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Shape memory alloy properties, modelling aspects and potential applications - a review

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Abstract. Shape Memory Alloys (SMAs) are an interesting class of materials for researchers over the past few decades. With the advancement in material science and technology, more importance is given to active materials whose properties can be tailored according to the needs, enabling the development of engineered materials that are strong, lighter in weight, and occupy less volume. The shape memory alloys stand apart from the other metals in terms of the recoverable strain it can undergo upon excitation by a thermal stimulus. Due to this unique nature the SMAs possess dual functionality, wherein it poses both as a sensor as well as an actuator, and hence finds its applications in diverse fields. The current paper will give a brief introduction to the SMA and its key effects, review and discuss the different types of SMAs, their material characteristics, behavior, advantages, modeling aspects that will aid in the practical implementation of the SMAs and potential applications.

1. Introduction to SMA

SMA also popularly known as memory alloy or smart alloy is a unique class of material capable of remembering a pre-programmed shape when excited by a thermal stimulus and interests the researchers for the past few decades [1], [2], [3]. The SMA has two key properties: Shape Memory Effect (SME)and Super Elasticity (SE) [4]. The SME is due to temperature-induced phase transformation and SE is due to stress-induced phase transformation of the SMA [5],[6]. The SMAs undergo a phase transformation from martensite state (cold temperature state) to austenite state (hot temperature state) and vice versa [7] when subjected to a cycle of heating and cooling undergoing a cycle of recoverable %strain in the process associated with a good amount of force, which can be used to do some work. There are two types of SMA viz. one-way SMA (OWSMA) that remembers only hot temperature shapes and two-way SMA(TWSMA) that remembers both hot and cold temperature shapes [8]. Figure 1a shows the SMA wire at room temperature that undergoes a strain or displacement when heated as shown in figure 1b and stays at the same length when cooled as shown in figure 1c. The SMA needs a bias force to reset it back to the original form once the thermal excitation is removed by either using a spring or dead weight so that it is ready for the next cycle of operation as shown in figure 2.

2. SMA Material properties

SMAs broadly fall under the categories of Niti based alloys, iron-based alloys, copper-based alloys, and magnetic SMAs (MSMA) [9]. Nickel-Manganese-Gallium is one example of MSMA.

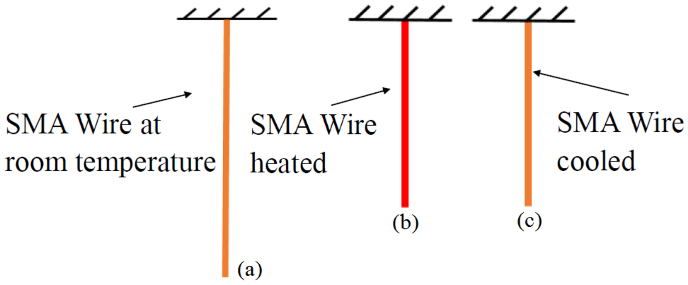

Figure 1. SMA wire without bias force

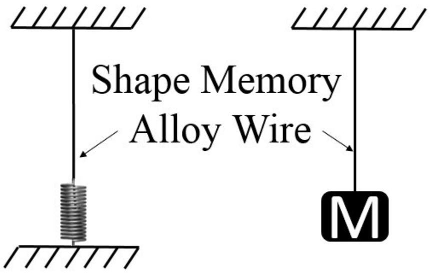

Figure 2. SMA wire with bias force

Few examples of popular commercially available SMAs are copper-aluminum-nickel Iron-Manganese-Silicon, Copper-Zinc-Aluminium, and nickel-titanium (NiTi) among which NiTi is most popular due to better reproducible thermomechanical characteristics, greater mechanical strength, a wider range of hysteresis and biocompatibility [8] [10].The material properties of few commercially available SMAs are compared in figure 3 [8], [11], [12]. Figure 4 illustrates the

