SMART COMPOSITE MATERIALS AND THEIR APPLICATIONS

SY. Du*, JS. Leng
Centre for Composite Materials and Structures, Harbin Institute of Technology, Harbin, China
* Corresponding author(sydu@hit.edu.cn)

Keywords: *shape-memory polymer, composites, smart materials, applications*

1 General Introduction

Shape-memory polymers (SMPs) are a class of stimuli-responsive materials that can switch between two shapes on command, from a temporary shape to their permanent shape upon exposure to an external stimulus. The shape-memory phenomenon in SMPs arises from a dual segment system, in which one segment is highly elastic and the other is able to remarkably reduce its stiffness in the presence of a particular stimulus [1]. Recent technological advances have allowed the SMPs to be triple-shape or multi-shape memory materials [2,3]. SMPs differ from their metallic counterpart, shape-memory alloys (SMAs) by their glass transition or melting transition that is responsible for the shape-memory effect, while martensitic/austenitic transitions are for SMAs. Furthermore, there are distinct advantages over SMAs, including higher capacity for elastic strain (more than 100% in most cases), lower density, tunable transformation temperature and easier processing. In addition to these advantages, low cost not only for the materials themselves but also in processing and fabrication enables the use of SMPs for a broad range of applications [1]. This presented work summarizes the recent advances in synthesis of a novel epoxy-based SMP, design as well as characterization of SMP composites (SMPCs) driven by electrical approach as well as constitutive modeling, and their potential applications.

2 SMP composites (SMPCs)

The main limitation of thermoplastic SMPs for the practical application is irreversible deformation during memory programming due to the creep. Here the covalent cross-linking has been introduced to improve in creep for a novel epoxy-based SMP, which also has an excellent capability of strain recovery ratio and strain fixity rate, where they are two important quantities for describing shape-memory effect. Additionally, experimental results reveal that this epoxy-based SMP has a tunable glass transition temperature from 37 to 150°C, higher elastic modulus of 2 to 3 GPa at room temperature, stronger anti-oxidative properties to γ-irradiation *etc*. SMPs can be activated not only by heat/magnetism (similar to SMAs), but also by water and even a change in pH value. Beyond this, light-induced shape-memory effect of SMPs has been realized through the incorporation of optic fiber that acts as a heat delivery system. Upon irradiation with light of a suitable wavelength, the light is sent through the heat delivery system to trigger the SMP, as shown in Figure 1 [5].

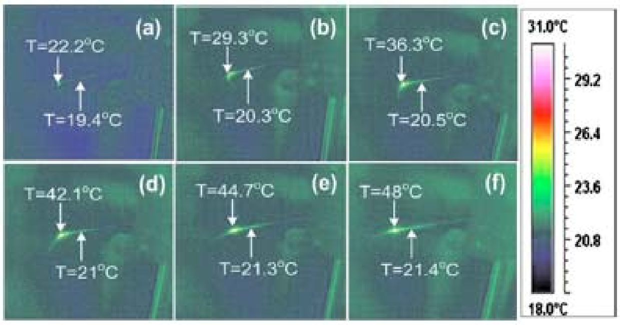


Fig. 1. Temperature distribution snapshots of the SMP during the mid-infrared laser-driven process. (a) t=2 s; (b) t=4 s; (c) t=6 s; (d) t=8 s; (e) t=10 s; and (f) t=12 s. Reprinted with permission from Reference 5. ©2010, American Institute of Physics.

The utilization of electricity to induce the shape-memory effect of SMP materials is desirable owing to controllable and effective. Extensive research have been done on conductive SMPCs by blending conductive fillers, such as carbon black [6], chained Ni powder [7], conductive hybrid fibers [8] and continuous carbon fibers [9]. Recently, we introduce carbon-based nanopaper and carbon nanofibers (CNFs) to the SMP, where CNFs were blended to facilitate heat transfer and improve electro-active response behavior of the SMPC, as shown in Figure 2 [10].

