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Characteristics of multi-functional composites using elastomer embedded with Shape Memory Alloy wires

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A B S T R A C T

Multifunctional composites consist of Shape Memory Alloy and elastomer in the form of a hybrid system, in which every phase performs a different but necessary function. In this study, elastomer embedded with thermally responsive Shape Memory Alloy (SMA) wires forms one kind of multifunctional composites. The hyper elasticity of elastomer and reversing transformation temperature austenitic finish (A_f) of SMA play highly complementary roles in achieving the multifunctional behavior. The composites show good in-plane deformation capability under the external force driving whether the temperature is under martensitic start temperature (M_s), or above austenitic finish temperature (A_f) of SMA. The composites also show out-of-plane deformation ability under the external force driving when the temperature is under martensitic start temperatures (M_s) of SMA. Varying stiffness behaviors of the multifunctional composites can be obtained by changing the environment temperature from $M_{s.}$ to A_f, by which the grains of SMA wires could be switched from martensitic phase to austenitic phase. In this study, the varying stiffness characteristics of the SMA-elastomer composites are experimentally proved to be effective and theoretically investigated.

1. Introduction

Shape Memory Alloy (SMA) is one kind of smart materials that is gaining industrial and academic popularity in terms of property investigation and product development [1–3]. The two key characteristics of SMA are the shape memory effect (SME) and the pseudoelastic effect or the superelastic effect (ability to recover large strains under certain isothermal conditions) [4]. The reversing transformation temperatures martensitic start (M_s), martensitic finish (M_f), austenitic start (A_s) and austenitic finish (A_f) of SMA are usually used to characterize the phase change. SMA is softer in the martensitic phase but stiffer in the austenitic phase. One important application of SMA is for actuating devices, due to their large recovery stress and reasonable strain recovery of up to 8% [5]. The two key characteristics have also enabled SMA to achieve various applications [6–11].

Elastomer is a class of soft materials capable of large strain (more than 100% area strain had been reported [12,13]). The mechanical characteristics of this soft material had been studied deeply by many researchers [14,15]. Leng et al. [16] proposed one kind of morphing skin with 8 mm thickness that composed of silicon elastomer and shape memory polymer (SMP) composite tube. Significant varying stiffness for that morphing skin can be obtained through changing its environment temperature. Feng et al. [17] employed one kind of active morphing skin embedded with pneumatic muscle fibers into elastomer for camber morphing structures. The chord-wise bending airfoil structure was achieved by employing this kind of active morphing skin. Peel et al. [18] created a shape-changing panel with 10.2 mm thickness that embedded McKibben-like rubber muscle actuators into neat elastomer. They investigated the effect of actuator spacing and modeling methods on the performance of these panels.

Tobushi et al. [19] fabricated a shape memory composite (SMC) belt with a TiNi-Shape Memory Alloy (SMA) wire fiber and a polyurethane-shape memory polymer sheet matrix. The bending actuation characteristics of the belt are investigated. Srinivasa et al. [20] proposed a multistate and smart-bias component using Shape Memory Alloy and shape memory polymer composites. The proposed multifunctional smart material system (MSMS) can operate under three different temperature regimes, with one material constituent being passive and the other active at a given temperature.

In this paper, a method for designing SMA-elastomer "multifunctional systems" is proposed, that allows for the system to have different tunable characteristics in different temperature regimes. For example, it is possible to design a system with different functions under different application requirements, as discussed later in Section 3. Such a multifunctional composite that involves the combination of SMA and elastomer with huge different Young's modulus (Fig. 1), not only improves these properties but also results in a multi-function with a new set of response characteristics.

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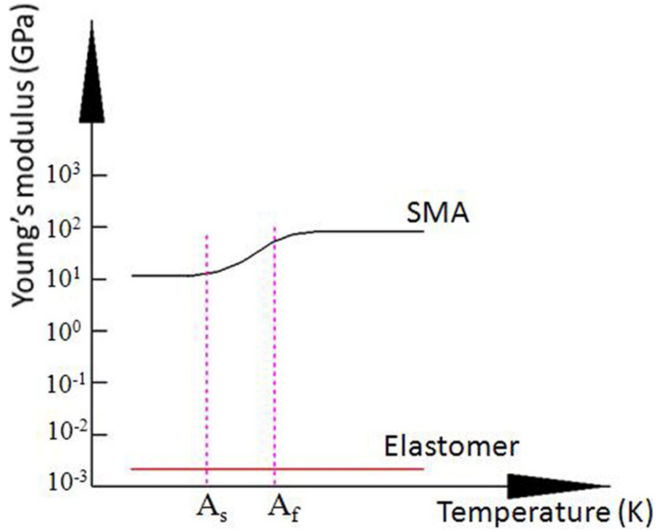

Fig. 1. SMA vs Elastomer Young's modulus comparison on a temperature scale with particular emphasis of critical transformation temperatures of SMA.

