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Shape change/memory actuators based on shape memory materials†

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Abstract

Major techniques currently available to implement typical shape memory materials (such as shape memory alloys and polymers) for three basic types of shape switching actuations--one-time shape memory actuation, cyclic shape memory actuation and cyclic shape change actuation--were explored in detail. Typical actuators corresponding to these three types of actuations are systematically discussed. Possible combination of different types of shape memory materials/shape change materials and/or different stimuli for actuators with novel functions, which are not easily achievable, in particular at small scale, using conventional approaches, is presented to reveal the great potential of shape memory material based actuators in engineering applications. We provide a road map to guide engineers in the process of evaluation and selection of the right type of mechanism to meet the requirement(s) of a particular application.

Keywords: Shape memory material; Shape memory actuator; Shape change actuator; Mechanism

1. Introduction

Instead of utilizing various traditional mechanical mechanisms, we are able to use a range of different types of actuators to drive mechanical motion for path generation, motion generation and/or function generation. In addition to traditional driving mechanisms for activating these actuators, many smart materials, such as piezo-electrical material, electro-active material and shape memory material, have been used to simplify the mechanism for actuation. In general, all these smart materials can be classified under two categories: Shape memory material (SMM) and Shape change material (SCM). Both are featured by their capability of shape switching in response to the applied right stimulus [1]. Typical stimuli include heating/cooling (thermo-responsive), light (photo-responsive), chemical (chemo-responsive) and electrical/magnetic field (electro/magneto-responsive), etc. [2-6]. The main difference between SMM and SCM is that a piece of free-standing SMM is able to maintain the temporary shape without the requirement of the right stimulus to be applied continuously, while a piece of SCM needs the presence of the right stimulus or otherwise, applying a locking mechanism, to keep the temporary shape.

Whether a particular material belongs to SMM or SCM depends on the energy barrier between the permanent shape and temporary shape [7]. A high energy barrier effectively prevents the material returning to its permanent shape, so that additional driving force (stimulus) is required to overcome the energy barrier for shape recovery. Hence, this material is SMM and this shape recovery phenomenon is technically called the Shape memory effect (SME). However, if the energy barrier is low or almost none, the material is able to gradually or instantly recover its original shape without the help of additional stimulus. Therefore, this material is the SCM and the corresponding shape switching phenomenon is known as the Shape change effect (SCE).

As pointed out in Ref. [8], depending on the exact working conditions and the applied stimulus, a material may be SMM or SCM. For instance, at low temperatures, a heating-responsive Shape memory alloy (SMA) is able to return its original shape only when it is heated, and thus it shows the heating-responsive SME; while at high temperatures, it responds super-elastically to mechanical loading and hence, it has the mechano-responsive SCE. Another typical example is hydrogel. According to Ref. [4], at a lower water content (or in a lower moisture environment), a hydrogel has both the moisture-responsive SME and heating-responsive SME; while at a higher water content (or in a high moisture environment for a long period of time), it becomes rubber-like in response to mechanical loading. Piezo-electrical and electro-active materials are mostly applied in engineering applications as an electro-responsive SCM. On the other hand, typical SMMs include SMA, Shape memory polymer (SMP) (including shape memory gel, SMG), Shape memory ceramic (SMC) and Shape memory hybrid (SMH) [1, 3, 7].

Corresponding to two different types of materials, namely

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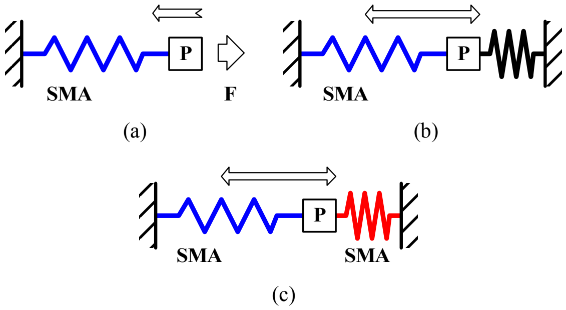


Fig. 1. Three basic types of SMA based actuators: (a) One-way actuator [one-time shape memory actuation]; (b) biased actuator [cyclic (reversible) shape change actuation]; (c) two-way actuator [cyclic shape memory actuation]. (Reproduced from Ref. [9] with permission from Elsevier).

SCM and SMM, naturally there are two types of actuators: Shape change actuator (SCAc) and Shape memory actuator (SMAc). Both types are useful for different types of engineering applications. Since energy is only required during switching from one shape to the other in SMAcs, this important feature apparently results in significant energy saving in actuators for long-term operation.

Due to the shape switching feature, both the SME (the feature of SMM) and SCE (the feature of SCM) can be implemented to drive actuators. We only focused on SMM, in particular SMA and SMP, activated SCAcs and SMAcs.

The purpose of this paper is to briefly summarize the state-of-the-art techniques to implement typical SMMs (such as shape memory alloy and shape memory polymer) in both SCAc and SMAc, which may significantly widen the application area of novel actuators.

Sec. 2 presents the basic working mechanisms for three different categories of actuations: One-time shape memory actuation, cyclic shape change actuation and cyclic shape memory actuation. Sec. 3 shows some typical implementations of these mechanisms in typical actuators, including possible combination of different SMMs/SCMs and/or different stimuli for more useful features. Main conclusions are summarized in Sec. 4.

2. Basic working mechanisms for SCAc and SMAc

2.1 Traditional working mechanisms

According to, for instance Ref. [9], there are three basic types of SMA based actuators: One-way actuator, biased actuator and two-way actuator (Fig. 1).

In Fig. 1(a), a piece of pre-stretched SMA spring is able to return to its original length only when heated to above its transition temperature (i.e., austenite finish temperature, A_f). To repeat this process, re-stretching the SMA spring, a process technically known as programming within the SMM community, is required. This type of actuation may be more precisely renamed as one-time shape memory actuation. Essentially, such actuators are one-time SMAc.

