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Erstveröffentlichung in / First published in:

Textile Research Journal. 2018, 88(3), S. 345 – 353 [Zugriff am: 07.08.2019]. SAGE journals. ISSN 1746-7748.

DOI: <https://doi.org/10.1177/0040517516679151>

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Development and testing of controlled adaptive fiber-reinforced elastomer composites

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Textile Research Journal
2018, Vol. 88(3) 345–353
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sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0040517516679151
journals.sagepub.com/home/trj

Abstract

The integration of shape memory alloys (SMAs) into textile-reinforced composites produces a class of smart materials whose shape can be actively influenced. In this paper, Ni-Ti SMA wires are inserted during the weaving of a glass fiber reinforcement textile. This “active” reinforcement is then combined with an elastomeric matrix to produce a highly flexible composite sheet, which maintains high rigidity in the longitudinal direction. By activating the SMAs, high deflection ratios of up to 35% (relative to the component’s length) are achieved. To adjust the composite’s deflection to defined values, a closed-loop control is set up to adjust the current flow through the SMA wires. A control algorithm is designed and evaluated for several test cases. The high deformability and the controllable behavior show the high potential of these materials for applications such as aerodynamic flow control, automation and architecture.

Keywords

shape memory alloys, smart materials, fiber-reinforced plastics, elastomer

Shape memory alloys (SMAs) can be used as light-weight actuators. When a SMA is heated above its specific transition temperature, its crystalline structure transforms from a martensite to an austenite phase, a process that is accompanied by a reduction in length.¹ Cooling below the transition temperature reverses the phase change and expands the material. Although other phase change materials such as shape memory polymers have been investigated in recent years (see e.g. Zalba et al.² and Sun et al.³ for an overview), SMAs are the material of choice for many applications due to their relatively high actuating forces. Since SMAs are electrically conductive, the heating for the phase change can be easily affected by connecting an electric current to the SMA wires. Typical transition temperatures of industrially used SMAs vary between 30°C and 120°C.⁴

In recent years, composite materials integrating SMAs and polymers have been researched for a variety of applications (see Ratna and Karger-Kocsis⁵ and Mohd Jani et al.⁶ for an overview). In medical applications, SMA-based composites are used for dirigible catheters^{7–9} and deformable cell scaffolds.¹⁰

SMAs have been widely used for micro pumps,^{11,12} deformable wings in aeronautics (see Sofla et al.¹³ and Hartl and Lagoudas¹⁴ for an overview), underwater vehicles with fin propulsion^{15–18} and for crawling micro robots.¹⁹ However, in all these cases either the deformations were relatively small (maximum 4–10%, relative to the active component’s length), or no fiber reinforcement was present, resulting in a general low stiffness of the structure. For many applications, it is desirable to combine a high bending flexibility with a

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high stiffness of the structure in the longitudinal direction; examples for such applications include adaptable surfaces for aerodynamic flow control, automation applications, such as valve opening and shutting, and architectural applications, such as switchable building surfaces. The presence of a fiber reinforcement will not only lead to higher stiffness, but also to increased durability of the structure and allow easier positioning of the SMA wires during production.

The goal of this paper is therefore to integrate SMA wires in a textile reinforcement and realize a highly deformable composite sheet. In order not to limit the composite's deformation to two states – relaxation and maximum heating of the SMA wires – a control loop is necessary to adjust the heating current so as to achieve defined deformation values. In previous research, proportional–integral–derivative (PID) controller designs have been shown to be effective for this task,^{20–23} and will thus be investigated for the produced specimen.

Specimen preparation

The basic design concept of the textile-reinforced composite sheet with integrated SMAs is shown in Figure 1. The textile reinforcement is placed in the center (neutral) plane, so it will not increase the bending stiffness. SMAs are placed close to the top surface, so that a phase transition (and length reduction) of the SMA wires will bend the composite. The bending will be maximized by placing the SMA wires farthest away from the neutral plane.