As previous mentioned, there have been many attempts by-researchers in the pursuit of embedding SMPC tube, or pneumatic artificial muscle into elastomer to form a useful skin. The important aspect of their works was the use of varying stiffness for a single shape deformation requirement, in which the greater thickness of their specimens would limit the application. There have also been many attempts by researchers in the pursuit of combining thermally responsive SMA and SMP to form a useful SMC. All of these previous works inspired and promoted us to continue this study. As we reported in this paper, a different idea of combining SMA wire fibers and elastomer was proposed and explored to form one kind of multifunctional composites. The fabrication details and multifunctional characteristics of the composites with potential applications in form of in-plane and out-of-plane deformation properties were experimentally and theoretically investigated as follows.

2. SMA-elastomer composites: development detail

2.1. Basic characteristics: each of the composites

In this work, the SMA wires (purchased from KRL Inc., USA) with one-way shape memory effect are employed, and thus the SMA wires work under the effect of two external agents: an applied deformation and a thermal motivation. The reversing transformation temperature and varying stiffness of SMA play a critical role in designing process. The transformation temperatures of concern for SMA in this work are:

- A_s: Austenitic start temperature.
- A_f: Austenitic finish temperature.

Below A_s, the SMA is martensitic phase and can be easily deformed by smaller force. If above A_f, SMA switches to a austenitic phase that is difficult to deform.

The elastomer used in this work is one kind of silicone elastomer (purchased from BJB Inc. USA, product type: TC-5005 A/B-C). TC-5005 A/B-C is a room temperature vulcanizing rubber intended primarily for making silicone skins, but is also used as a general purpose, high strength elastomer [21]. The main features of this product which meet the requirements in this work are [21]:

- Excellent physical properties with high tear resistance.
- Low viscosity and easily poured.
- Can be used in many high-temperature applications.
- High elongation.

The composites fabrication details will be discussed in Section 2.2.2. The properties of NiTi SMA and silicone elastomer are enlisted in Table 1.

As is seen in Fig. 1, the modulus of SMA varies against a temperature scale and the modulus of elastomer remains the same value in the variation temperature range for SMA. Fig. 1 also shows the modulus of SMA in either its martensitic or austenitic phase is three orders of magnitude greater than that of elastomer. The manufacturer provided the Young's modulus of SMA, which is obtained from their experimental test (Table 1). In Chen et al' study [16], the Young's modulus of elastomer (TC-5005 A/B-C silicone elastomer) was experimentally obtained. Here the same type of elastomer was used in this study, and the modulus of elastomer was enlisted in Table 1.

Such a large modulus difference indicates that the SMA must play a predominant role in the composites deformation process if the SMA volume fraction in the composites is not too low. Such a large modulus difference may also generate SMA debonding from the elastomer matrix in the composites deformation process, but it can avoid the SMA debonding from the elastomer matrix due to the compliant deformation properties and excellent physical properties with high tear resistance of the elastomer matrix.

2.2. Fabrication details

2.2.1. SMA wires preparation

The nickel-titanium (50% wt. Ni) SMA wires with 1 mm diameter were used in this paper. The A_f of these SMA wires was 318 K. The NiTi SMA wires were in straight annealed condition as received from the supplier (Fig. 2). In other words the memory shape (or permanent shape) of SMA wires that were used in this study is straight. It could be seen the SMA could keep same straight shape either under room temperature or in the hot water (Fig. 2b and c). The wires were cut in specific lengths as per requirement and used as reinforcements during SMA-elastomer composites fabrication.

2.2.2. Multifunctional composites specimen

The composites consist of Shape Memory Alloy and elastomer in the form of a hybrid system. Firstly SMA wires were reinforced and embedded parallel in the acrylic mold. The elastomer solution was prepared by the mixture of resin matrix A, catalyst B, and plasticizer C with a specific weight ratio. Then the solution was put into a vacuum machine to-remove the air. After degassing and mixing, the elastomer solution was poured into the mold. Finally, the mold was put into a closed but ventilate oven and cured at room temperature for 35 h. The composites specimen with 2 mm thickness was obtained and shown in Fig. 2.

