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Experiment and analysis of morphing skin embedded with shape memory polymer composite tube

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Abstract
In this study, a kind of morphing skin composed of silicon rubber and shape memory polymer composite tube is designed, manufactured, and investigated. Significant stiffness variation for the morphing skin can be obtained through changing its environment temperature. First, in order to investigate the basic elastic properties of the morphing skin, the Rule of Mixture is used to predict the effective engineering modulus and modulus ratio with different matrix volume fractions. The tensile test is conducted on the skin in two states (cold state and heated state) to validate the accuracy of the theoretical method. Second, the temperature distribution of shape memory polymer composite tube heated by the hot fluid is obtained through the finite element analysis. Moreover, a corresponding heating system is designed and manufactured to provide heat for the morphing skin. Based on the heating system, the deflection and recovery performances are also investigated through the stress-bearing capability and thermal cycling tests, respectively. Finally, the infrared test is carried on the morphing skin to show the temperature distribution during the heating process.

Keywords
Shape memory polymer composite, variable stiffness, morphing skin, Rule of Mixture, infrared test

Introduction

The performances of the aerospace systems can be influenced by design approaches and innovation of novel materials. New solutions in morphing structures may lead to a decrease in operating costs by reducing weight. In an integrated flight cycle with continuously varied flight parameters, for the traditional aircraft, it is too difficult to define a single configuration able to maximize the aerodynamic efficiency, maneuverability, stability, and fuel consumption in any circumstance (Bubert et al., 2010). However, morphing aircrafts could adapt to the outside flight environment through changing their wing shapes (Thill et al., 2008). They are able to offer great potential for performance improvements in comparison with traditional aircrafts. Morphing skin is one of the key techniques to realizing morphing aircraft (Bartley-Cho et al., 2004). In order to realize the great changes of chord length, span length, sweepback angle, and wing area, the skin must be able to withstand large enough deformation (Reich et al., 2007; Thuwis et al., 2010). Moreover, the skin should have enough out-of-plane stiffness to maintain the aerodynamic loading during the deformation process; at the same time, the in-plane stiffness of skin should be as little as possible to reduce the energy requirements (Thill et al., 2008; Yin et al., 2008).

Traditional flexible skin like rubbery material is one kind of morphing skin (Andersen et al., 2007). Although this kind of skin could meet the large deformation and gas tightness requirements of the wing, its bearing capacity is limited. In this way, it can only be used in the low-speed flight range. Although the bearing capacity of the rubber skin can be improved by increasing prestress, it will reduce the available deformation ability.

Another morphing skin is designed based on shape memory polymer (SMP). SMP is an emerging class of active polymers that have dual-shape capability. When exposed to specific external stimulus, such as heat, magnetic field, electricity and solvent, they can change their shape from the temporary state to the original state

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(Behl and Lendlein, 2007; Leng et al., 2009; Liu et al., 2009). Based on SMP material, a new kind of folding hinge was designed and used in the morphing wing by Lockheed Martin Company (Bye and Mcclure, 2007; Ivanco et al., 2007). Embedded nickel chrome wires acted as the activation system for the SMP hinge (Love et al., 2004, 2007). The experimental results showed that this kind of heating method could make the temperature reach up to the glass transition temperature of SMP, but fracture phenomenon of heating wire was found in folding experiments after several cycles. Yin et al. (2008) had also completed the heating process of SMP skin by embedding with heating wire springs and driving by a DC motor. In comparison with straight wire heating phase, this kind of method shows an easier and effective heat driven way. In this way, the feasibility of this heating mode was confirmed. However, SMP and heating wire springs were also separated after several heating processes, which restricted its further application. Thus, it can be seen that SMP material can meet the requirements of the skin deformation, but the heating mode needs to be further improved.