For the specimen production, the Ni-Ti alloy wires are covered with a glass fiber-polypropylene sheath. In previous research, it was established that such a sheath significantly reduces friction between the SMA and the matrix, thus allowing higher deformation forces and higher bending degrees. The covering is done with a DREF friction spinning machine. Details for this preparation and material specifications can be found in Kluge et al.^{24,25} The reinforcement textile in this study is a single-layer plain glass fiber weave, in which the covered SMA wires are integrated as weft yarns. In the resulting fabric, the SMA wires are on the upper side of the fabric with a distance of 8.2 mm between the SMA wires. The individual wires are

connected with metal clamps to form an electrically conductive loop.

In the second step, the reinforcement fabric is impregnated with a pourable two-component silicone rubber matrix to form the composite sheet. After impregnation of the fabric, the composite is cured for 2 hours at 50°C. The thickness of the composite is 5 mm, its length 260 mm and its width 125 mm. Table 1 summarizes the material and production parameters and Figure 2 shows the produced composite. Note that out of the eight SMA wires in the structure, only the inner six are supplied with a current in this experiment.

Measurement and control loop set-up

Figure 3 shows the set-up of the measurement and control loop. The elastomer composite is placed vertically and clamped on the upper side. The SMA wires are connected to a power supply, so that the heating from the electrical current through the SMA wires results in the contraction of the phase change SMA material and the bending of the composite. When the current is interrupted, the SMA wires cool to ambient temperature and the composite deforms back to its original shape.

The deflection is measured by an optical triangulation sensor, which generates an output signal based on the measured deflection. This voltage is used as input signal for a microcontroller, which functions as a switch in the SMA's electric circuit. To adjust the current flow, the microcontroller switches the electrical circuit on and off at high frequencies. Depending on the relation of turn-on and turn-off durations, a mean current flow results over average time, a technique known as “pulse width modulation” (PWM). In the microcontroller, the triangulation sensor's voltage signal is discretized, filtered for noise reduction and converted into the actual deflection in mm; for the latter, the triangulation sensor's non-linear calibration curve is stored in the microcontroller.

As a triangulation sensor, a Sharp GP2Y0A41SK0F is used. The microcontroller is an Atmel ATmega328 on an Arduino Uno Board, which switches on and off a motor driver L298N to control the current in the SMA wire loop. Similar set-ups are common in mobile robotics.²⁶ The reference point of the

Figure 1. Design of the fiber-reinforced active composite. SMA: shape memory alloy.

Table 1. Material and production parameters

Component	Type	Manufacturer	Property	Value	Symbol
Glass fiber fabric	–	ITM	Yarn count	300 tex	
			Weave type	1 × 1 plain	
			Area weight	280 g/m ²	
Shape memory alloy wires	Ni-Ti alloy H	Memry GmbH, Germany	Diameter	0.3 mm	d_2
			Transition temperature	95–110°C	
			Elongation after phase transition	1%	ε_2
			Young's modulus	56 GPa	E_2
Matrix	Silicone rubber Sylgard® 184	Dow Corning GmbH, Germany	Young's modulus	0.1 GPa	E_1
Composite			Length	260 mm	l_1
			Width	125 mm	b_1
			Thickness	5 mm	h_1

Figure 2. The textile-reinforced active composite used for testing.

triangulation sensor is set at a distance of $l = 210$ mm from the clamping.

Control loop design

The described system is set up as a closed-loop control. The target (“reference”) value for the deflection is set from a PC, using the USB interface of the microcontroller. From the deflection measured by the triangulation sensor, the microcontroller calculates the difference

(“error”) between the reference and the actual (“output”) deflection, and adjusts the electric current through the SMA wires based on this error. The calculation of the appropriate output current is done by a control algorithm, which is stored as a program on the microcontroller. The advantage of this closed-loop control system, compared to a possible open-loop alternative (which would control the current based on a defined program, not based on the actual deflection) is its tolerance for ambient conditions, such as temperature, clamping angle, additional forces and production tolerances. Figure 4 shows the schematic set-up of the control loop. Note that the controller internally operates with digital inputs and outputs. The triangulation sensor’s measurement voltage is thus discretized (by an analog–digital converter) with a fixed gain of $K_{in} = 1024$ digits/5 V. From this digital input, the controller calculates a digital output value, which is then converted to a voltage by the driver, with a fixed output gain of $K_{out} = 5$ V/256 digits. The hardware implementation of the loop is shown in Figure 5.