3. Multi-function of SMA-elastomer composites

3.1. Experimental procedures

The three-point bending test was conducted on the Testing Machine (Zwick/Roell Z010, load cell: 10 kN) at a constant rate of 1 mm/min, as shown in Fig. 3. Three-point bending tests with loading were carried out

Table 1
Properties of NiTi SMA and silicone elastomer.

Properties	NiTi SMA	Elastomer
Density(g/cm^3)	6–8	1.05 [18]
Austenitic finish temperature(K)	318	N/A
Low temperature modulus (MPa)	20,000	1.4 [14]
High temperature modulus (MPa)	70,000	1.4 [14]

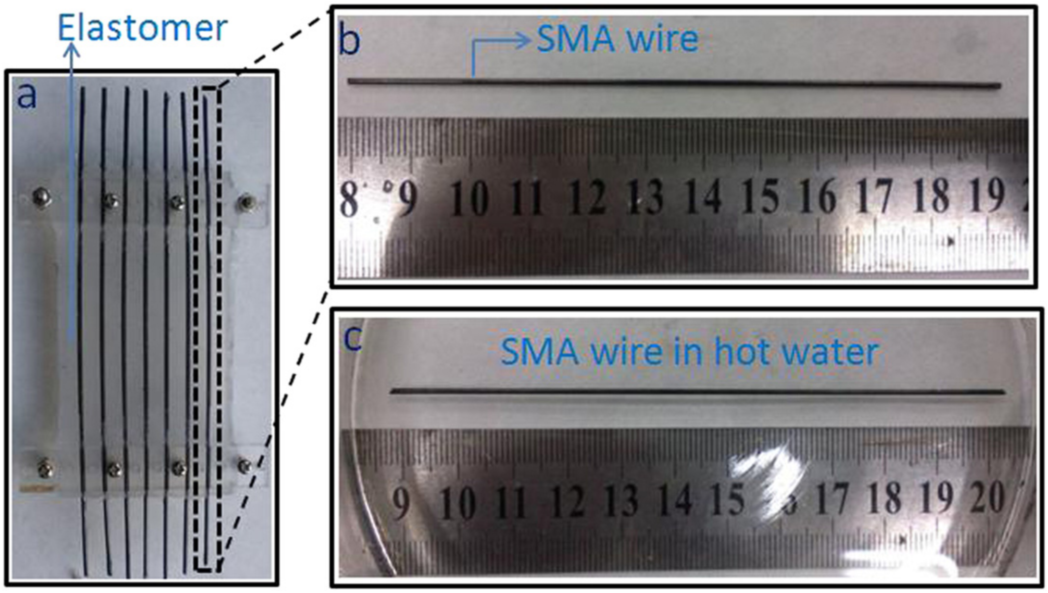

Fig. 2. Multifunctional composites consist of Shape Memory Alloy and elastomer. (a) Multifunctional composites specimen. (b) SMA wire under room temperature. (c) SMA wire in the hot water.

at different constant ambient temperatures. The specimen (geometric dimensions: 70 mm × 25 mm × 2 mm) was used for three-point bending test. Maximum displacement was set as 10 mm. Ambient temperatures were set as $A_f - 22$ K (room temperature 296 K) and $A_f + 22$ K (340 K). Three-point bending tests of the components specimen were repeated three times at $A_f - 22$ K and $A_f + 22$ K respectively. For simplicity, only one group of force–displacement curve which is approximately equal to the average value was used in Fig. 4.

3.2. Three-point bending test result and discussion

The relationship between force and displacement obtained by the Testing Machine (Zwick/Roell Z010) at $A_f - 22$ K and $A_f + 22$ K is shown in Fig. 4. The slope of the linear loading curve denotes the spring constant for bending of the composites. Fig. 4 shows the spring constant and maximum force are low at lower temperatures but are high at higher temperatures.