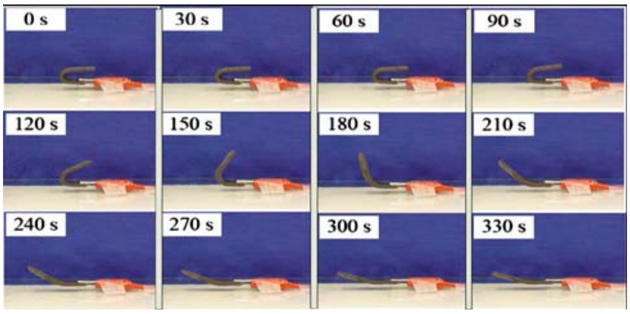


Fig. 2. Series of photographs demonstrating the macroscopic shape memory effect of the SMPC. The permanent shape is a flat strip, and the temporary shape is a right-angle shape. Reprinted with permission from Reference 10. ©2010, American Institute of Physics.

Currently, a novel nanopaper enabled SMPC has been developed with vertically aligned magnetic multi-walled carbon nanotubes (MWCNTs), as shown in Figure 3 [11]. Experimental results revealed that the induction time of SMPC with vertically aligned MWCNTs was 15.9 s shorter than that with randomly dispersed CNTs under the 36V triggering voltage.

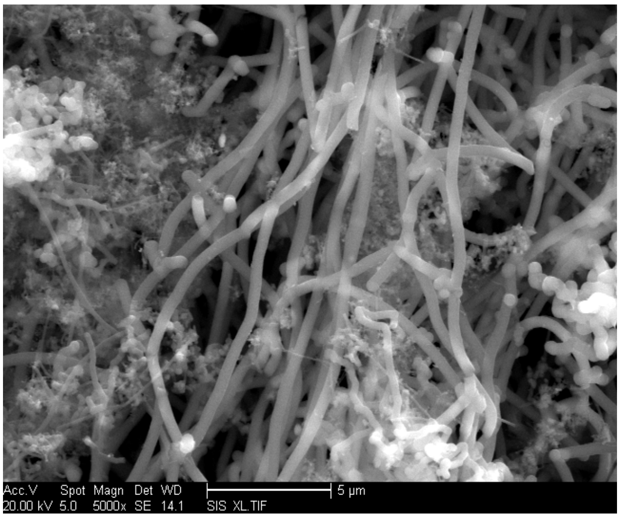


Fig. 3. The SEM image for the orientating of the nickel nanostrands at the scale of 100 μm. Reprinted with permission from Reference 11. ©2011, American Institute of Physics.

At the same time, hybrid filler of magnetic nickel nanostrand and CNF has been added into SMP for making conductive SMPC. The Figure 4 presented that the nanostrand had a very porous three-dimensional lattice of interconnected strands, and the nanofibers and nanostrands were entangled with each other. These interconnected nanofibers and nanostrands would create conductive paths throughout the resin for electrons. As a result, the electrical conductivity of SMPC is therefore significantly improved. Figure 5 recorded the shape recovery of this type of SMPC driven by electrically resistive heating [12].

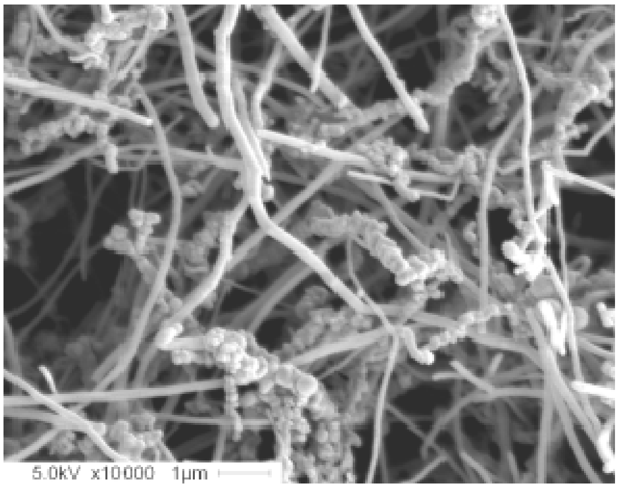


Fig. 4. Morphologies and network structure of hybrid mixture making of nickel nanostrands and CNFs. Reprinted with permission from Reference 12. ©2011, Institute of Physics and IOP Publishing.