For this closed-loop controller, a controller with proportional, integral and differential behavior (PID controller) is implemented. The controller’s digital output $u(t)$ is calculated from the error value at the present moment (proportional part), its integral and its derivative

$$u(t) = K_P \cdot e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \quad (1)$$

with $e(t)$ being the error value at the present moment and K_P , K_I and K_D the proportional, integral and derivative coefficients, respectively. This formula is discretized and implemented into the microcontroller software. The determination of the coefficients is discussed in the results and discussion section.

Figure 3. Measurement and control loop set-up schematic (a) and photograph (b).
SMA: shape memory alloy.

Figure 4. Control loop for adjusting the deformation.

Due to the limited maximum energy input (current limit of 2 A in this case), the integral part of the controller is set to remain below the current limit, in order to prevent wind-up effects.²⁷ This is also done for the lower limit of the integral part, which is set to zero, as back-bending is caused by cooling the SMA actuators in the composite body, and depends exclusively on ambient temperatures.

Results and discussion

Maximum deflection

For obtaining the maximum deflection, no control loop is required. The current is set to the maximum current (2 A for this experiment), which results in the fastest heating of the SMA wires. Figure 6 shows the deflection. The heating is started at $t = 100$ s. Ca. 300 s after the start of the heating, at $t = 400$ s, the maximum deflection of ca. 49 mm is reached.

Note that the measured deflections are taken at the triangulation sensor's reference point at $l = 210$ mm. The deflection at the bottom of the sample (at $l = 260$ mm) was measured as 90 mm or 35% relative to the sample's length, which is sufficiently high for complex surface modifications. Figure 7 shows the bending movement at different states.

Controller design and evaluation

The controller parameters have been empirically determined, as is common practice for unknown processes. For equation (1), $K_p = 1$ was set, as larger values of K_p would have resulted in increasing the noise of the triangulation sensor (clearly visible as oscillations of the red curve in Figure 6). Since input and output values of the controller are in digits, K_p is without units. The value of K_i is then increased, which results in a faster approach of the reference value, but also increasing overshoots after reaching it. At $K_i = 0.2$ digits/s, the overshoots have been found to be acceptable (<10% of the reference value) while a fast control movement was found. For the differential part, $K_d = 1$ digits*s resulted in a fast convergence on the reference value, while not increasing the noise too much.

To evaluate the resulting possibilities for a controlled deformation, the following test cases were investigated:

1. step from zero (relaxed state) to a defined deflection of 50 mm;
2. cycle of 10 repetitions from 20 to 30 mm;
3. step from 0 to 30 mm with additional load.

For the following experiments, the maximum current was decreased from 2 to 1.2 A. Since the maximum current was not investigated, a lower current was used to guarantee no heating damage is done to the composite.

Figure 8(a) shows the deflection response for a step from 0 to 50 mm. The red curve shows the reference deflection (input), which is changed from zero to 50 mm at $t = 0$ s, and back to zero at $t = 900$ s. It can be seen that the controlled composite reaches the target

Figure 5. Hardware implementation of the controller.
SMA: shape memory alloy.

Figure 6. Heating and cooling cycle ($I = 2\text{ A}$, no control loop). (Color online only.)

Figure 7. Active bending movement of the composite at 0 mm (a), 50 mm (b) and 90 mm (c) deflection at the bottom.

Figure 8. Controlled deflection step from 0 to 50 mm. First repetition (a) and set of 10 repetitions (b) (curves smoothed). (Color online only.)