For investigating Young's modulus of SMA-elastomer composites, the Rule of Mixture [22] is used in this paper. SMA-elastomer composites can be simplified to be a fiber reinforced composite where SMA wires are reinforced fiber and elastomer is matrix. SMA-elastomer composites are also simplified to satisfy the following assumption in this paper. First, the SMA wires are firmly bonded to elastomer matrix. Second, the axial strain of the SMA wires is equal to the matrix in the longitudinal direction. Third, the surface of the composites is kept as a plane during the elongation. According to the Rule of Mixture, the following formulations could be obtained [22]

$$E = E_a V_a + E_m V_m \tag{1}$$

where E, E_a and E_m are Young's modulus of the composites, SMA wire fiber and elastomer matrix respectively. V_a and V_m are the volume fractions for SMA wire fibers and elastomer matrix, respectively. Thus the

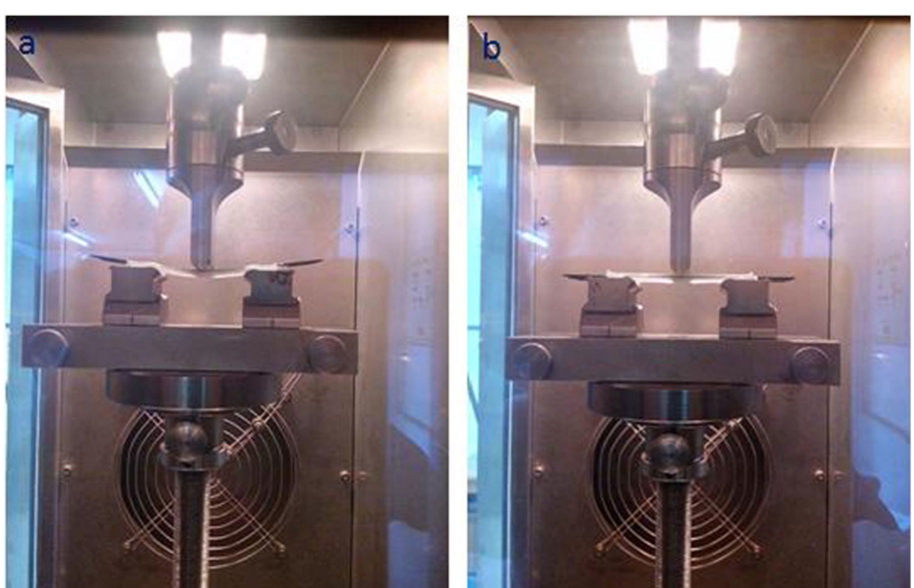

Fig. 3. Three-point bending test procedure at $A_f + 22$ K.

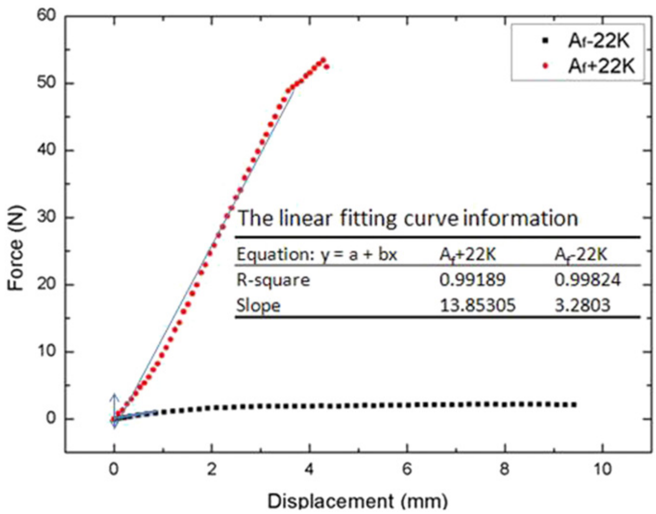

Fig. 4. Relationship between force and displacement in the three-points bending test at various temperatures.

equivalent Young's modulus of SMA-elastomer composites could be obtained, as enlisted in Table 2.

Tobushi et al. [19] employed bending-spring constant method to investigate the bending actuation characteristics of shape memory composite with SMA and SMP. Just like the analysis method used by Tobushi et al. [19], the bending-spring constant method is employed for investigating the varying stiffness characteristics of SMA-elastomer composites in this paper.