In Fig. 1(b), a piece of pre-stretched SMA spring is connected to a piece of ordinary elastic spring. When the SMA spring is heated, it contracts and thus stretches the elastic spring to become longer. Upon cooling, the SMA spring gradually becomes soft and therefore the elastic spring shrinks and, consequently, pulls the SMA spring to become longer. After a couple of cycles, the relationship of the motion of *P* against the temperature of SMA spring becomes stable and fully repeatable upon further thermal cycling. Note that heat is required to keep the high temperature temporary position, which could be a problem in terms of energy saving. Herein, this type of actuation is called the cyclic (reversible) shape change actuation**.** Therefore**,** the corresponding actuators are cyclic SCAc.

In Fig. 1(c), two SMA springs are connected together. At least one of them has been pre-stretched. If we alternatively heat one of the SMA springs, the heated one shrinks, while the cold one is stretched. Here, we have two stable positions at low temperatures and no heat is required to maintain these two stable positions at all. This type of actuation is termed cyclic shape memory actuation. Thus, the corresponding actuators are cyclic SMAc.

In Fig. 1(b), a constant force may be applied to replace the elastic spring. Depending on the required number of cycles, NiTi SMA may carry up to 400 MPa of load with a reversible strain of about 7 % [9]. For SMPs, up to 50 % reversible strain has been reported in a high density polyethylene under an externally applied constant load of 1 MPa [10]. However, if the applied constant force is too small, this mechanism is essentially similar to the case of Fig. 1(a), so that re-programming is required before the next round of operation.

Instead of having an elastic spring or applying a constant force for cyclic shape change actuation as shown in Fig. 1(b), an internal stress field may be introduced into the material itself via different ways of thermomechanical training to achieve the same kind of cyclic actuation but without the requirement of external spring/loading. Such a mechanism for cyclic shape change actuation has been extensively investigated in SMAs for decades [11], but only reported in some semi-crystalline SMPs in recent years [12]. These SMAs with a built-in internal stress field have been traditionally known as material two-way SMA in the past, while original SMAs without training, referred to as one-way SMA, can always be integrated with an external elastic spring/load to generate cyclic actuation (i.e., mechanical two-way effect) as revealed in Fig. 1(b).

According to the Ref. [11], SMAs that are based on internal stress field for cyclic shape change, actuation is more applicable in sensor applications, since they are not able to provide either high actuation force/stress or high displacement/strain (2 % strain or less in NiTi based SMAs). Furthermore, the internal stress field tends to shift under cyclic operation unless the external load/stress is very small [11]. As for SMPs, in order to implement this mechanism, in addition to introducing an internal stress field into the polymer during the process to fix its permanent shape (e.g., via dual-time curing), the transi-

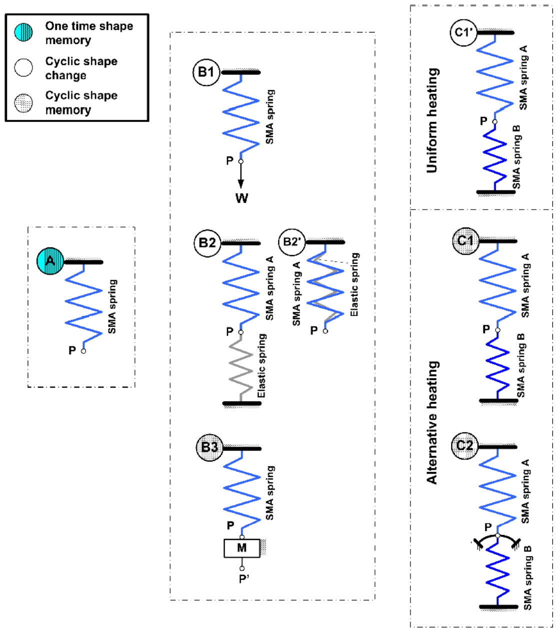


Fig. 2. Extended family of working mechanisms for different types of actuations.

tion used for cyclic actuation must be melting/crystallization [13], unless a special physical phenomenon, such as significant volume expansion in the embedded transition component [1, 3], is utilized. Furthermore, it is essential to generate enough crystallization induced internal stress upon cooling in the polymer. Such SMPs have only been reported in recent years, and so far most of the reported applications are based on free-standing configuration of a polymer without much significant output (actuation) force [13, 14]. According to the previous experience with SMAs, it is reasonable to say that mechanical two-way actuation should be more applicable for SMP actuators as well for cyclic operation in real engineering applications.

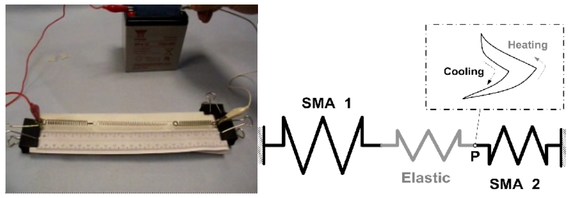
Above-mentioned three types of working mechanisms are well-known at present. They are basic design concepts and have been implemented in many engineering applications in the past.

2.2 Extended family of working mechanisms

With the recent development in SMMs and shape memory technology, some new working mechanisms for both shape memory actuation and shape change actuation have emerged. We may still take heating-responsive one-way SMA as an example SMM and sketch the extended family of working mechanisms for different actuations in Fig. 2.

2.2.1 One-time shape memory actuation

As shown in Fig. 2(a) (i.e., one-way actuator in Fig. 1(a) is meant for one-time shape memory actuation. Re-programming to re-setup the temporary shape is always required before the next round of operation.



(a) (b)

Fig. 3. A system with two SMA springs and one elastic spring (a); illustration (b). Inset in (b): Sketch of the trajectory of the motion at *P* (horizontal axis) against electrical current (vertical axis) in a full thermal cycle. The electrical current (from left to right) passes through all springs as shown in (a).

With a carefully designed programming process, both SMPs and some SMAs can have the multiple-SME [15, 16]. Consequently, upon heating for shape recovery, there is at least one stable intermediate shape, before the permanent shape is finally reached.

2.2.2 Cyclic shape change actuation

The configurations of (B1), (B2)/(B2') and (C1') in Fig. 2 are meant for cyclic shape change actuation. In (B1), a constant force (W) is always applied to automatically re-setup the low temperature shape so that the motion of *P* can be predicted with good accuracy. Whereas, in (B2) and (B2'), an externally or internally integrated elastic spring is used to provide a variable force, and thus, simulation should be relatively more complicated.

