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Smart soft composite actuator with shape retention capability using embedded fusible alloy structures

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ABSTRACT

This work presents a new kind of shape memory alloy (SMA) based composite actuators that can retain its shape in multiple configurations without continuous energy consumption by changing locally between a high-stiffness and a low-stiffness state. This was accomplished by embedding fusible alloy (FA) material, Ni–chrome (Ni–Cr) wires and SMA wires in a smart soft composite (SSC) structure. The soft morphing capability of SMA-based SSC structures allows the actuator to produce a smooth continuous deformation. The stiffness variation of the actuator was accomplished by melting the embedded FA structures using Ni–Cr wires embedded in the FA structure. First, the design and manufacturing method of the actuator are described. Then, the stiffness of the structure in the low and high-stiffness states of the actuator were measured for different applied currents and heating durations of the FA structure and results show that the highest stiffness of the actuator is more than eight times that of its lowest stiffness. The different shape retention capability of the actuator were tested using actuators with one or two segments and these were compared with a numerical model.

1. Introduction

Certain biological muscular systems such as the trunk of the elephant and the arm of the octopus are able to locally switch between a low-stiffness state when interacting with the external environment and a high-stiffness state when manipulating objects. This principle has been an inspiration for new biomimetic structures capable of changing their stiffness locally or globally, deforming under internal or external forces and retaining their deformed shape such that they can withstand external loads and stimuli. These materials and structures capable of modulating their stiffness have become an integral element of various applications ranging from medical science to mechanical engineering. Structures with variable stiffness were used in tools to conduct colonoscopies to improve the reliability and avoid tissue damage [1,2]. Light-weight morphing structures with variable stiffness were used in an adaptive building skin capable of modifying energy flows, reducing noise and preventing fires [3]. Structures capable of changing their stiffness under actuation can be applied to shape reconfigurable structures such as morphing wings for micro air vehicles [4,5]. Furthermore, soft robots have become a popular field of research [6] and their capabilities could be enhanced by implementing sub-structures that could change between being soft and hard-bodied based on the different tasks they need to accomplish. This kind of structure has been implemented by varying the temperature of materials with low melting temperatures such as thermoplastics [7] and fusible alloys [8] embedded in a rigid or soft matrix. However, the structures presented in these studies are not capable of deforming themselves into complex user-defined shapes.

Mechanical structures comprised of components such as motors, linkages and gears can be used to create structure capable of retaining specific shapes, but their use increases the system's complexity and they are not capable of producing complex and continuous deformations. Pneumatic soft actuators can generate complex deformations and retain their deformed configuration by controlling the internal air pressure of the deforming structure. However, because they require an air compressor and air valves, it is difficult for these actuators to be built into an independent system at small scales [9,10]. Adaptive composite structures with multi-stable configurations can be used as morphing structures with good shape retention capabilities and can withstand adequate loads, but they possess limited deformation capabilities and can

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only retain specific combinations of shapes [11,12]. EAP actuators are an attractive option for robotic applications [13,14], but the relatively small actuation force, short lifetime, high response times or high driving electric fields of these EAP materials limits their applications and there is no research on EAP actuators with shape retention. Shape memory polymers (SMPs) with a thermo-temporal shape memory cycle can be deformed at high temperatures and then fixed upon cooling to retain a bent or twisted shape [15]. However, SMPs have a longer response time and produce smaller actuation stresses in comparison with shape memory alloys (SMAs) [16]. Although SMA elements have a small working strain, soft composite actuators with embedded SMA elements were developed that are capable of large, continuous and complex deformations. Smart soft composite (SSC) actuators consisting of a low-stiffness matrix with embedded SMA elements [17]. Following research has developed SSC actuators with bending, twisting and bending-twisting motions [18–20]. However, since SMA elements need to maintain a certain temperature to remain in the deformed shape, this type of structure needs constant energy input to maintain the desired deformation. Because of this and the low energy efficiency, long-term actuation of SMA elements is not a viable option due to the high energy requirements [21]. An SMA-based woven-type composite structure has been studied in Ref. [22] which is capable of retaining its deformed shape after bending, but this structure was capable of a limited deformation and the loading capability of the structure was not tested.