If a concentrated force F is applied at the center of a simply supported beam, the maximum deflection w is expressed by the following equation

$$w = \frac{Fl^3}{48EI} \tag{2}$$

where E, I, and l denote Young's modulus, second moment of area, and distance between two supports. The relationship between F and w is expressed by using the bending-spring constant k as follows:

$$F = k \cdot w. \tag{3}$$

As mentioned above, SMA-elastomer composites are simplified to be a fiber reinforced composite in this paper. In this case the composites of a rectangular cross section with width b and thickness t, by using second moment of area $I = bt^3/12$, the bending-spring constant k is expressed by the following equation

$$k = \frac{4bt^3}{l^3}E \tag{4}$$

where E is the equivalent Young's modulus of SMA-elastomer composites.

The experimental result and calculated result of k are shown in Table 3. Obviously the value of bending-spring constant of the composites $A_f + 22$ K is 13,853 Nm which is great larger than that of the composites $A_f - 22$ K. This means varying stiffness capability of the composites can be obtained by varying the temperature of SMA under or above the transformation temperature A_f.

Table 2
The equivalent Young's modulus of SMA-elastomer composites.

Parameters	NiTi SMA	Elastomer	Composites
Volume fraction	0.07854	0.92146	1
Low temperature modulus (MPa)	20,000	1.4 [16]	1560
High temperature modulus (MPa)	70,000	1.4 [16]	5460

Table 3
Experimental and calculated results of bending-spring constant.

Bending-spring constant	Experimental results	Calculated results
Low temperature constant (Nm)	3280	3630
High temperature constant (Nm)	13,853	12,734

3.3. In-plane and out-of-plane deformation characteristics of the composites

Wu et al. [23] developed a Carbon fiber-reinforced plastic rods-reinforced and Kevlar-reinforced silicone rubber matrix composite skin that that can perform ±30° pure shear morphing. In this paper the SMA-elastomer composites are not only with capability of performing pure shear deformation, low demand for the actuating force and resistance to out-of-plane deformation under steady aerodynamic load [23] but also with capability of out-of-plane deformation and varying stiffness under different application requirements.

3.3.1. In-plane deformation

The designed SMA-elastomer composites are with capability of performing pure shear deformation (Fig. 5) and of low demand for the driving force due to the elastomer of hyper elasticity used as the matrix. As seen in Fig. 6, minor hand force can actuate SMA-elastomer composites performing pure shear deformation. In this paper, the pure shear morphing angle of SMA-elastomer can easily reach up to 20° without obvious wrinkle generating (Fig. 6).

Fig. 6 demonstrates the good in-plane deformation capability of SMA-elastomer composites under the external force driving when the ambient temperature is under martensitic start temperature (M_s) of SMA. It can be found SMA-elastomer components specimen could deform from shape “A” (Fig. 6 (a)) to shape “B” (Fig. 6 (b)) reversibly in the positive angle deformation cycle. Similarly SMA-elastomer composites specimen could deform from shape “A” (Fig. 6 (a)) to shape “C” (Fig. 6 (c)) reversibly in the negative angle deformation cycle. Obviously SMA-elastomer composites specimen can deform from shape “A” to shape “B”, and then to shape “C”, finally return to shape “A” in the whole pure shear morphing cycle.

3.3.2. Out-of-plane deformation

Due to the fast recovery speed of SMA, SMA-elastomer composites can deform from the given shape quickly to the permanent shape. As seen in Fig. 7, the given deformed shape of SMA-elastomer composites specimen is arcuation. Fig. 7 shows that through heating it by calorifier SMA-elastomer composites specimen deforms from shape “A” (given

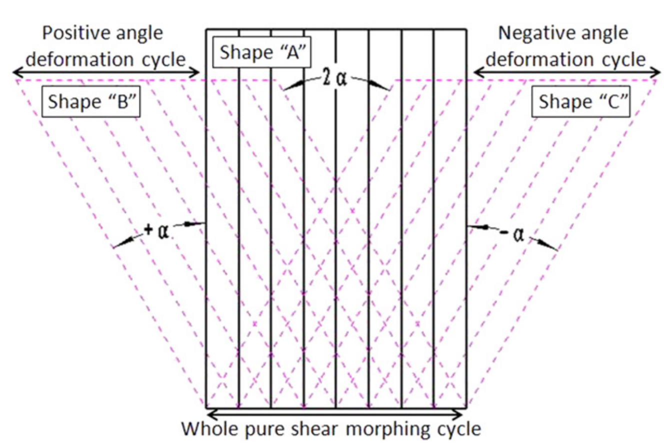

Fig. 5. In-plane deformation sketch of SMA-elastomer composites.