In comparison with (B1), (B2) and (B2'), in which there is only one SMA component, in (C1'), two pieces of SMA springs are connected in series. These two springs may have different transition temperatures or different geometrical configuration, and at least one of them has been pre-stretched. For convenience here, we may assume both of them have been stretched. Therefore, upon passing an electrical current through both of them, the SMA spring, which is joule heated to reach its transition temperature first, will contract first. Hence, the other spring is stretched accordingly. Upon further joule heating, the other spring reaches its transition temperature and starts to contract. Therefore, based on the properties of the two SMA springs and their geometrical configurations, *P* can be designed to have monotonic but sophisticated nonlinear motion against the applied electrical current. More sophisticated motion, e.g., forward-backward-forward motion upon continuous joule heating or cooling, can be produced if more component(s) (either elastic spring or SMA spring) are integrated into the system. Refer to Fig. 3 for an example of a system including two SMA springs with one elastic spring in-between.

2.2.3 Cyclic shape memory actuation

In (B3) of Fig. 2, a pre-compressed SMA spring is connected to a special mechanical mechanism *M*. *P'* is part of *M*. When the SMA spring is heated once, *M* is pushed, and thus, *P'* moves down. Upon heating the SMA spring again, *P'*

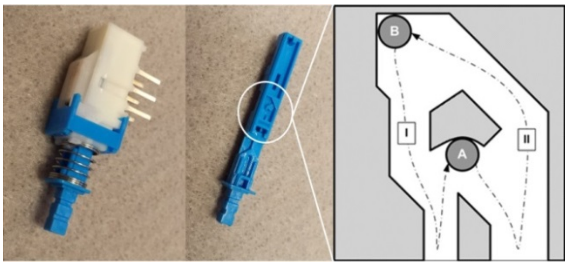


Fig. 4. A typical self-lock switch (left) and details of the mechanism (middle and right).

moves up. Mechanical mechanisms with such feature have been used in mechanical pencils and self-lock switches.

Fig. 4 illustrates the internal structure of a typical mechanism used in self-lock switches, in which the moving part has only two stable positions (namely *A* and *B* as marked). When being pushed, it jumps from one position to the other following either path (I) or path (II). Although the apparent advantage is highly reliable, because the size of the whole system is mainly limited by the actual size of the self-lock mechanism, it is not easy to miniaturize the whole system to a very small size.

In (C1) (same as Fig. 1(c)), there are two SMA springs. Upon heating one of them, *P* moves toward that spring. This is a simple and traditional approach, but it lacks the precision to fix the exact locations. To get rid of this problem, in (C2), an arch, which is essentially a bi-stable structure [17], is integrated into the system, to ensure both stable positions can be precisely fixed.

3. Typical implementations in actuators

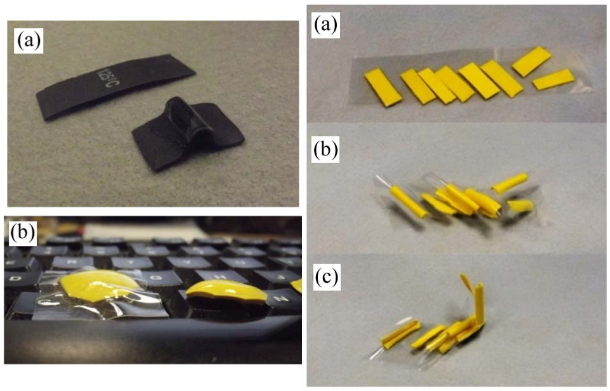
Among above-mentioned working mechanisms, we can select the most suitable one according to the requirement(s) of a particular application. Subsequently, an actuator, either SCAc or SMAc, can be designed properly with the optimized performance.

For simplification, unless otherwise stated, we limit our discussion to using only one-way SMM for activation. Furthermore, we consider the term “actuation” in a more general sense to include a wide range of motion/function generation beyond conventional mechanical actuators.

3.1 One-time SMAcs

In many engineering applications, the required actuation is only for one-time. Typical examples of such applications include active assembly, active disassembly, self-fitting and self-tightening suture/staple [7, 18].

Although seemingly the term “SME” was first coined for a particular SMA in 1930s, polymers with such a feature have been well-known far before this term was *invented*, even well before any artificial SMPs were developed. For instance, silk naturally has the heat-/water-responsive SME, as do human hair and nails. Recent investigation reveals that most polymers, including many engineering polymers and biopolymers (e.g., protein), are intrinsically heat-/chemo-responsive SMP.



(I) (II)

Fig. 5. Heat assisted self-assembly using heat-shrink polymer. (I) Pre-stretched in one direction (a) (bending); two directions (b) (dome). (II) Origami (folding to form a 3D structure), (a) original shape; (b) after slight heating; (c) after further heating (placed upside down).

Heat-shrink tube is one of the early applications of man-made polymes based on the heat-responsive SME, and it is still widely used today. In Fig. 5(Ia) (top-left piece), a small piece of Ether-vinyl acetate copolymer (EVA) based SMP is cut from a large sized heat shrink tube. Upon heating to 125 ^{o}C, it shrinks remarkably in one direction, but the size in the other direction remains unchanged. If a piece of printing transparency (its softening temperature is well above 200 ^{o}C) is pre-coated on its top using, for instance, superglue, upon heating the substrate shrinks while the top transparency does not. Consequently, after heating, the piece coated with printing transparency atop becomes curved (Fig. 5(Ia), bottom-right piece). In Fig. 5(Ib), the polymer is pre-stretched in two directions and then coated with printing transparency atop. Hence, after heating, a dome is formed. By means of coating a piece of printing transparency at some prescribed locations with patches of 1-D pre-stretched heat shrink polymer (as shown in Fig. 5(IIa)), upon heating, self-assembly to form a 3-D structure is achieved (Figs. 5(IIb) and (IIc)).