In recent years, a variable modulus composite material based upon SMP reinforced with fluidic flexible matrix composite (F2MC) tubes is fabricated (Philen et al., 2006, 2007, 2009). Based on this, a new kind of variable stiffness tube is fabricated composed of SMP and carbon fiber. The shape memory polymer composite (SMPC) tube possesses the rigidity under low-temperature condition and flexibility under high-temperature condition (Chen et al., 2012), which shows great potential in morphing aircraft application. In this work, a new class of variable stiffness skin composed of SMPC tube (as the reinforcement) and flexible matrix is designed and fabricated. The variable stiffness properties of the morphing skin have been investigated from a theoretical and experimental point of view. Based on the Rule of Mixture, the theoretical values of the engineering modulus can be obtained. In contrast with the tensile test results, it can be found that the analysis method possesses satisfactory accuracy in predicting the axial elastic modulus and modulus ratio of the morphing skin. In addition, a kind of heating method is presented and analyzed in this research. Based on this method, a corresponding circulating heating system is designed for heating the SMPC tube. Then the validity of this heating method is verified by experimental tests. This new kind of morphing skin with variable stiffness properties provided great potential in morphing aircraft application.

SMPC tube fabrication and experimental test

SMPC tube fabrication

The SMPC tube is made of SMP and carbon fiber. The Veriflex®S, VF 62 SMP material with a density of 0.92 g/cm^3 (purchased from CRG, Inc., Dayton, Ohio, USA) used in this article is styrene-based shape memory resin with glass transition of 62°C, which belongs to thermosetting resins (Lv et al., 2011). As shown in Figure 1, it was wet filament wound by using a digital computer-controlled filament-winding machine ($3FW250 \times 1500$, Harbin Composite Equipment Co.). Before filament winding, the stainless steel mandrel (Diameter 4 mm) enclosed with demolding cloth was fixed by a metal connection. With the rolling of the mandrel, the carbon fiber (T300, 3K) could go though the resin bath before winding. The speed of the mandrel was 20 r/min and the tension held on the wire was about 5 N. Through controlling the computer, the carbon fiber was spiral winded on the mandrel with the angle of $\pm 40^{\circ}$. After putting the mold in a closed environment at 75°C for 24 hours, the SMPC tube specimen was obtained with an inner diameter of 4 mm and an outer diameter of 5.8 mm, as shown in Figure 2. In addition, the actual fiber volume fraction is 0.32 through measurement and calculation.

Figure 1. Filament wound of SMPC tube.
SMPC: shape memory polymer composite.

Figure 2. SMPC tube specimens.
SMPC: shape memory polymer composite.

Figure 3. Experiment setup of SMPC tube.
SMPC: shape memory polymer composite.

Isothermal tensile test

In order to avoid the local end damage caused by the clamps of materials testing machine, two metal tube connections ($20\,\mathrm{mm}, \phi 4$) were put into the ends of SMPC tube. In consideration of the glass transition of styrene-based SMP (62°C), the SMPC tube specimens with a length of 122 mm were tested in two states: cold state (T = 23°C) and heated state (T = 90°C), which is more than 20° lower and higher than the glass transition temperature. The tensile tests were conducted on the Materials Testing Machine (Zwick/Roell Z010, load cell: 10 kN) at a constant rate of 1 mm/min, as shown in Figure 3. Three groups of samples were used in the tensile tests. The computer recorded the values of force and displacement during the tensile test progress. For simplicity, only one group of stress–strain curve which is approximately equal to the average value was used in Figure 4. In order to maintain consistency with the calculated Rule of Mixtures stiffness predictions of the skins later, the engineering stress is calculated as the tensile force divided by the entire cross-sectional area of the SMPC tube specimen. The strain is calculated as the displacement divided by the original length of the tube specimen (Chen et al., 2012). It is noted that the original length used in this section is the distance between the clamps. From the calculation of the slope of the linear portion of the stress–strain curve, the modulus can be obtained. From Figure 4, it can be found that the axial effective engineering elastic moduli are 1418.5 MPa in the cold state and 18.0 MPa in the heated state.