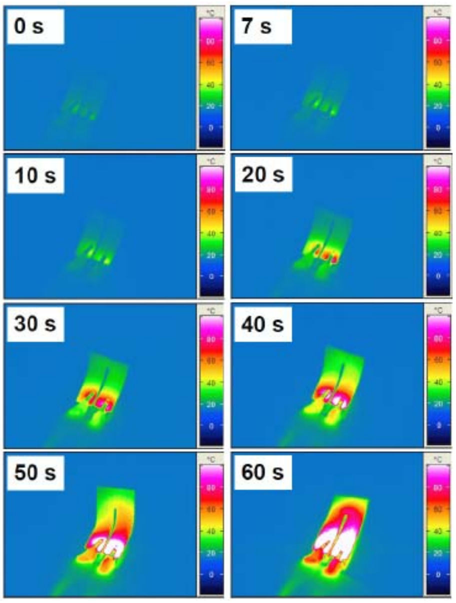


Fig. 5. Time-resolved photographs showing the electro-active shape-memory effect and temperature distribution of SMP with 2.5 wt.% CNFs and 7.5 wt.% nanostrands, under a constant DC voltage of 36 V. Reprinted with permission from Reference 12. ©2011, Institute of Physics and IOP Publishing.

However, the pure SMPs in general exhibit lower strength and stiffness, which limits their use for many applications. The low stiffness produces a small recovery force in the process of temperature transition. Thus incorporation of reinforcing fillers have been investigated to improve the mechanical properties and diversify the applications of SMPs. It was reported that increase in elastic modulus, due to the incorporation of SiC. The increase in failure stress and decrease in recovery rate had been demonstrated, as a result of addition of glass fiber. Similar observation was reported for SMPCs by using carbon fiber reinforcement [1].

Based on the large deflection deformation of fiber reinforced SMPC, we discuss its mechanism that is required for design principle of deployable structure, as shown in Figure 6 [13]. The strain energy expression of the SMP/fiber system was derived. According to the minimum energy principle, the expression for all key parameters was derived, including critical buckling curvature and neutral plane position, *etc*. Here the microbuckling of carbon fiber reinforced SMPC was utilized to realize large geometrical deflection deformation for deployable and morphing structures.

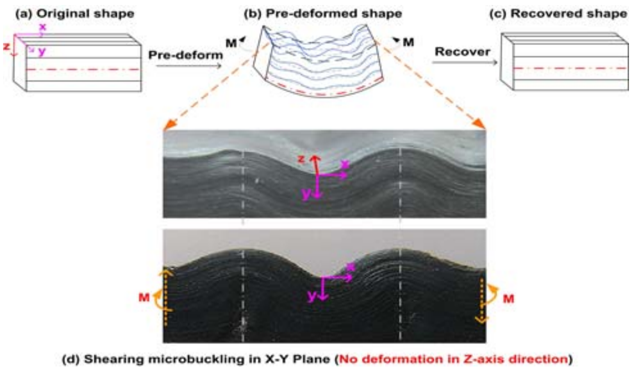


Fig. 6. Shearing microbucking of carbon fiber reinforced SMPC in X-Y plane. Reprinted with permission from Reference 13. ©2010, Harbin Institute of Technology.

3 Applications of SMPCs

Sensing and actuating capabilities of SMPC integrated with hybrid filler of carbon black (CB) and chopped short carbon fibers (SCF) were firstly explored. The output recovery force of electro-activate shape-memory effect of SMPC was utilized and actuating capability was consequently demonstrated to actuate the motion of a table tennis ball being recorded simultaneously by a video camera, which is shown in Figure 7 [14].

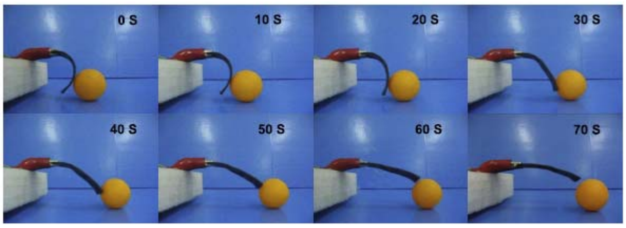


Fig. 7. Series of photographs showing the macroscopic shape memory effect of SMP/5CB/2SCF composite and actuating the motion of a table tennis ball. Reprinted with permission from Reference 14. ©2009, Institute of Physics and IOP Publishing.