Above application only utilizes the original concept of the SME, i.e., the dual-SME, in which only two shapes of an SMM, namely, the permanent shape and temporary shape, are involved. Recent research progress on the fundamentals of various types of SMMs has effectively widened the shape memory phenomenon in many ways. The temperature memory effect and multiple SME are two examples, among others [15, 16, 19, 20].

Based on the finding of the relationship between pre-strain and transition temperature for shape recovery in SMAs [21], we can achieve step-by-step shape recovery in a pre-determined manner. In Fig. 6(a), a piece of straight NiTi SMA ribbon is bent at two locations to two different curvatures. In the subsequent gradual and uniform heating process (Figs. 6(b)-(f)), the bottom part, which is less bent, recovers first at lower temperatures, while the top part, which is bent more,

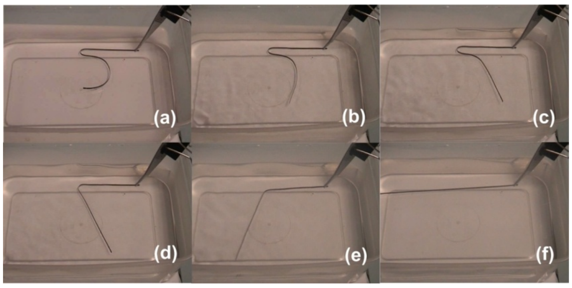


Fig. 6. Sequence of shape recovery upon heating after local bending to introduce a gradient transition temperature field (Reproduced from Ref. [3] with permission from Elsevier).

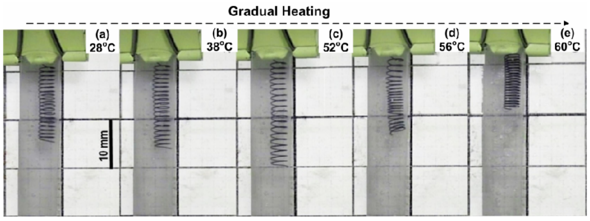


Fig. 7. Shape changing in an NiTi coil upon gradual heating from 28 ºC to 60 ºC.

only recovers at higher temperatures. In Fig. 6(f), the ribbon fully returns not only its original shape, but also all its properties, and it is ready for re-programming again for next cycle of the SME.

Instead of pre-bending at different locations to introduce a pre-strain field which results in a gradient transition temperature field within a piece of SMA as shown in Fig. 6, it is possible to pre-deform a piece of SMA uniformly to achieve step-by-step shape recovery in a uniform manner [16]. As shown in Fig. 7, in a monotonic and uniform heating process, a piece of pre-programmed NiTi SMA spring expands continuously at first and then shrinks back upon further heating. This kind of phenomenon is known as the triple-SME, since there is an additional temporary shape (intermediate shape), which is also stable, in the whole shape recovery process. The material may be re-programmed in the same way or a different way in the next round of SME cycle again and again, since the material always recovers not only its original shape, but also its properties after each full SME cycle. However, as reported in Ref. [16], in addition to the requirement of a special programming method, there are certain conditions on the material itself in order to realize the triple-SME in SMAs.

While the triple-SME presented in Fig. 7 is only applicable to certain SMAs, which satisfy some special conditions, and the programming methods are special, almost all SMPs can be programmed in an easy way to have at least one intermediate shape during shape recovery [15, 16, 19, 20, 22].

Poor thermal conductivity in most polymeric materials is likely to produce a gradient temperature field upon *immersing* into a gas or liquid medium of a constant high temperature. Therefore, in addition to step-by-step heating or gradual heating, a programmed SMP is able to achieve triple-SME upon

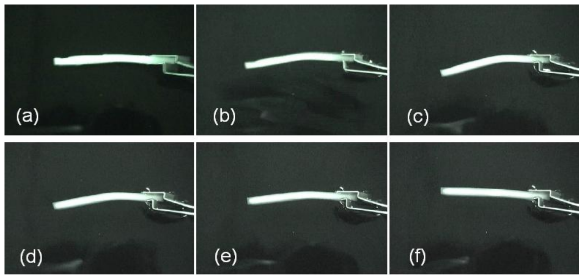
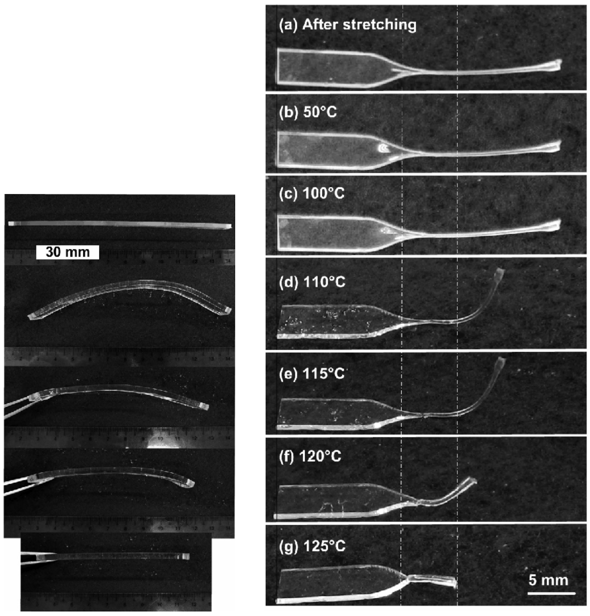


Fig. 8. Bending downward and then upward in a piece of originally flat SMP upon immersing in hot water of a constant temperature (Reproduced from Ref. [1] with permission from Elsevier).



(I) (II)

Fig. 9. Instability induced triple SME in pre-stretched PMMA upon heating in 120 ºC silicone oil (I) (reproduced from Ref. [24] with permission from AIP Publication); gradual heating (II).

immersion in a constant high temperature medium as shown in Fig. 8. Here, the piece of SMP is originally flat and is programmed (bending) in two steps at two different temperatures. The temperature of the second time bending (curve-up to make the sample flat) is lower than that in the first time bending (curve-down).

Instead of programming a few times at different temperatures, instability during shape recovery may be utilized to achieve the triple-SME, although the intermediate shape may not be precisely controlled [23]. In Fig. 9, two pieces of Poly(methyl methacrylate) (PMMA) are pre-stretched, but subsequently, one piece (Fig. 9(I)) is immersed into 120 ^{o}C silicone oil, while the other piece (Fig. 9(II)) is gradually and uniformly heated. Buckling occurs in both of them before full recovery is finally observed.