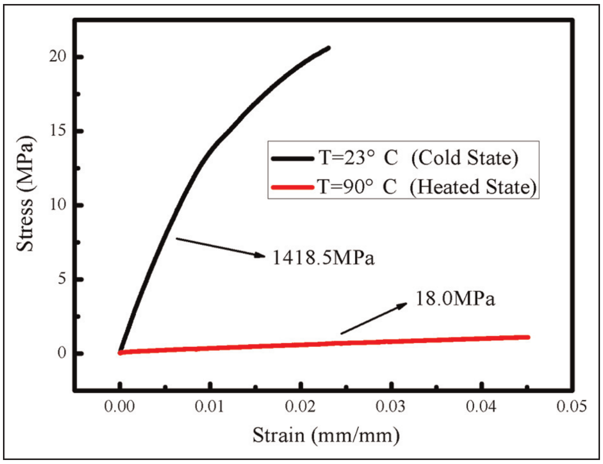

Figure 4. Experiment curves of engineering stress versus strain of SMPC tube.
SMPC: shape memory polymer composite.

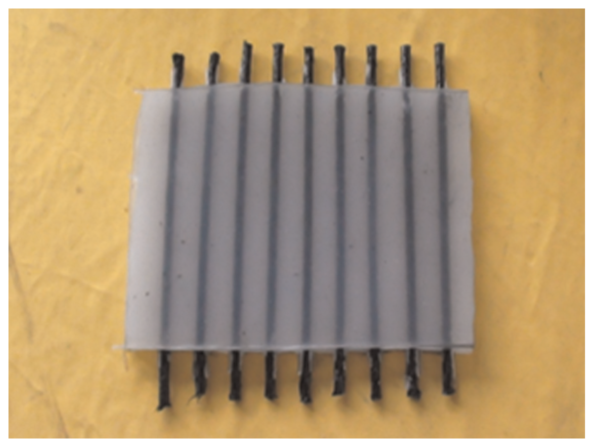

Figure 5. Morphing skin specimen.

Morphing skin

Morphing skin fabrication

The morphing skin is composed of silicon rubber (BJB TC5005 A-B/C) and SMPC tube. The manufacturing process can be divided into four steps. First, the silicone rubber 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. Third, after mixing and degassing, the silicone rubber solution was poured into the mold and the SMPC tubes were embedded parallel into the solution. Finally, the mold was put into a closed oven and cured at room temperature for 35 hours. The morphing skin specimen was obtained and shown in Figure 5.

Table 1. Geometric parameters of morphing skin specimens.

Geometric dimensions: length/width/height (mm)	Number of specimens	Number of tubes in each specimen	Test
138×57×8	3	3	Tensile test
142×105×10	1	5	Stress-bearing capability test
135×95×9	1	5	Infrared test

Isothermal tensile test

According to the Rule of Mixture, the morphing skin based on SMPC tube can be simplified to be a fiber-reinforced composite. Based on this theory, it should satisfy the following three assumptions. First, the SMPC tube is perfectly bonded to silicone rubber matrix, which means no delaminating phenomenon exists. Second, the axial strain of the SMPC tube is equal to the matrix in the longitudinal direction. Finally, the surface of the morphing skin is kept as a plane during the elongation (Chen et al., 2011). According to the Rule of Mixture, the following formulations could be obtained (Hamed et al., 2008)

$$\sigma_1 = \sigma_f V_f + \sigma_m V_m \tag{1}$$

$$E_1 = E_f V_f + E_m V_m \tag{2}$$

In these formulas, $(\sigma_1, \sigma_f, \sigma_m)$ and (E_1, E_f, E_m) are the stresses and elastic moduli for the longitudinal direction of morphing skin, reinforcement and matrix, respectively. (V_f, V_m) are the volume fractions for the reinforcement and matrix, respectively.

