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Review

Stimulus methods of multi-functional shape memory polymer nanocomposites: A review

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A B S T R A C T

This review is focused on the most recent research on multifunctional shape memory polymer nanocomposites reinforced by various nanoparticles. Different multifunctional shape memory nanocomposites responsive to different kinds of stimulation methods, including thermal responsive, electro-activated, alternating magnetic field responsive, light sensitive and water induced SMPs, are discussed separately. This review offers a comprehensive discussion on the mechanism, advantages and disadvantages of each actuation methods. In addition to presenting the micro- and macro- morphology and mechanical properties of shape memory polymer nanocomposites, this review demonstrates the shape memory performance and the potential applications of multifunctional shape memory polymer nanocomposites under different stimulation methods.

Contents

1. Introduction

Shape memory materials (SMMs) have the capability to respond to certain stimuli and to deform from a temporary shape to the original shape. Currently, among all types of SMMs developed, shape memory alloys (SMAs) and shape memory polymers (SMPs) are the most extensively studied and being applied broadly and effectively. In general, SMAs are divided into two categories with respect to the stimulus methods, thermos-responsive SMAs triggered only by heating and magneto-responsive SMAs activated by static or variable magnetic field as well. As a type of smart materials with unique characteristics, SMAs are widely used in various areas especially in medical and industrial fields, specific examples in which include dental wires, arterial stents, fire security systems and helicopter blades [1–5]. Since the discover of SMPs in 1980, SMPs offer more stimulation methods, such as heating, electrical current, alternating magnetic fields, light exposure and water immersion [6–8], which result from the underlying large extensibility due to the intrinsically elastic polymeric networks. SMPs possess special characteristics, such as the density range of

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900–1100 kg/m^3, up to 800% extent of deformation, recovery speeds from less than 1 s to several minutes, the Young's modulus of 0.1–10 MPa above transition temperature, the Young's modulus of 0.01–3 GPa below transition temperature, stress of 1–3 MPa required for deformation and generated during recovery [9–13]. In addition to the above mentioned special properties of SMPs, they are easy processing, low cost, potentially biocompatible and biodegradable, able to bear large deformation and can be produced into many structures [9,14]. Due to these advantages, SMP and their composites, in which polymers matrix systems act as binder or matrix to make incorporated particulates, fibers or other reinforcements placed properly, have multifarious applications. In aerospace engineering, SMPs could be used for space environment evaluation and related testing [15], and space-deployable components such as hinges [16], antennas [17] and rover wheels [18]. In biomedical field, SMPs were made into medical cast [19], artificial muscles [20], endovascular thrombectomy device [21], and devices to prevent aneurysm rupture and cardiovascular stent [22,23] which are feasible. As for textile, breathable clothing made of SMP can provide better comfort under various temperature and moisture [24,25]. By creating a functional gradient varying the glass transition temperature (Tg), Qi et al. achieved spontaneous and sequential shape changing properties [27]. Such shape changing sequence can be controlled precisely by created SMP components with properly assigned spatial variation of the thermodynamical property distribution. Meanwhile, with the development of 3D printing technique, the application of 3D printing technique has become a hot research topic in recent years, according to the virtue of high resolution, large design freedom and potential manufacture of immediate engineering productions [26]. Combining 3D printing technique, the potential applications of the printed 4D devices based on SMP and their composites could be broadly extended. For example, sequential self-folding structures were obtained via 3D technique with digital shape memory polymers, which can behave differently to specified shapes when exposed to thermal stimulus. A simplified reduced-order model and metric were used to predict self-collision [27]. Qi et al. designed and fabricated active origami with 4D printing concept, which signified the time-dependent shape change after printing. A series of active origami components, such as box, pyramid, and airplanes, were demonstrated with the guidance of a theoretical model, which was developed for valid selection of design parameters, as shown in Fig. 1 [28].