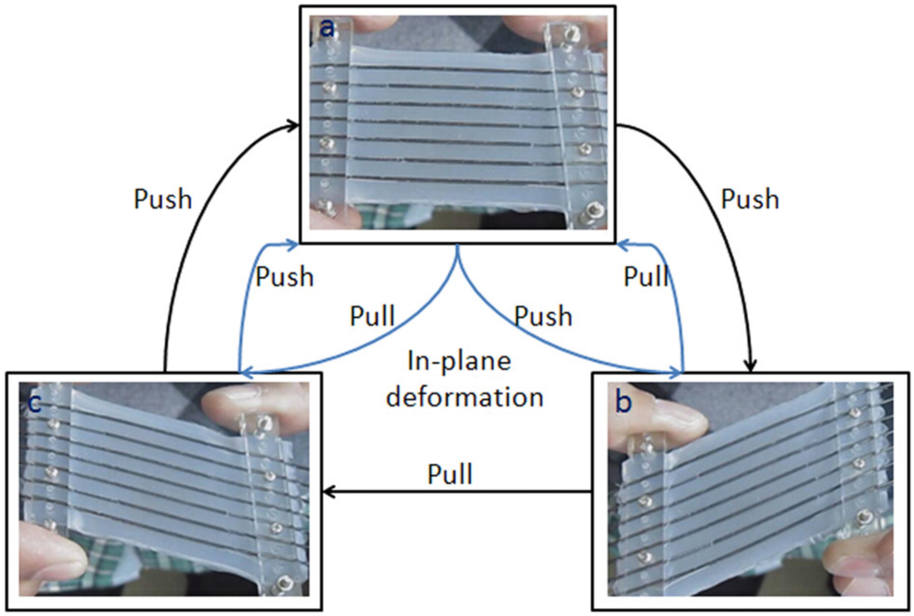

Fig. 6. SMA-elastomer composites showing in-plane deformation.

shape, Fig. 7 (a)) to shape "D" (permanent shape, Fig. 7 (d)) in four seconds. Here the output temperature of the calorifier is 373 K. Considering the heat loss, the output temperature of the calorifier is higher than austenitic finish temperature of SMA. This out-of-plane deformation capability of SMA-elastomer composites may be very useful for expandable structures and other morphing structures. If for engineering practice using, it can be applied voltage to SMA wire to heat itself.

As seen in Fig. 8, the given deformed arcuation shape of SMA-elastomer composites specimen is with angle of 90.21° and curvature radius of 52.7 mm. SMA–elastomer composites specimen deforms from arcuation shape to plane shape under the stimulus of thermal field on the arcuation section (Figs. 7 and 8). Fig. 8 also shows that the instant arcuation shape of SMA-elastomer composites specimen is with angle of 120.1° and curvature radius of 68.6 mm after two seconds in the heating process. The instant arcuation shape of SMA-elastomer composites specimen is with angle of 142.93° and curvature radius of 99.2 mm after three seconds in the heating process. Finally SMA-elastomer composites specimen returns to the permanent plane shape after four seconds in the heating process (Fig. 7).

3.3.3. Varying stiffness capability demonstration

In the Section 3.2, the varying stiffness capability of SMA-elastomer composites can be obtained through the three-point bending testing results. In this part one more experimental demonstration is done for explaining the varying stiffness capability of SMA-elastomer composites more directly and visibly.

As seen in Fig. 9 (a), a weight with 497 g is placed on the upper surface of SMA-elastomer components specimen at room temperature. The shape of specimen deforms from plane (permanent shape, Fig. 9 (b)) to surface. The specimen returns to the permanent shape through