The geometric parameters of morphing skin specimen used in the tensile test are listed in Table 1. And the volume fraction of matrix for morphing skin specimen is 0.83. Before fixing it on the clamps, two metal tube connections (20 mm, $\phi 4$) were put into the ends of each SMPC tube. Then, four polished thin plates were glued to the surface of silicon rubber in order to increase the friction force between the skin specimen and the clamps. The tensile tests were also conducted on the Materials Testing Machine (Zwick/Roell Z010, load cell: 10 kN) at a constant rate of 1 mm/min, as shown in Figure 6. As mentioned above, three groups of samples were also used in the tensile tests. For simplicity, only one group of stress–strain curve which is approximately equal to the average value was used in Figure 7. From the calculation of the slope of the linear portion of the stress–strain curve, the modulus can be obtained. From Figure 7, it can be found that the axial effective engineering elastic moduli are 232.6 MPa in the cold state and 3.9 MPa in the heated state. Therefore, a modulus ratio of 59.6 is obtained.

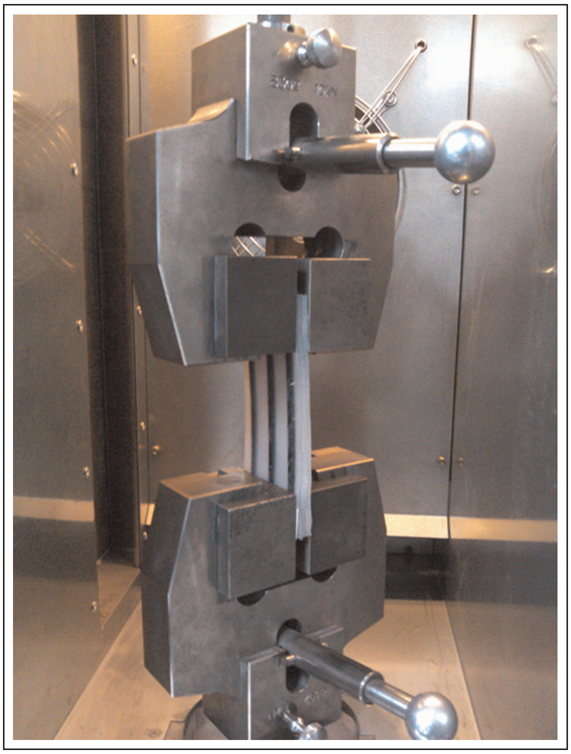

Figure 6. Experiment setup of morphing skin.

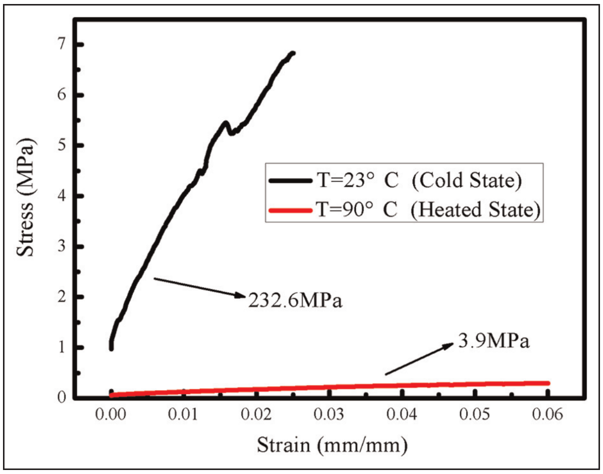

Figure 7. Experiment curves of engineering stress versus strain of morphing skin.

The experimental results are compared with the predicted results. The basic material parameters of the reinforcement and matrix for theory analysis are listed in Table 2. The comparison between predicted results and experimental results is listed in Table 3. The error values associated with the experimental data shown in Tables 2 and 3 are standard deviations. Although the modulus of the theoretical predicted results is higher than experimental value (6.2% in cold state and 7.3% in heated state), it can still be found that good agreement of the modulus ratio is observed in general, with the predicted result showing a slight decrease (1.4%) over the experimental result. The errors of modulus

Table 2. Basic material parameters of SMPC tube and matrix.