Figure 9. Cycle of 10 repetitions from 20 to 30 mm (a) and detail (b).

deflection after ca. 600 s and remains steady after reaching it. As can be seen, the back-bending to 0 mm takes a very long time, since the cooling rate is dependent on the difference in the ambient temperature, which decreases. Therefore, for shorter cycle times it is advisable not to use the whole deformation range of the SMA wires, but to set the base deflection (“operating point”) so that it already requires heating above ambient temperature.

Figure 8(b) shows 10 consecutive repetitions of the controlled heating to 50 mm. It can be seen that the first and second repetitions (blue and green curves) warm up slightly slower, but cool off slightly faster than subsequent repetitions. This might be due to the composite matrix absorbing and storing some of the heat energy of the first repetitions. Nevertheless, the general shape of the curve is similar, and after the third cycle no differences between the curves is noticeable. A small unsteadiness can be seen at ca. $t = 100$ s ($s = 18$ mm), which needs to be further investigated. Note that the curves in Figure 8(b) have been slightly smoothed to generate more distinct curves.

Figure 9(a) shows the result for the second test case, a cycle of 10 repetitions from 20 to 30 mm. It can be seen that the specimen follows the targets smoothly. In Figure 9(b), detail of one of the cycles is given, which shows that the heating process (positive deflection) takes ca. 20 s and the cooling process ca. 15 s, making cycle times of ca. 35 s possible. It is clear that shifting between higher deflections (e.g. between 30 and 40 mm) will increase the time required for the positive deflection, and will decrease the time for negative deflection (due to the higher difference in ambient temperature and thus the faster cooling). Future work will aim at considerably decreasing this cycle time by adding more SMA wires and maximizing the heating current.

In order to evaluate the influence of external forces, a weight of 20 g was added at the very bottom of the sample and fixed with double-sided adhesive tape. This last test case is similar to what would occur under gravity, variations in composite stiffness (e.g. due to manufacturing variations in thickness) or a decrease in ambient temperature. Figure 10 compares the

Figure 10. Step from 0 to 30 mm, green curve with added weight (20 g). (Color online only.)

deflection movement for a step from 0 to 30 mm with and without added weight. It can be seen that the additional weight (blue curve) increases the time for the deflection, as the SMA wires have to be heated to a higher temperature to supply the required forces. However, contrary to what could have been expected, the back-bending of the composite under added weight is not faster than that without weight. These results will have to be investigated further.

Simple physical modeling

In order to prepare a modeling of the complex deformation behavior of the active composite, a simple physically justified estimation of the deflection behavior is desirable. In the theory of “two-layer flexure beams with external excitation”, one active component beam applies a bending moment to another, passive, beam.²⁸ This model can be readily applied to the SMA-actuated elastomer composite with textile reinforcement, if the following assumptions are made.

- The SMA wires are effectively attached to the surface of the textile–elastomer composite.
- Due to the temperature-induced elongation of the SMA, a bending moment is caused, leading to the deflection of the composite.
- This bending moment bends the two-layer arrangement of silicone rubber (elastomer) and SMA.
- The textile structure is located in the neutral axis (center) of the composite. Therefore, it does not contribute to the geometrical moment of inertia.
- For the “active beam” representing the SMA wires, an effective thickness h_2 can be calculated by

assuming that instead of the six SMA wires, there is a closed SMA layer covering the elastomer: $h_2 = \pi \cdot d_2^2 / b_1$.