All above-mentioned cases are based on the heating-responsive SME. The other type of thermo-responsive SME is to apply cooling, instead of heating. So far the cooling-

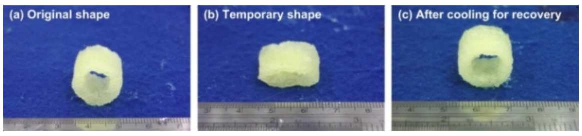


Fig. 10. Cooling-responsive SME in a P407 based SMH (Reproduced from Ref. [7] with permission from Elsevier).

responsive SME has only been reported in few limited materials [8]. While $Co_2Cr(Ga,Si)$ ferromagnetic Heusler alloys and silicone/tin hybrids might be used in some low temperature applications [3], the most applicable cooling-responsive SMM for around-room temperature applications should be poloxamer 407 (P407) based polymeric Shape memory hybrid (SMH) [25]. According to Refs. [1, 3], SMH is defined as an SMM with two components, in which as an individual, either of them has the SME within the given working conditions.

In Fig. 10, a piece of tube-shaped SMH is made of P407 and an elastic sponge. The temporary shape of the SMH can be fixed at above the body temperature when P407 becomes relatively hard hydrogel. Upon cooling to 10 ^{o}C, P407 melts, so that the elastic sponge recovers its original shape. Since P407 is biocompatible, it is a good potential candidate for biomedical applications to avoid possible over-heating in the activation process of heating-responsive SMMs.

Hydrogels are characterized by significant swelling upon wetting in water. The SME has been realized in some specially synthesized wet hydrogels (e.g., Ref. [26]). On the other hand, as reported in Refs. [4, 27], depending on the exact water content, a piece of relatively dry hydrogel can be either SMM or SCM. Regardless of the exact amount of swelling, wetting in water or other chemicals for shape recovery may be utilized for chemo-induced rapid actuation via buckling [23, 24].

In Fig. 11(a), a polymeric composite wire is pre-stretched to 600 % at high temperatures when it is soft. The wire is made of Poly(lactic-co-glycolic acid) (PLGA) thin wire with a layer of Polyethylene glycol (PEG) coated on its surface. Both polymers are biodegradable and have been approved by the Food and Drug Agency (FDA), USA for medical applications. Upon dipping the right part of the wire into room temperature water (about 22 ^{o}C), water-induced SME occurs within this part of PEG. However, the PLGA and non-wetted inner part of PEG within this part prevent the wire from shrinking. Upon reaching a critical point (after about 60 seconds of immersion in this particular case), the wire starts to lose its stability and buckles into a tangled shape (Fig. 11(b1)) [23]. Upon keeping the wire in air for a while, the tangled part gradually becomes straight, but the inner core of PLGA maintains waved (Figs. 11(b2) and (b3)). Utilizing the buckling phenomenon, we can not only significantly reduce the actuation time, but also control the actual time of buckling to fully block blood vessels in, for instance, liver cancer treatment. After PEG and PLGA are dissolved in blood, the vessel is able to re-open in a few weeks of time.

If we embed an array of inclusions close to the top surface

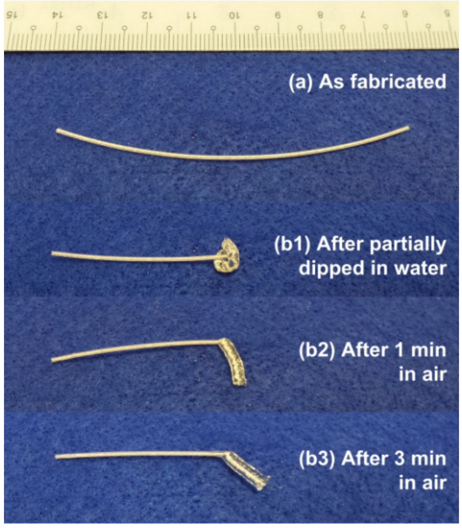


Fig. 11. Room temperature water induced buckling in a PEG/PLGA biodegradable plug. The unit of the ruler at the top is in mm (Reproduced from Ref. [29]).

of a soft/elastic matrix (Fig. 12), depending on the actual material used for the inclusions, an array of protrusions may be formed in different ways. If the inclusions are made of a hard material, so that they may be considered as rigid body, upon compression in the horizontal direction of the elastic matrix [28], an array of protrusions, which are located between the inclusions, may result (Fig. 12(I)). If the inclusions are made of a relatively softer material, which is elastic and non-compressible, upon compression protrusions are formed right above the inclusions (Fig. 12(II)). In both cases, the protrusions disappear if the compression force is removed. To maintain the array of protrusions, we may use phase/state change material for the inclusions. As illustrated in (Fig. 12(IIIa)), upon heating, the inclusions become soft. Subsequent compressing results in the formation of an array of protrusions (Fig. 12(IIIb)), which is the same as in (Fig. 12(II)). However, after cooling, the inclusions become hard and keep the deformed shape (Fig. 12(IIIc)), even after the compression force is removed (Fig. 12(IIId)). The protrusions can be fully removed upon heating to soften the inclusions again (Fig. 12(IIIe)). The phase/state change material used for the inclusions may or may not have the SME. The actual performance of this system can be simulated by finite element analysis. An example is presented in Fig. 13, in which the matrix is silicone and the inclusion is wax.