Material	Property	Value
SMPC tube	E/(MPa) (cold state)	1426.8±39.8
	E/(MPa) (heated state)	18.2±1.0
Matrix (silicon rubber)	E/(MPa)	1.4
	v	0.49

SMPC: shape memory polymer composite.

Table 3. Comparison of experimental and predicted results.

	Axial elastic modulus (cold state) (MPa)	Axial elastic modulus (heated state) (MPa)	Modulus ratio
Experimental results	229.5±16.6	3.9±0.4	58.8
Predicted results	243.7	4.2	58.0
Relative error	6.2%	7.3%	1.4%

and modulus ratio may be attributed to the following reasons: first, the volume fraction of matrix in predicted values may not be the same as the actual values of specimen; second, there is deformation between the SMPC tube and glued plates during the tensile test.

Stress-bearing capability test

Heating method. In the stress-bearing capability test, the morphing skin specimens are studied in cold and heated states. However, it is difficult to heat the SMP material and its composite with the traditional method. In view of this, a heating method with hot fluid was used in the following research. In order to demonstrate the feasibility of this method, a simulation is used by finite element analysis (FEA) (Ansys Fluent 13.0). Water is chosen as the fluid medium, the inlet water velocity is measured as 4.4 m/s. Since the thermal conductivity of carbon fiber in the fiber direction (600 W/m K) is much larger than that in perpendicular direction, the thermal conductivity in perpendicular direction could be estimated as 60 W/m K based on the rough estimated value of carbon-fiber composite samples (Tian and Cole, 2012). However, in comparison with carbon fiber's, the thermal conductivity of the SMP (0.17 W/m K) is quite lower. Therefore, in consideration of the fiber volume fraction of 0.32, the thermal conductivity of the entire SMPC tube can be approximately calculated as 19.2 W/m K. Moreover, the size of the tube simulated equals that of the SMPC tube sample. Other parameters are the default values. Then the temperature distribution of the tube is obtained, as shown in Figure 8. From observing Figure 8, it can be found that the steady state of wall temperature can reach up to 76°C (glass transition temperature: around 62°C), when the inlet water and external environment temperatures are 90°C and 23°C, respectively. It can also be seen that the tube is heated uniformly, which demonstrates the feasibility of this heating method.

Design of heating system. In order to ensure the heating uniformity of SMPC tube, a kind of circulating heating system was designed and fabricated to heat the morphing skin, as shown in Figure 9. The system includes a variable power high-temperature water pump (SIHAWILO, TF-110), a valve, a constant temperature heating tank (Mutong Company, 10 kW), a slideway, ten tube fittings, a fixed main pipe, and a parallel removable main pipe. The parallel removable main pipe is assembled on the slideway, which can make the skin installed with no damage. Five threaded holes were