Continuous fiber reinforced SMPCs currently cover a broad range of application areas ranging from outer space to automobiles. Recently, they are being developed and qualified especially for deployable hinges, trusses, antennas and smart mandrels, as well as morphing skin. Here the carbon fiber reinforced SMPC has been used in the actively deformable structure. A deployable SMPC hinge that consists of two curved shells is placed together in opposing directions, as shown in Figure 8 [15].

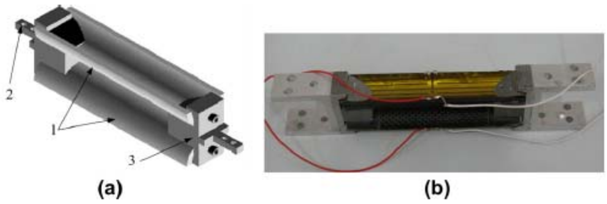


Fig. 8. Shape-memory polymer composite hinge: (a) Illustration of the hinge (1: curved SMPC shell; 2, 3: fixture of the hinge) and (b) real scale hinge. Reprinted with permission from Reference 14. ©2009, Institute of Physics and IOP Publishing.

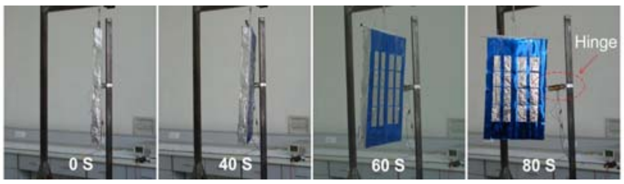
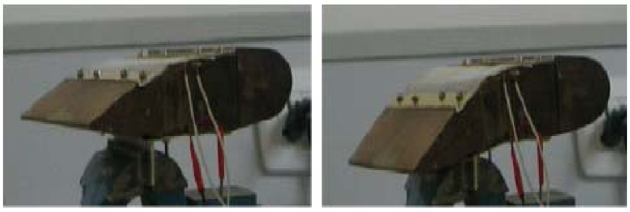


Fig. 9. Shape recovery process of a solar array prototype actuated by an SMPC hinge. Reprinted with permission from Reference 14. ©2009, Institute of Physics and IOP Publishing.

Figure 9 shows the deploy process of the prototype of a solar array actuated by carbon fiber reinforced SMPC hinge. The solar arrays were suspended on a setup that simulated a zero-gravity environment. Applied by a 20 V, the hinge was bent to a storage angle of 90^{o} by the application of an external force at 80^{o}C. After fixing the deformed shape at room temperature, the hinge was heated again by applying the same voltage. The solar array was deployed from 90^o to 0^o in 80s [15].

On the other hand, a morphing concept of a variable camber wing had been developed based on the flexible SMPC. A metal sheet was utilized to keep the surface smooth during the camber changing. And the high-strain capable honeycomb was used to provide distributed support to the flexible skin. The flexible SMP skin is covered to create the smooth aerodynamic surface, as shown in Figure 10 [16]. Beyond this, the analysis of the morphing wing made from SMPC was then conducted [17]. Moreover, we also achieved the SMPC morphing skin from by designing a wear flexible training-edge wing.



(a) Original configuration (0 deg) (b) Morphing configuration (15 deg)

Fig. 10. Photograph of the original and morphing configurations of the variable camber wing. Reprinted with permission from Reference 14. ©2009, SPIE (Society of Photonics and Instrumentation Engineers).

We have witnessed rapid development in SMPs and SMPCs. Their advantages have attracted attention from academic researchers as well as industrial engineers. The SMPs and SMPCs will both have a bright future, and many more products are currently being developed. With the further development and the emergence of new types of SMPs and SMPCs, the range of applications is expected to expand more widely in the near future.

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