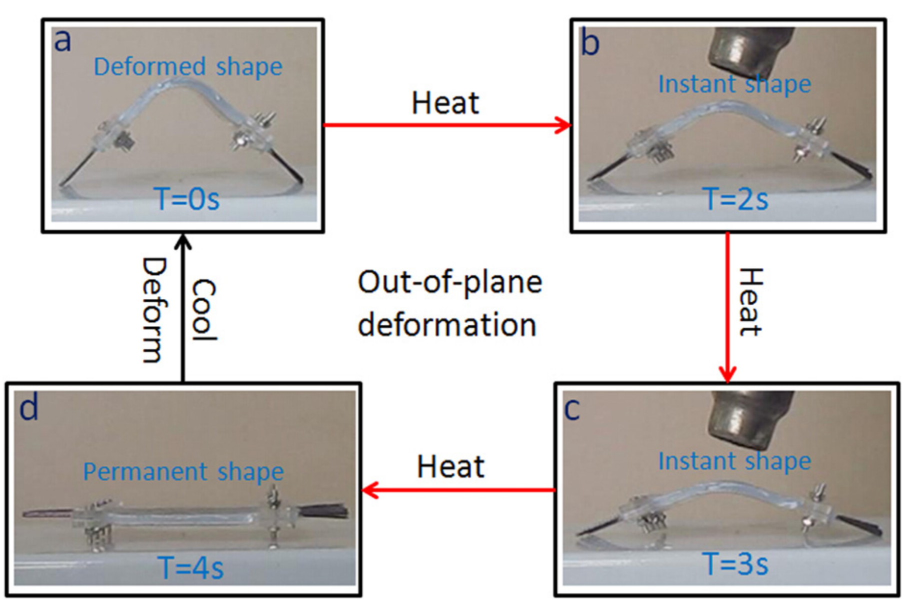

Fig. 7. SMA-elastomer composites showing out-of-plane deformation.

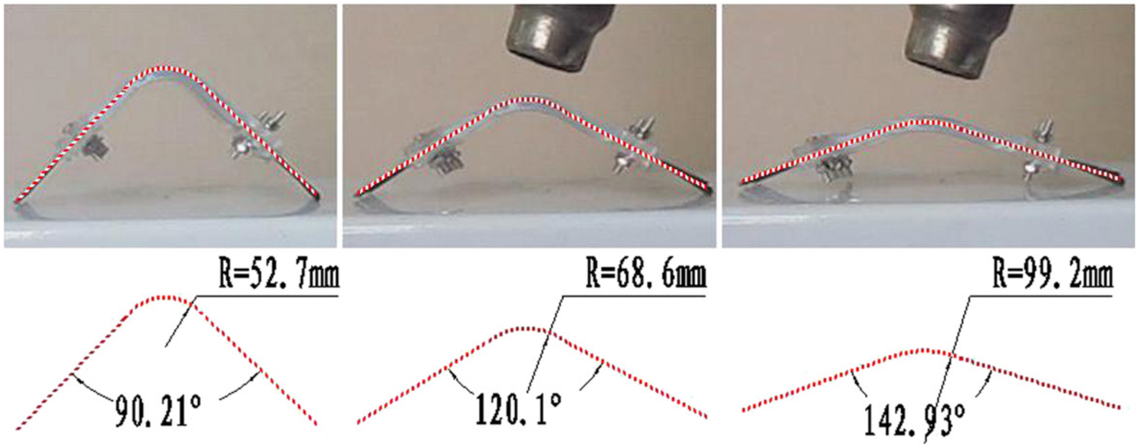

Fig. 8. SMA-elastomer composites morphing shapes and angles in out-of-plane deformation process.

Fig. 9. Demonstration of the varying stiffness capability of SMA-elastomer composites.

heating it by calorifier (Fig. 9 (b)). Then the weight is placed on the upper surface of the specimen of which is still at high temperature immediately, and the specimen almost does not deform under the macroscopic observation (Fig. 9 (c)).

4. Conclusions

In this paper, a multifunctional composite using elastomer embedded with thermally responsive Shape Memory Alloy (SMA) wires was designed, fabricated and investigated. Practical and valid method based on the Rule of Mixture and bending-spring constant method was used for predicting the bending-spring constant of SMA-elastomer composites. The accuracy of the theory method was verified by the results of three-point bending tests. The bending-spring constant at $A_f - 22$ K is 3280 Nm and at $A_f + 22$ K is 13,853 Nm from experimental results. As we demonstrated in this paper, SMA-elastomer composites, which were capable of not only in-plane deformation but also out-of-plane deformation, could be further able to vary stiffness by changing environmental temperature to satisfy different application requirements. At the low temperature, the multifunctional composites can achieve in-plane deformation and out-of-plane deformation easily under the external force driving. At the high temperature, the multifunctional composites can achieve in-plane deformation and greater stiffness for resistance to out-of-plane deformation under normal load. The multifunctional composites also can fast return to the permanent memory shape through the thermal stimulation. Such a multifunctional composite could be used for morphing skins especially which need to meet multi-mission requirements or expandable morphing structures.

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