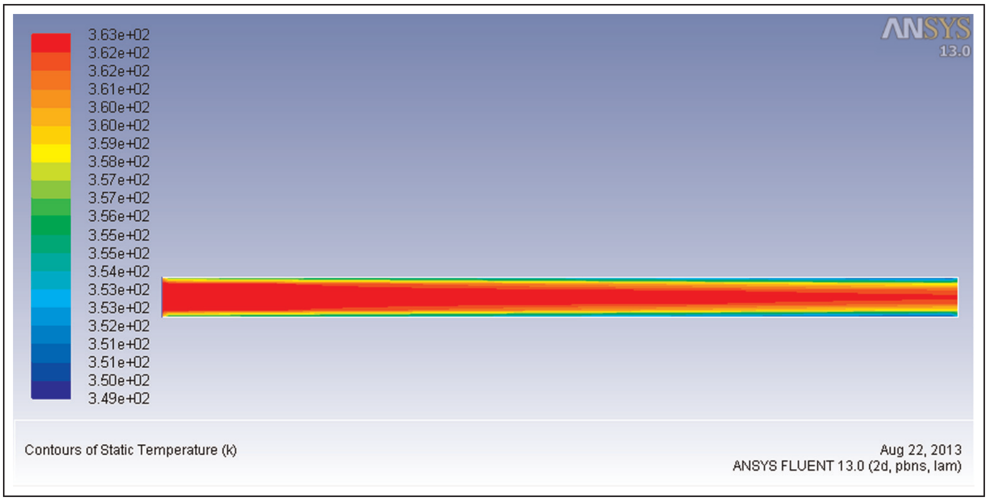

Figure 8. Temperature distribution of SMPC tube with applying hot water.
SMPC: shape memory polymer composite.

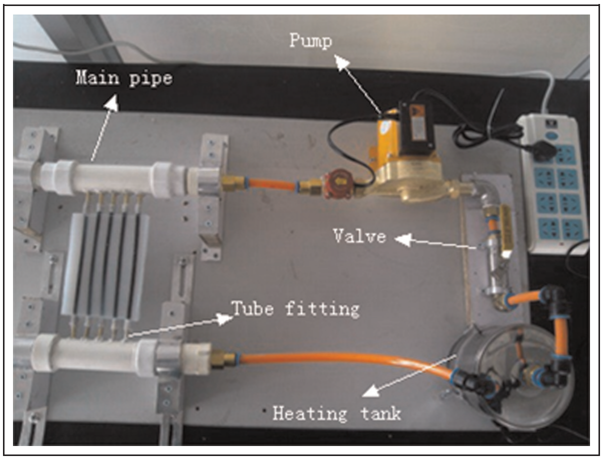

Figure 9. Circulating heating system.

placed on both of the main pipes, where one end of either pipe was blocked. The other end of the fixed pipe was connected to the pump, while another one was connected to the heating tank. In this way, the morphing skin can be heated by the circulating heating system.

A stress-bearing capability test was conducted on the skin; the relationship between deflection and time could demonstrate the efficiency of the heating system, as shown in Figure 10. The geometric parameters of the morphing skin specimen are listed in Table 1. The experiment was conducted in a condition of applying hot water at room temperature. For the experimental test, the weight (500 g) was placed on the upper surface of the skin. Then the qualitative analysis of relationship between deflection and time is obtained.

From Figure 10, it can be seen that the morphing skin keeps a higher stiffness in the initial state and the skin has no deflection in the perpendicular direction. Then, the deflection value increases with the increasing temperature for the skin when the hot water is applied to the SMPC tube. In addition, significant change of deflection could be observed after 180 s.

Experiment results. In order to simulate the aerodynamic loading, different weights were used as the perpendicular load. Since the surface area of the skin specimen was kept constant, different pressures could be obtained. In addition, dial indicator was used for skin central displacement measurement. The reinforcement (SMPC tube) was longer than skin at each end in order to assemble with the tube fittings. After the morphing skin was installed on the heating system, the deflections in the middle of morphing skin were recorded with three conditions, including (a) no water, (b) cold water, and (c) hot water.

The hot water is applied to the tube, which realizes the change of skin from stiffness state to flexible state, as shown in Figure 11. In order to test the recovery capability of skin, this article investigated the cyclic heating–cooling process for several times. Moreover, the heating–cooling process from (a) to (c) and then (a) was defined as one cycle. The interval of each test is always kept constant (24 h). Figure 12 shows the