3.2 Cyclic SCAcs

In Fig. 14, artificial NiTi SMA wire can be joule heated to become straight. When the applied electrical current is removed, if the stiffness of the SMA wire after cooling back to room temperature is not enough to support the self-weight of the SMA wire, it bends down. Such motion is fully repeatable when the applied current is applied in an on/off manner for

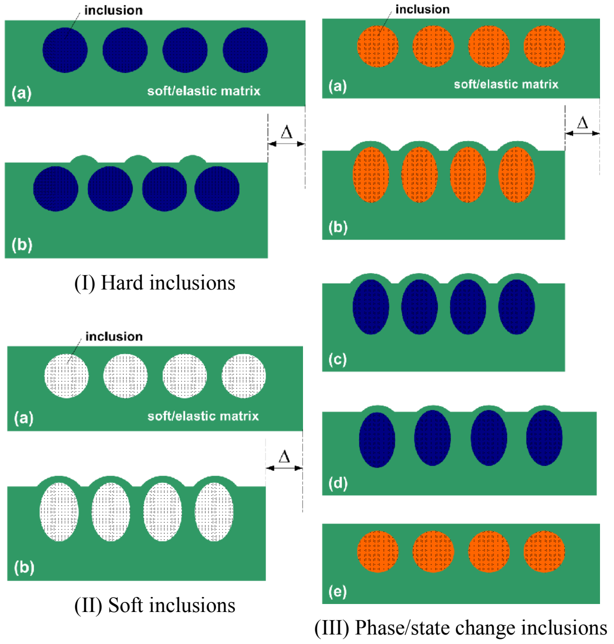


Fig. 12. Formation of an array of protrusion using (I) hard inclusions; (II) soft inclusions; (III) phase/state change inclusions.

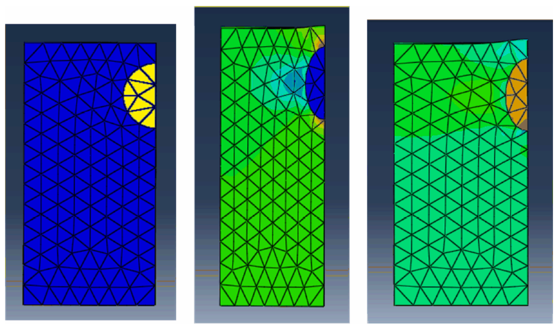


Fig. 13. Finite element simulation (using ANSYS): (Left) Original shape; (middle) after compression at high temperatures; (right) after cooling and then removal of the compression force.

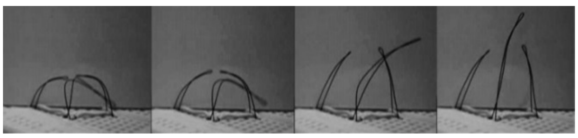


Fig. 14. Artificial wig using 0.1 mm diameter NiTi SMA wire. From left to right: Upon joule heating.

cyclic actuation.

Instead of utilizing self-weight, in Fig. 15, NiTi SMA wire of 0.2 mm in diameter is embedded in an elastic silicone beam. The SMA wire is pre-stretched, so that upon joule heating, it shrinks, which results in bending-up of the silicone beam. When the applied electrical current is removed, the beam bends back to the original flat shape. Stable motion can be obtained after a few actuation cycles.

Due to the nature of the martensitic transformation, SMAs are stiffer at higher temperatures (austenite phase) and weaker

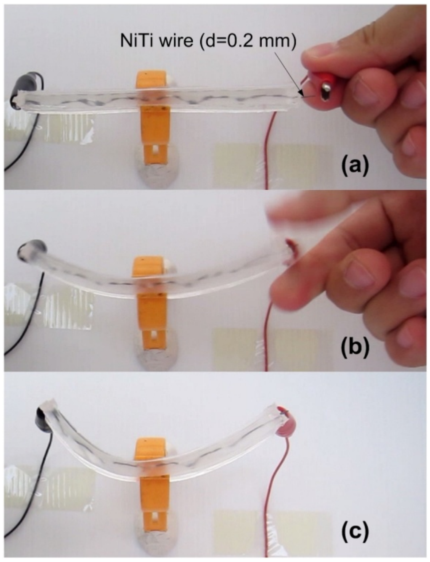


Fig. 15. Bending of silicone beam via joule heating of embedded SMA wire.

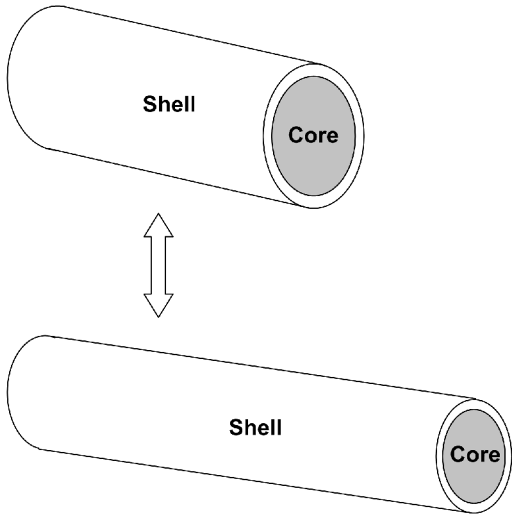


Fig. 16. Polymeric core/shell actuator for reversible motion (extension/contraction) upon thermal cycling.

at lower temperatures (martensite phase). As a result, higher actuation force is produced by the SMAs when they are heated. Although SMPs are normally softer at high temperatures and harder at low temperatures, which is opposite to that in SMAs, some semi-crystalline polymers (e.g., Ref. [30]) are able to generate reversible motion against a variable or constant force upon thermal cycling as that in SMAs as well.

Fig. 16 shows a polymeric core-shell structure, in which for the core and the shell, one of them is made of a semi-crystalline polymer with the reversible SME, while the other is made of an elastic material, which essentially functions as an elastic spring. Following the right process to fabricate the core-shell structure (refer to, e.g., Ref. [31]), reversible extension/contraction upon thermal cycling can be produced. Other types of motions, e.g., bending and torsion, can be generated

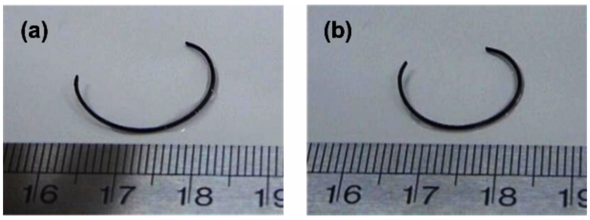


Fig. 17. Material two-way SME in NiTi SMA wire: (a) At room temperature; (b) upon heating (Reproduced from Ref. [3] with permission from Elsevier).

