de-swelling induced water-responsive SCE.

Fig. 4(a)(left) is an example of heating-responsive SME, in which paraffin wax is melted and then absorbed into an elastic sponge. Upon heating the hybrid above the melting temperature of wax, the hybrid is compressed. After cooling back to room temperature, wax becomes solid again, and hence the recovery of the elastic sponge is largely prevented [Fig. 4 (left)]. Upon heating above melting temperature of wax again, the elastic sponge is able to fully return its original shape.

As shown in above two examples, the performance of the hybrid (silicone/hydrogel and sponge/wax) is dependent on the materials selected for the elastic component (silicone and sponge) and the transition component (hydrogel and wax). It is obvious that by means of selecting a right combination of two (or more) materials for the elastic component and the transition component according to the actual requirement(s) of a particular application, we can design a hybrid with the tailored performance.

As we can see in the above cases, the components of a hybrid do not have the SME as an individual. On the other hand, in a shape

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