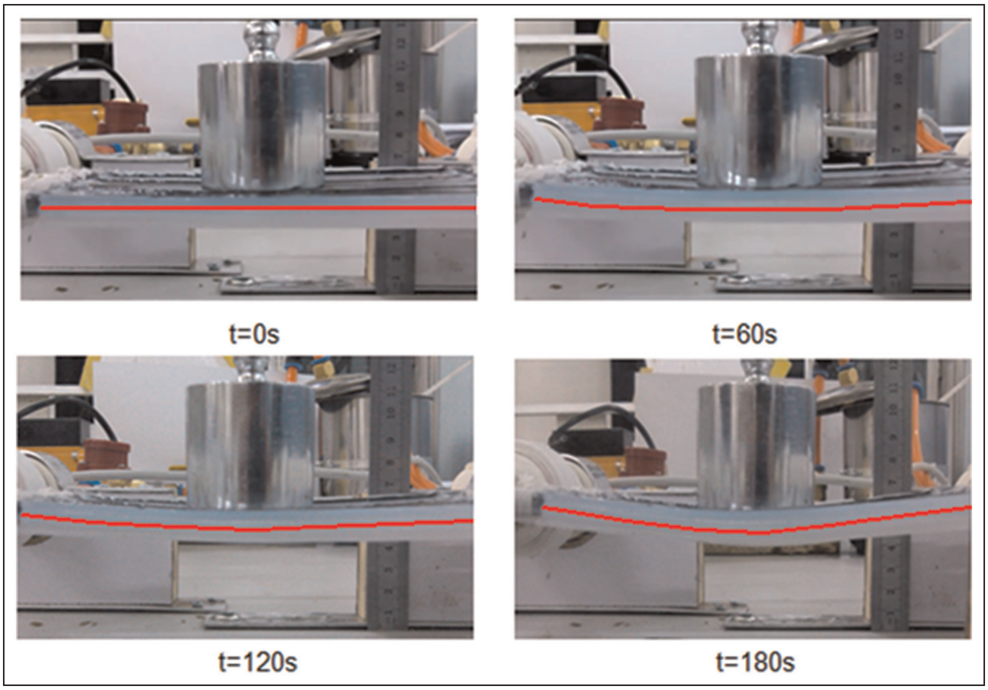

Figure 10. The experimental deformation process of morphing skin.

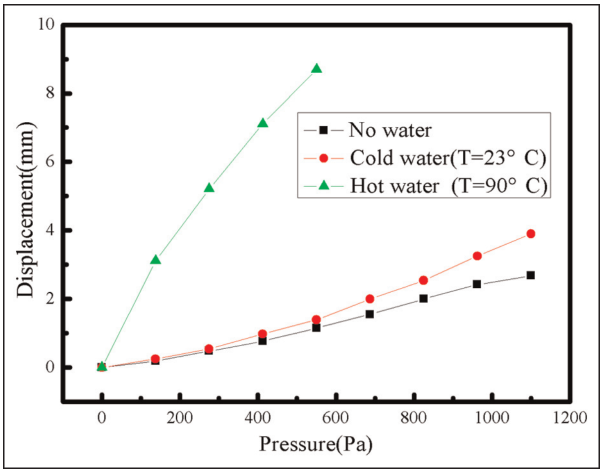

Figure 11. Experiment curves of displacement versus pressure.

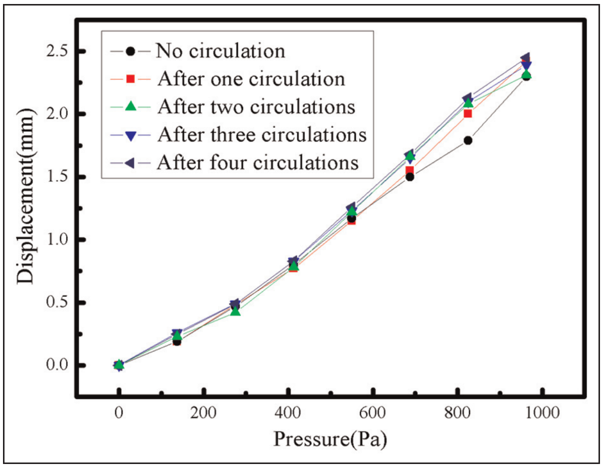

Figure 12. Experiment curves of displacement versus pressure under multiple circulations.

experimental curves of displacement and pressure for four cyclic times.