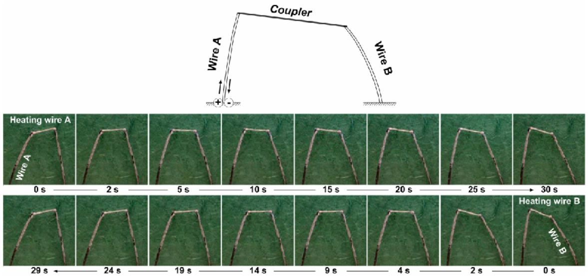


Fig. 18. SMA *Four-bar* linkage (Reproduced from Ref. [3] with permission from Elsevier).

accordingly in a similar way.

As mentioned, the external spring (or a kind of) may be introduced into a SMM itself, so that material two-way SME, instead of mechanical two-way SME, can be realized. In Fig. 17, a piece of NiTi SMA is heat-treated twice at the same high temperature (but a shorter time period in the second heat treatment) for two different shapes. Consequently, an internal elastic stress field is produced inside of the material. Thus, upon thermal cycling, the piece of SMA is able to switch between two shapes. The reversible motion becomes highly stable after a few thermal cycles [32].

While a number of thermomechanical methods to train a piece of SMA to work out a built-in internal elastic stress field have been well documented in the Ref. [33], approaches to introduce an internal stress field into some semi-crystalline SMPs to have the material two-way SME only emerged in 2013 [12, 14]. Since then several two-step curing methods have been demonstrated to produce built-in internal stress field for reversible motion generation in some semi-crystalline polymers upon thermal cycling [34].

According to the previous experience in SMAs, the mechanical two-way SME is more applicable for actuators, while the material two-way SME is mostly for sensor-type of applications, in which the required actuation force is very small, if not zero.

3.3 Cyclic SMAcs

Different from cyclic SCAcs, cyclic SMAcs are highly efficient for energy saving in operation, since energy is only required during shape switching.

As shown in Fig. 18, upon alternative joule heating on either the right side of SMA wire or the left side of SMA wire, the coupler is able to move correspondingly. Such a system is not meant to replace standard four-bar linkages for motion generation with high precision, but it is useful for some applications in which there are only two positions required.

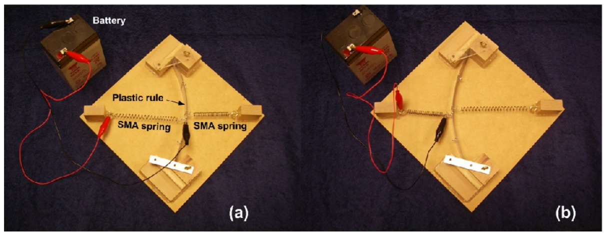


Fig. 19. Bi-stable arch (a piece of plastic rule) activated by alternate joule heating two SMA springs: (a) After the right-side spring is heated; (b) left-side spring is heated (Reproduced from Ref. [3] with permission from Elsevier).

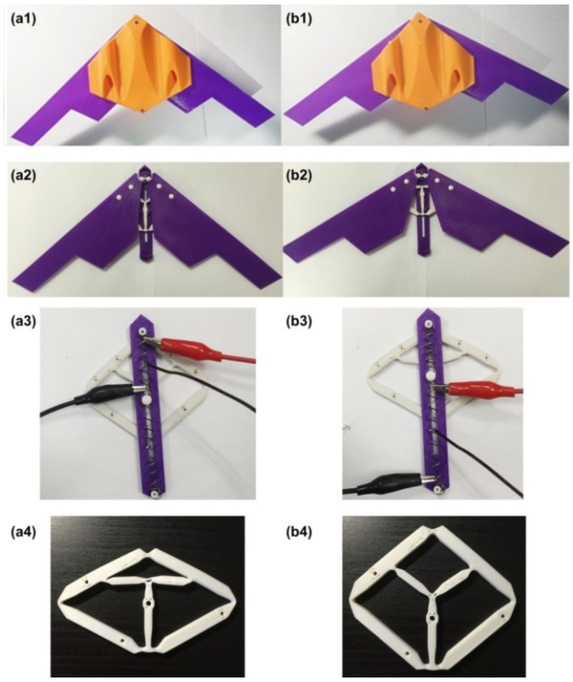


Fig. 20. SMA activated unmanned aviation vehicle (3D printed model): (a) and (b) are for two morphing wing positions. (1) With cover; (2) without cover and SMA; (3) joule heating for activation; (4) the bi-stable structure.

To ensure high precision in the two required positions, a bi-stable structure based on either a simple arch as shown in Fig. 19 or a bi-stable compliant structure [17] as shown in Fig. 20, may be used. Therefore, shape switching between two precise positions can be activated via joule heating of the corresponding SMA spring.

A combination of different SMMs/SCMs and/or stimuli has great potential to provide great flexibility for enhanced performance. Three examples are illustrated here.

3.3.1 Photo-responsive SCP (or SMP)/heat-responsive SMP

A photo-responsive SCP refers to a polymer which has the

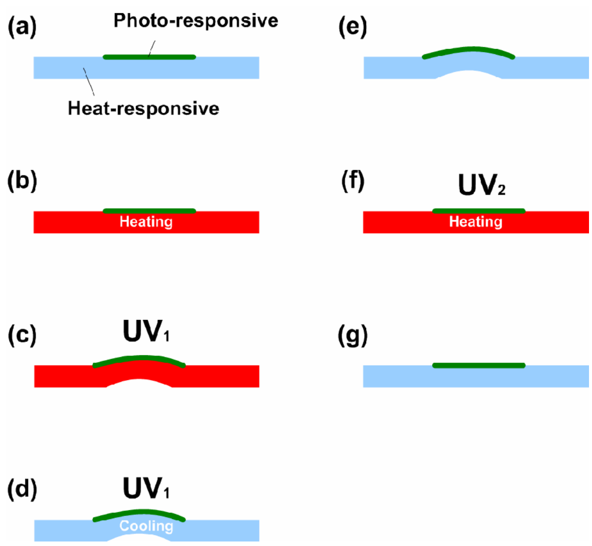


Fig. 21. Photo-responsive polymer/heat-responsive SMP composite.

capability of shape switching in response to the applied stimulus of a particular wavelength of light [35]. Conventional definition of photo-responsive SMP refers to the shape recovery phenomenon in a polymer at the presence of light [36]. In recent years, photo-responsive SMP activated by different wavelengths of light for forward and backward shape switching has been reported [37]. In the present discussion, the photo-responsive SMP is meant for the latter, i.e., applying different wavelengths of light for forward and backward shape switching.

