Mechanical properties of shape memory polymer composites enhanced by elastic fibers and their application in variable stiffness morphing skins

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Abstract
Shape memory polymers are temperature-controlled variable stiffness materials, which have potential for use as morphing skins. Shape memory polymer skins undergo large strain in their flexible, rubbery state and resist aerodynamic loads in their stiff, glassy state. However, pure shape memory polymers are brittle in their glassy state, and in their rubbery state, they tear rapidly along micro-cracks formed under tension. Due to these disadvantages, the shape memory polymers are not safe and reliable enough for application. In this article, elastic fibers were mixed into pure shape memory polymers to solve these problems. The mechanical properties of the shape memory polymer composites were investigated. The strength and Young's modulus of pure shape memory polymers at high temperature were improved by elastic fibers, and the toughness of pure shape memory polymers at room temperature (glassy state) was enhanced with acceptable reduction in Young's modulus. The tear strength of shape memory polymers was significantly improved by elastic fibers, especially at high temperature. Recovery properties and thermal performance were also discussed. Finally, shape memory polymer composite skins were used in a variable camber wing structure to demonstrate their application.

Keywords
Shape memory polymers, elastic fibers, composites, mechanical properties, morphing skins

Introduction
Previous researches have already verified that morphing technology can bring optimized aerodynamic performance to an aircraft under different flight conditions by changing its wing shape, in terms of sweeping, folding, expansion, variable camber, and flapping (Anthony, 2007; Barbarino et al., 2011a; Gomez and Garcia, 2011). The morphing skin is one of the most important components for morphing structures (Thill et al., 2008), with two abilities: withstanding the aerodynamic loads on wing surface and supporting a deformable smooth aerodynamic cover. Elastomer skins (Bubert et al., 2010; Chen et al., 2011; Olympio et al., 2010) and inflatable skins (Kheong and Jacob, 2008; Simpson et al., 2006) have large strain capability for morphing but low stiffness for resisting aerodynamic loads. Segmented structures (Barbarino et al., 2011b; Long et al., 1996) and corrugated structures (Thill et al., 2010; Yokozeki et al., 2006) are transformable and stiff, but not smooth on the surface. Novel variable stiffness materials are required urgently to solve this problem (Kuder et al., 2013).

Shape memory polymers (SMPs) are considered as variable stiffness materials. SMPs are stiff like plastic in their glassy state. When heated above the transition temperature ($T_g$), they become soft and rubbery with large strain capability. Further following a cooling process, they become glassy again (Leng et al., 2011). Therefore, SMP skins could be used to withstand aerodynamic loads in their glassy state with high modulus and alter their shape in the rubbery state with low
modulus. SMP skins have already been investigated in a morphing chord wing (Reed et al., 2005), folding wing (Bye and McClure, 2007), deployable wing (Yu et al., 2009), variable camber wing (Yin et al., 2009), and shear morphing wing (Keihl et al., 2005).

However, some problems remain regarding the repeated use of pure thermoset SMPs. First, a slight out-of-plane deformation occurs in the pure SMP sample after a thermal–mechanical cycle (Keihl et al., 2005). This problem can be solved by the applied pre-strain. Second, SMPs are too brittle in the glassy state for bearing bending load (Perkins et al., 2004). Finally, stress concentrations occur near joints (McKnight and Henry, 2008) and rip easily at high temperature. Figure 1 shows the typical tears in a styrene-based SMP at high temperature under a shear load.

To improve the mechanical properties, reinforcement materials such as glass fibers or carbon fibers have been mixed into pure SMPs. The shape memory polymer composites (SMPCs) displayed high modulus and strength (Lan et al., 2009), but reduced elongation strain (Everhart et al., 2006). Due to the small extension strain of fibers, the glass fiber–enhanced SMPCs may fracture under a large extension strain (Jee, 2010). To achieve large strain, elastic materials were mixed into pure SMPs, improving the toughness by up to 200% (Everhart et al., 2006; Sun et al., 2013). This could make SMPs more reliable. In this article, elastic fiber–enforced SMPCs were fabricated. The mechanical, recovery, and thermal properties of SMPCs were investigated. Finally, morphing skins based on SMPCs were installed on a variable camber wing structure to demonstrate the potential application.