In this research, an SMA-based SSC actuator with shape retention capability is presented. The transformation from a high-stiffness structure to a low-stiffness one was accomplished by melting the embedded fusible alloy (FA) structures using Nichrome (Ni–Cr) wires. Afterwards, SMA wires are used to achieve a large continuous deformation of the structure and maintain the shape of the structure while the FA structures solidifies. Then, current input to the SMA wires can be stopped and the structure can maintain its shape without requiring constant energy input. First, the fabrication method of the actuator is described, then the flexural stress of the actuator is tested for different operating conditions. Afterwards, the shape retention capability of the actuator was tested for an actuator with a single segment and for an actuator with two segments. Finally, a model is proposed to predict the shape of the actuator's final retained configurations and is compared with the obtained results.

2. Materials and methods

2.1. Materials

The material used for the matrix of the actuator is Polydimethylsiloxane (PDMS, Dow Corning Sylgard 184). This material was selected due to its high flexibility, low thermal conductivity and high thermal stability [23]. Its main properties are listed in Table 1. The SMA wires are Flexinol wires (55 wt% Ni, 45 wt% Ti, Dynalloy, US) and their properties are listed in Table 2 [24]. There are many materials with low melting points including thermoplastics, such as polycaprolactone (PCL), and fusible alloys (FA), such as Field's metal, Lipowitz's alloy or Wood's metal. In this work, the FA Field's metal (RotoMetals, Inc) with a melting point of 62 °C was selected. This FA is an eutectic alloy of bismuth, indium, and tin (32.5 wt% Bi, 51 wt% In, 16.5 wt% Sn) and was selected due to its high thermal conductivity, low viscosity in the melted state, high-stiffness in the solid state, its non-toxicity, its melting point falls within the temperature range of the PDMS matrix and is lower than the SMA Austenite starting temperature. In order to melt the FA structure, Joule heating of a Ni–Cr (80 wt% Ni, 20 wt% Cr) wire is used [25]. The Ni–Cr wire has a diameter of 0.15 mm and is covered with a polyimide (PI) tube (D. Soar Green, China), which has a good thermal conductivity and are electrically non-conductive, to prevent the current from going through the fusible alloy. The dimensions and relevant material properties of the PI tubes are listed in Table 3.

2.2. Design and fabrication

The proposed actuator has a rectangular shape where two SMA wires, referred to as SMA-1 and SMA-2, are embedded in the PDMS matrix along the Y axis close to the upper and lower surfaces, as shown in Fig. 1. Two symmetrical FA structures are placed in parallel to the SMA wires in the middle of the matrix. The relative position of all the components is shown in the schematic of cross-section A–A of the actuator in Fig. 1.

The actuation process to change from one fixed shape to another is shown in Fig. 2 with the actuation sequence for the Ni–Cr wires and the SMA wires shown in Fig. 2a. During this process, the embedded FA structures are melted by applying current to the Ni–Cr wires from time t_0 until time t_1. Then, the current to the Ni–Cr wires is switched off and actuating either SMA-1 or SMA-2 from time t_1 to time t_2 will result in either an upward or downward bending deformation depending on which SMA wire is actuated. Then, current continues to be applied to the actuated SMA wire until time t_3 to allow the melted FA structures to solidify again. Fig. 2b to e shows the state of the actuator from time t_0 to time t_3.

The SMA wires were clamped with connectors to connect with the conductive wire and to prevent relative sliding between the SMA wires and the matrix [26]. The FA structure was built by

Table 2
Material properties of SMA (flexinol).

Parameter	Value
Martensitic Young's modulus	$E_{Mar} = 28$ GPa
Austenitic Young's modulus	$E_{Aus} = 75$ GPa
Martensitic start temperature	$M_s = 52$ °C
Martensitic finish temperature	$M_f = 42$ °C
Austenite start temperature	$A_s = 68$ °C
Austenite finish temperature	$A_f = 78$ °C
Wire diameter	0.152 mm
Resistance per meter	55 Ω
Initial strain	$\varepsilon_0 = 5\%$

Table 1
Main properties of PDMS (sylgard 184).

Parameter	Value
Temperature range	−45 to 200 °C
Specific gravity	1.03 @ 25 °C
Heat cure	12 h @ 50 °C
PDMS Young modulus	$E_{PDMS} = 1.8$ MPa @ 25 °C
Thermal conductivity	0.27 W/m K
Volume resistivity	2.9×10^{14} Ω-cm

Table 3
Material properties of PI tube (D. soar green).

Parameter	Value
Inner diameter	0.18 mm
Thickness	0.015 mm
Density	1.41×10^3 kg/m^3
Temperature limit	380 °C
Dielectric strength	>1.18×10^{10} kV/m
Heat conductivity coefficient	35.0×10^{-5} °C/cm