Nanoparticles are typically in the range of 1–100 nm in size, which behave as a whole unit from the perspective of transport and properties [29]. In addition, the properties of nanoparticles are quite size-related, varying from those of either fine particles or bulk materials. Recently, due to the potential that nanotechnology holds, there has been a strong emphasis on the development of nanocomposites. SMP nanocomposites play an important part in the field of SMP composites. Polymeric nanocomposites could be simply interpreted as a novel class of composite where there is at least one dimension of the component which is of the order of nanometer in polymeric system [30]. Nanoscale materials have a large surface area which is beneficial for different chemical and physical interactions between polymer matrix and nanoparticle fillers. In addition, with the help of high aspect ratio of certain nanoparticles, importing nano-scale fillers could reduce the level

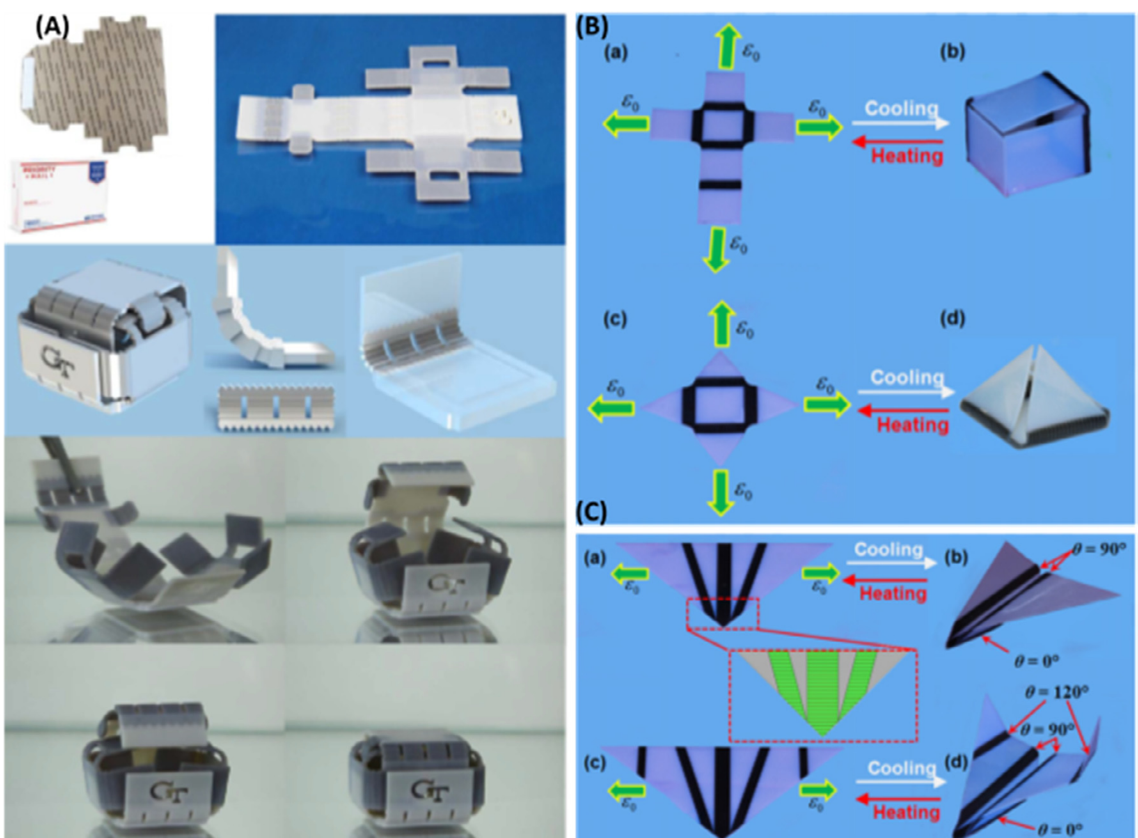

Fig. 1. (A) 3D folding structures mimicking the USPS mailbox [27] (B) Active origami box and pyramid. The printed flat cross shape in (a) assembles itself into a desired box shape in (b) after the programming steps. The printed flat Ninja star shape plate in (c) assembles itself into a desired pyramid shape in (d) after the programming steps. (C) Active origami airplanes. A flat triangle sheet with three hinges in (a) assembles itself into an origami airplane with a 0° angle in the middle hinge that bends upward and 90° angles in the two side hinges that bend downward in (b). A flat triangle sheet with five hinges in (c) assembles itself into an origami airplane with two winglets in (d) [28]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)