Although most of the reported stimuli for both photo-responsive SCPs and photo-responsive SMPs are ultraviolet [38], which is not so convenient and safe to use, activation by red-light has been achieved recently [39].

As shown in Fig. 21(a), a patch of photo-responsive SCP or SMP is deposited atop a heat-responsive substrate. Upon heating, the substrate becomes soft (Fig. 21(b)), so that after applying ultraviolet of wavelength 1 (UV_1) on the photo-responsive layer, local bending as illustrated in Fig. 21(c) results. After cooling to room temperature, the substrate becomes hard, while the bending remains (Fig. 21(d)). Subsequent removal of UV_1 does not cause much significant shape change (Fig. 21(e)). The substrate becomes flat only if it is heated again for shape recovery, and even requiring the presence of another wavelength of ultraviolet (UV_2) for full shape recovery in the photo-responsive SMP (Fig. 21(f)). After that, the substrate returns back to room temperature and is ready for another cycle (Fig. 21(g)).

3.3.2 Electro-active polymer/heat-responsive SMP

Essentially, at present most Electro-active polymers (EAPs) are electro-responsive SCP, i.e., able to respond in terms of shape change (mostly in the form of expansion or contraction) to the applied electrical voltage in a reversible manner [40]. There are two basic types of EAPs (including polymeric gels): Ionic EAP and electronic EAP [41]. While the required voltage for activation of electronic EAP is at a level of 100 V/µm, a few voltages is enough to trigger significant reversible strain in ionic EAP [42].

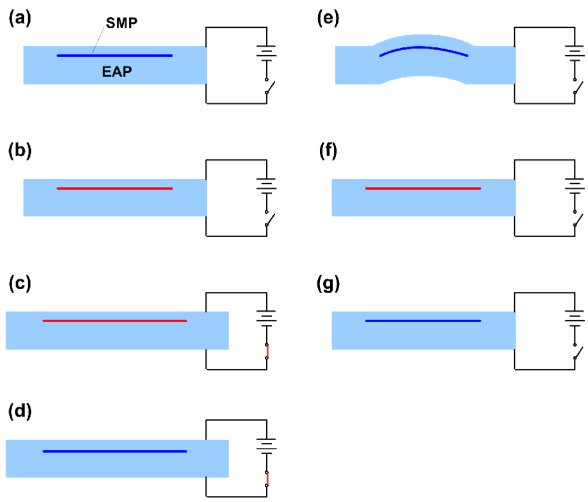


Fig. 22. EAP/heat-responsive SMP composite.

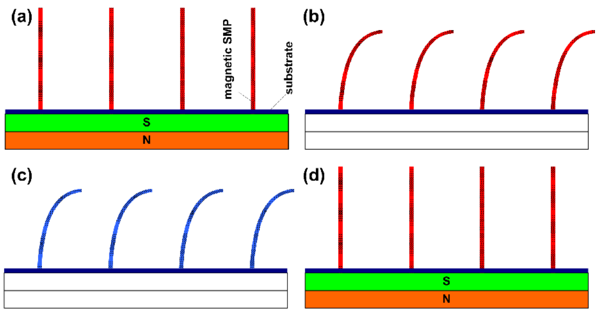


Fig. 23. Heat-responsive magnetic SMP composite.

In Fig. 22(a), a piece of heat-responsive SMP is embedded inside a piece of EAP. In the first step, the SMP is heated for softening (Fig. 22(b)), and then an electrical voltage is applied to stretch the whole piece of composite (Fig. 22(c)). After cooling back to room temperature, the stretched SMP becomes hard to deform (Fig. 22(d)), so that when the applied electrical voltage is removed, bending occurs in the composite (Fig. 22(e)). The curved shape remains unless the embedded SMP is heated for shape recovery (Fig. 22(f)). Subsequently cooling back to room temperature, the SMP is hard again and the whole composite is ready for another cycle (Fig. 22(g)).

3.3.3 Heat-responsive magnetic SMP composite

Different from that of magnetic SMAs [43], magneto-responsive SMPs reported in the literature so far (e.g., Ref. [44]) are actually activated by means of indirect heating, in which inductive heat is generated by the applied alternate magnetic field [45].

A heat-responsive SMP composite with embedded magnetic inclusions may be used for cyclic SMAcs. As shown in Fig. 23, an array of vertical magnetic SMP strings is produced on the top of a substrate. At high temperatures when the SMP is soft, a magnetic field is generated in the substrate to hold the array of SMP string straight (Fig. 23(a)). If the SMP strings are long enough, due to self-weight they tend to bend if the magnetic field is removed (Fig. 23(b)). The deformed shape is maintained after the strings are cooled to room temperature (Fig. 23(c)). Heating SMP strings to high temperatures again and with the help of the magnetic field, the strings become vertical again (Fig. 23(d)).

4. Conclusions

We have summarized the major state-of-the-art techniques to implement typical SMMs for three types of actuations: One-time shape memory actuation, cyclic shape memory actuation and cyclic shape change actuation. Typical actuators corresponding to these three actuations, one-time SMAc, cyclic SMAc and cyclic SCAc, are presented. Possible combination of different SMMs/ SCMs and/or different stimuli for more functions is discussed.

With the recent development in many new techniques, we are able to remarkably expand the family of the working mechanisms for different types of actuations, which correspondingly results in simple but high performance novel actuators, which are difficult to realize, in particular at small scale, using conventional approaches.

This paper may serve as a road map to guide engineers in the process of evaluation and selection of the right type of mechanism to meet the requirement(s) of a particular application.

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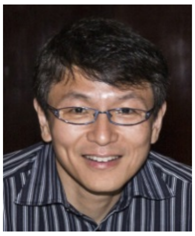

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