**Sample preparation**

The thermoset styrene-based SMP resin used in this study was prepared by the research group in Harbin Institute of Technology. Elastic fibers comprising 20% spandex and 80% nylon were bought from Liba Weaving Co., Ltd (Shantou City, China). The technical parameters of spandex fibers include the following: high elastic elongation strain (more than 400%), high elastic recovery rate (95%–99% recovery from 200% elongation), and low modulus of elasticity.

The SMPCs were prepared by mixing styrene-based shape memory resin and the elastic fibers. The experimental details are as follows. Elastic fibers were laid up on a flat plane in a laminate. The laminate was dipped in SMP resin to eliminate air among the fibers and avoid generating bubbles. The resin was injected into the mold and subsequently cured for 24 h at 75°C in a homothermal oven. The 2-mm-thick SMPC samples with 0%, 20%, and 40% volume fraction were fabricated for experiments.

**Experimental results and discussions**

**Dynamic mechanical analysis test**

Dynamic mechanical analysis (DMA) was used to show the relationship between storage modulus of the SMPCs and temperature. This relationship is shown in Figure 2. The moduli drop from 1400–1800 MPa to 10–30 MPa at around 60°C and remain at this low value for higher temperatures. Figure 3 shows the Tan Delta (loss angle) curves of the SMPCs. When compared to Figure 2, it can be seen that the temperature corresponding to the identified Tan Delta peaks coincides with the temperature at which the storage modulus drops. These temperatures, from 58.17°C to 62.55°C, are the transition temperatures ($T_g$) of the SMPCs.
Dumbbell specimens with different elastic fiber volume fractions were prepared according to ASTM standard D638. Figure 4 shows the curves of stress versus strain of pure SMPs in seven selected temperatures which are explained as follows: 25°C is room temperature; 63°C is considered the $T_g$—this is a little higher than the $T_g$ obtained from DMA testing to make sure it is above the transition temperature for all specimens; and 93°C and 43°C are 30°C above and 20°C below the $T_g$, respectively. Finally, the other three temperatures (35°C, 50°C, and 80°C) were obtained by interpolating between the four given temperatures. At 25°C, the samples can be considered as stiff materials due to the identified high modulus and strength. At 35°C, the samples undergo a large strain after a yield peak. At 43°C and 50°C, the specimens achieve over 150% strain. It is believed that the SMPs become very soft with very low modulus above 63°C ($T_g$) and break easily with the increase in temperature.

Figure 5 illustrates the different failure mechanisms of SMPCs samples with 20% volume fraction of elastic fibers. At 25°C, the failure section is a plane with the fibers and the matrix fractured together. The fibers reduce the strength of the SMPCs at room temperature. At 43°C, failure is caused by the splitting of SMP matrix from the elastic fibers.

Figure 6(a) shows the curves of Young’s modulus of the SMPCs with respect to temperature. Generally, Young’s modulus decreases with temperature. At 25°C, the SMPCs’ modulus decreases with the increase in fibers’ volume fraction, which is similar to the storage modulus curves from DMA test (shown in Figure 2). At 43°C, the modulus of 40 vol% SMPCs is larger than the others, indicating that the fibers play a more important role in the SMPCs due to the increasingly softening matrix at high temperatures. Young’s moduli are improved with the increase in fiber fraction at 63°C and 93°C.