From Figure 11, it can be seen that the displacement does not change a lot between processes (a) and (b).The small change may be attributed to the gravity of water. However, a significant change of displacement can be found in process (c), which is ascribed to the stiffness change of the tube. From Figure 12, it can be seen that the stiffness of the whole skin almost kept constant after four cycles, which deems the morphing skin possessing an excellent recovery capacity.

Infrared test

In this study, in order to study the relationship between the temperature of skin and time, the surface temperature of morphing skin is observed under the heating process by using infrared thermal imaging analyzer (AGEMA, Thermo-vision 900). The geometric parameters of the morphing skin specimen are listed in Table 1. The test was conducted at room temperature (23°C). A series of pictures of surface temperature of morphing skin versus time are shown in Figure 13.

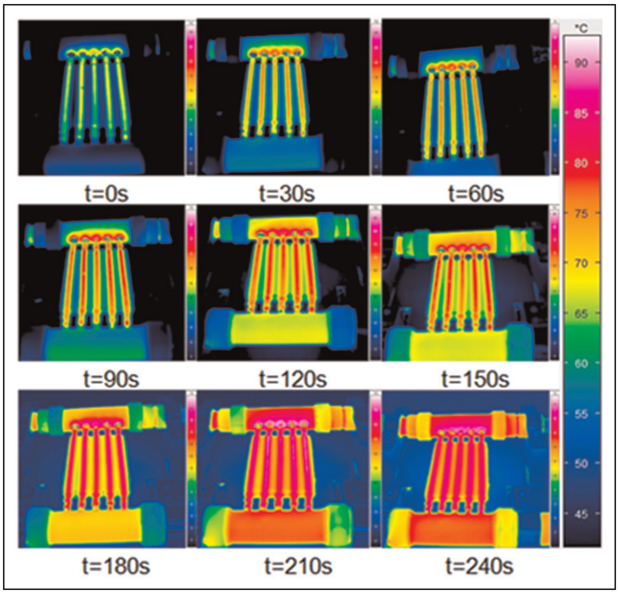

Figure 13. Infrared test of morphing skin.

From Figure 13, it can be seen that the temperature of inner tube wall first increased then slowly spread to the whole tube and skin. The time = 0 s is the time when the SMPC tube is out of air and filled with hot water. After applying the hot water for 30 s, the temperature of the skin reached up to 65°C, which is higher than the glass transition temperature of SMPC tube (62°C). After applying the hot water for 210 s, the temperature of the skin could reach up to 85°C, which is the highest temperature in this experiment. It will not reach up to 90°C because the heat exchange between the system and the external environment (room temperature 23°C) always exists. However, it has already showed the potential to heat the SMPC tube and change its stiffness.

Conclusion

In conclusion, a kind of variable stiffness morphing skin is fabricated and analyzed. Through changing the environment temperature, different effective engineering moduli could be obtained. Based on the Rule of Mixture, the effective engineering modulus of the morphing skin could be predicted. The accuracy of the theory method is validated by the tensile test results. Moreover, a heating method using hot fluid is presented and a corresponding heating system is also designed and fabricated. The deflection and recovery performances of the skin are also investigated based on the heating system. Good recovery capability is observed after four times for the morphing skin. However, the maximum pressure under high-temperature condition is only 600 Pa, which is caused by the failure of the designed connection but not the sample. The connection between the metal fitting and SMPC tube will be improved in our future work. In addition, to improve the mechanical performance of the morphing skin in both states (cold and heated), the SMPC tube with different material and geometry parameters, and the morphing skin with different density of SMPC tubes will also be studied. Finally, in order to obtain the temperature distribution during the heating process, the infrared test is carried on the morphing skin. The analysis presented in this work provides potential application in morphing wing with variable stiffness properties.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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