For this set-up, the curvature $d\varphi/dx$ (φ bending angle, x distance from clamping) can be derived as²⁸

$$\frac{d\varphi}{dx} = \frac{6 \cdot \varepsilon_2}{h_1} \cdot \frac{\frac{E_2}{E_1} \cdot \frac{h_2}{h_1} \cdot \frac{h_1 + h_2}{h_1}}{1 + \left(\frac{E_2}{E_1}\right)^2 \left(\frac{h_2}{h_1}\right)^4 + \frac{E_2}{E_1} \frac{h_2}{h_1} \left[4 + 6 \frac{h_2}{h_1} + 4 \left(\frac{h_2}{h_1}\right)^2\right]} \quad (2)$$

Here, symbols with index “1” refer to the matrix and symbols with index “2” refer to the SMA (cf. Table 1). ε_2 is the maximum SMA elongation after phase transition, E_1 and E_2 are the Young’s moduli, and h_1 and h_2 are the thicknesses of the silicone rubber matrix and the SMA, respectively. The deflection $s(l)$ at position l (measured from the clamping) can be derived by double integration with respect to x

$$s(l) = \frac{6 \cdot \varepsilon_2}{h_1} \cdot \frac{l^2}{2} \cdot \frac{\frac{E_2}{E_1} \cdot \frac{h_2}{h_1} \cdot \frac{h_1 + h_2}{h_1}}{1 + \left(\frac{E_2}{E_1}\right)^2 \left(\frac{h_2}{h_1}\right)^4 + \frac{E_2}{E_1} \frac{h_2}{h_1} \left[4 + 6 \frac{h_2}{h_1} + 4 \left(\frac{h_2}{h_1}\right)^2\right]} \quad (3)$$

With the material parameters and geometry data from Table 1, the parameter ratios in equation (4) yield

$$\frac{E_2}{E_1} = 5,6 \cdot 10^2 \text{ and } \frac{h_2}{h_1} = 4,6 \cdot 10^{-4}$$

Thus, with $\left|\frac{h_2}{h_1}\right| \ll 1$, equation (4) simplifies to

$$s(l) \approx \frac{3 \cdot E_2 l^2}{h_1} \cdot \frac{\frac{E_2}{E_1} \frac{h_2}{h_1}}{1 + 4 \frac{E_2}{E_1} \cdot \frac{h_2}{h_1}} \quad (4)$$

The maximum deflection at the position of the triangulation sensor can finally be calculated as

$$s(l = 210 \text{ mm}) = 67 \text{ mm}$$

This result is in some agreement with the measured deflection of 50 mm. In future work, a more detailed Finite element analysis modeling will have to take into account the actual physical set-up (SMA wires with covering sheath) and pay attention to the conditions on the SMA–sheath–matrix interfaces. Formula (4) nevertheless can be useful for a quick estimate of the influence of the different mechanical and design parameters on the deflection result.

Conclusion and outlook

In this study, SMA wires were integrated into a glass fiber weave. A highly flexible silicone rubber elastomeric matrix was used for impregnation. By connecting the SMA wires to an electrical current, high degrees of deformation (up to 35%) could be achieved for the composite. To actively control the deflection, a controller loop was set up, consisting of a triangulation sensor, a microcontroller and a motor driver to switch the input current. It could be shown that a controller design with a PID controller leads to good results for different test cases. For a more precise and robust adjustment of the deformation state, a more complex closed-loop controlled system would be desirable, which would take into account effects such as the hysteresis behavior of the SMA wires (different force generation for heating and cooling) and the complex interactions between the components. A simple estimation of the deflection based on beam theory allows the identification of the influences of the material parameters on the deflection result.

In future work, the external deflection measurement (i.e. the triangulation sensor) could be replaced by a suitable, textile-integrated sensor. This sensor should detect the current deformation of the textile reinforcement and feed it directly to the controller. “Smart” sensor-actuator-coupled systems like this could then be used as very robust, error-tolerant shapeable surfaces in a variety of technical applications.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Parts of this work were carried out in the IGF research project 18808 BR of the Forschungsvereinigung “Forschungskuratorium Textil e. V.”, which is funded through the AiF within the program for supporting the “Industriellen Gemeinschaftsforschung (IGF)” from funds of the Federal Ministry of Economics and Energy (BMWi) by a resolution of the German Bundestag. Financial support is gratefully acknowledged.

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