From classical lamination theory, Young’s modulus in the direction of the fibers is given by

$$E(T) = V_m E_m(T) + V_f E_f$$  \hspace{1cm} (1)$$

where, $V_m$ and $V_f$ are the volume fraction of matrix (SMP resin) and elastic fibers in the SMPCs, respectively; $E_m(T)$ and $E_f$ are Young’s modulus of pure SMP matrix at temperature $T$ and elastic fibers, respectively. $E_f$ is obtained as 6.92 MPa following a standard tensile test (not shown here). Substituting $E_m(T)$ with values from inset of Figure 6(a), Figure 6(b) describes the theoretical fiber content dependence of Young’s modulus at different temperatures. It can be seen that an agreement is displayed between the experimental data and the predicting values calculated from the above theory.

Figure 7 Describes the strength of SMPCs at different temperatures. The results demonstrate that...
increasing fibers’ volume fraction reduces the strength at room temperature. Nonetheless, the fibers enhance the mechanical strength when the temperature exceeds than 43°C, revealing that the SMPCs will be safer to use at high temperature. The curves of strain at break versus temperature are shown in Figure 8. In general, the SMPCs’ breaking strain was larger than that of the SMPs at low temperature (25°C), which shows that the elastic fibers improve the toughness of pure SMPs by avoiding brittle failure. However, the strain was smaller over 43°C because of the fibers separating from the matrix. The maximum breaking strain occurs at 43°C due to the SMP matrix’s property (see Figure 4).

Tear strength test

The pure SMPs are brittle at room temperature or lower temperature and easily tear along micro-cracks at high temperature. A tearing test was performed according to the ASTM standard D1938-02. The two feet of the T-shaped sample were clamped by the grips of tensile testing machines (Zwick Roell). The tear strength was calculated from the breaking force divided by the thickness, which drops with increasing temperature (presented in Figure 9). The tearing strength is rather small for the pure SMPs above \( T_g \) (0.9 K N/m at 63°C and 0.21 K N/m at 93°C, respectively), indicating that the pure SMPs will split rapidly along a micro-crack or break at high temperature. The results show dramatic improvements of tear strength by mixing with elastic fibers, which increases with the fibers’ volume fraction at the selected four temperatures. This development can improve the reliability of SMPC structures in application.

Recovery rate

SMPs can recover to their original shape at high temperature because of the shape memory effect. Figure
10(a) shows a photograph of specimens prepared for recovery test. The specimen size is 80 mm × 10 mm × 2 mm. The testing process is shown in Figure 10(b). An SMPC strip (initial length \(L_0\)) was stretched by a tensile device to \(L_1\) (tensile strain \(\varepsilon_1 = (L_1 - L_0)/L_0 \times 100\%\)) at high temperature (above 150°C). After cooling down at room temperature, the sample was kept at a length of \(L_1\). Then, the sample was released and heated again. Because of the shape memory effect, the sample shortened to \(L_1\) (\(\varepsilon_2 = (L_2 - L_0)/L_0 \times 100\%\)). So, the recovery rate \(\eta\) is calculated as follows

\[
\eta = \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1} \times 100\%
\]

Under a constant tensile strain (\(\varepsilon_1 = 14\%\)), the recovery rates are 99.73%, 99.50%, and 98.12% with 0 vol%, 20 vol%, and 40 vol% SMPCs, respectively. To achieve full recovery in tension, the SMPCs should be pre-stretched in the compressed state of the structure.

**Conductive heat transfer performance**

To heat the SMPCs, a resistance heating film was placed under the SMPCs, and the rectangular sample top surface was kept at room temperature. Heating powers of 6.48 W (10 V input), 9.39 W (12 V input), and 14.63 W (15 V input) were selected. The temperature on upper surface was measured by a thermal infrared imager (Jenoptik InfraTec, Dresden, Germany) from vertical distance of 400 mm. Figure 11 shows the relationship between the average temperature of the specimens’ top surface (80 mm × 50 mm × 2 mm) and heating time. Data were obtained using the IRBIS 3 professional software.

From the curves in Figure 11, it can be seen that the elastic fibers do not impact the heating efficiency of SMPCs. The elastic fiber is made of 80% nylon (0.24 W/(m K); Moore et al., 2009) and 20% spandex (0.023–0.035 W/(m K); Lee and Park, 2012); therefore, the equivalent thermal conductivity is about 0.2 W/(m K), which is similar to the thermal conductivity of styrene (0.2–0.21 W/(m K); Saxena et al., 1999). Under 6.48 W input, the temperature on the upper surface of the specimen reached 43°C after 40 s and subsequently 63°C after 5.5 min. The temperature increased quickly while the power increased. Under 9.39 W input, it took 25 s to reach 43°C and 160 s to reach 63°C. It was fastest under 14.63 W input; only 15 s to 43°C and 70 s to 63°C were required. Therefore, pre-heating should be prepared to make the SMPCs reach a predetermined temperature for application in morphing skins.

**Application in a variable camber wing**

To demonstrate the potential applications, the elastic fiber-enhanced SMPCs were used in a variable camber morphing wing structure as morphing skins. As shown in Figure 12, the designed structure consists of a fixed leading edge, trailing edge, a metal sheet, pneumatic...
artificial muscle (PAM) actuator (Festo Co., Esslingen am Neckar, Germany), and SMPC skins. The PAM actuator was installed at the bottom of the metal sheet. By applying air pressure, the actuator shortened, resulting in a change in the wing’s camber. The 2-mm-thick SMPCs with 20 vol% fibers were used in the upper and lower surfaces to keep the surface smooth. The skins can withstand an aerodynamic loading in glassy state and change shape with the wing in rubbery state. When the trailing edge flaps down, there is tensile strain on the upper surface and compressive strain on the bottom. The lower skin should be pre-stretched before

Figure 11. Temperature on the upper surface of the SMPC specimens versus time under different input powers: (a) 6.48 W, (b) 9.39 W, and (c) 14.63 W.
SMPC: shape memory polymer composite.

Figure 12. Photograph of the morphing variable camber wing.
SMPC: shape memory polymer composite; PAM: pneumatic artificial muscle.
installing, and it could shrink itself due to the shape memory effect.

The angle of the camber wing can be defined as \( \theta = \tan^{-1}(D/L) \) (presented in Figure 13), where \( L \) is the distance between the left of the metal sheet and the end of the trailing edge and \( D \) is the deflection of the end of the trailing edge, which can be measured via experiment.

To avoid wrinkles, 5% pre-stretched strain was applied to the upper and lower SMPC skins while installing on the wing surface by rivet connection. The morphing skins were heated up by a 9.39-W resistance heating film for 200 s to ensure the whole SMPC skins reached \( T_g \) and were soft enough. The wing’s shape was morphed by inflating air into the PAM actuator. In the whole process, the SMPC skins were smooth and intact. The deflection of the end of the trailing edge was recorded by a vertical caliper under different input pressures. Figure 14 describes the calculated angle of the trailing edge. The angle increases with the increase in the input pressure. The maximum angle was 1.69\(^\circ\), when input pressure of the PAM was 0.6 MPa.

Conclusions

In this article, elastic fibers were mixed into the pure SMPs in order to improve the mechanical properties. The 20 vol% fiber-enforced SMPC skins were used in a variable camber morphing wing structure. The main conclusions are as follows:

1. SMPCs improved the toughness of SMPs at room temperature with acceptable reduction in Young’s modulus, which make the material tenacious in their glassy state.
2. SMPCs enhanced the strength and Young’s modulus of SMP at high temperature, showing that elastic fibers can improve the safety of using SMPCs above \( T_g \).
3. The tear strength of SMPs was significantly enhanced by elastic fibers, especially at high temperature. This implies that the SMPC structure is easy and safe to install from application point of view.
4. The SMPC’s recovery rate and heating speed were not greatly influenced by the elastic fibers.
5. The application of SMPC morphing skins was demonstrated using a variable camber wing structure. The results show that the current variable camber wing with SMPC skin can be used for airplane taking off and landing. In order to apply such materials in a practical morphing aircraft, the materials should be tested in flight conditions including lower temperature, sand, dust, rain, and hail.

Declaration of conflicting interests

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