		NiTi	CuZnAl	CuAlNi
Specific heat (J/Kg°C)		450–620	390–400	373–574
Thermal conductivity (20°C) (W/mK)		8.6–18	84–120	30–75
Density (Kg/m^3)		6400–6500	7540–8000	7100–7200
Latent heat (J/Kg)		19 000–32 000	7000–9000	7000–9000
Electrical resistivity (10^6 Ωm)		0.5–1.1	0.07–0.12	0.1–0.14
Thermal expansion coefficient (10^{-6}/K)		6.6–11	17	17
Maximum recovery stress (Mpa)		500–900	400–700	300–600
Normal working stress (Mpa)		100–130	40	70
Fatigue strength (N = 10^6) (Mpa)		350	270	350
Maximum transformation strain (%)	$N = 1$	6–8	4–6	5–6
	$N < 10^2$	6–8	4	4
	$N < 10^5$	2–4 (3)		
	$N < 10^7$	0.5		
Normal number of thermal cycles		$> 10^5$	$> 10^4$	$> 5 \times 10^3$
Young's Modulus (Gpa)		28–83	70–100	80–100
Shape memory transformation temperature (°C)		−200–200	−200–150	−200–200
Hysteresis (°C)		2–50	5–20	20–40
Maximum overheating temperature (°C)		400	150	300
Damping capacity (SDC%)		15–20	30–85	10–20
Grain size (μm)		1–100	50–150	25–100
Melting, casting and composition control		Difficult	Fair	Fair
Forming (rolling, extrusion)		Difficult	Easy	Difficult
Cold-working		Fair	Restricted	Very difficult
Machinability		Difficult	Very good	Good
Cost ratio		10–100	1–10	1.5–20

Figure 3. Properties of few commercially available SMAs compiled and adapted from [8], [11] and [12]

typical displacement versus temperature curve of the SMA when subjected to a complete cycle of heating and cooling, with austenite start A_s, austenite finish A_f, martensite start M_s and martensite finish M_f temperatures marked [10].

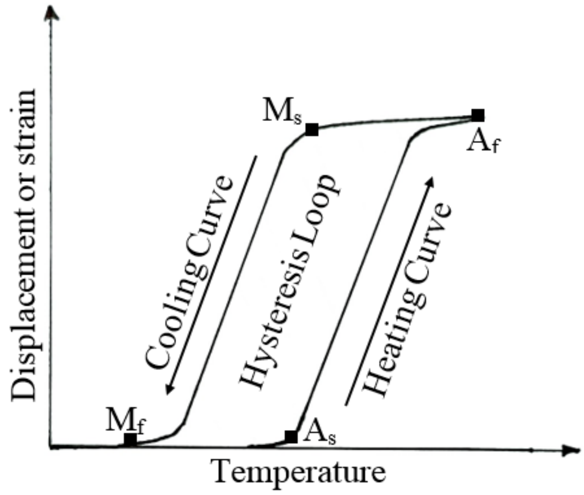

Figure 4. Typical strain versus temperature curve of SMAs.

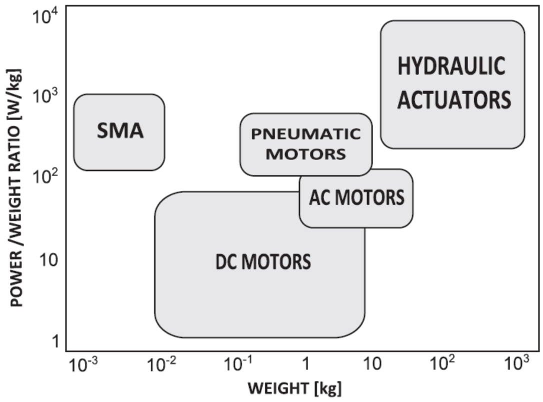

Figure 5. Power to weight ratio versus weight comparison of widely used actuators adapted from [13], [14] .

3. SMA as an actuator

The strain or displacement experienced by the SMA upon thermal excitation is associated with a good amount of force that can be utilized to do some work thus making SMA suitably used as an actuator. Both linear and rotary SMA based actuators have been reported in the literature. An SMA wire with one end fixed and the other end in series with a dead weight will pull the dead weight up against gravity when thermally excited, serving as a linear actuator. The SMA based rotary actuators can be further divided into limited and unlimited motion type actuator. Paper [15] discusses the design of linear actuators using the SMA. Paper [16] discusses a limited motion rotary type actuator with only to and fro motion. Paper [17] and [18] discuss about an unlimited rotary motion type actuator in both clockwise and anti-clockwise directions. A common practice in engineering to measure which unit or design is better is by calculating Power-to-weight ratio[13], [14]. The power to weight ratio comparison of the widely used actuators adapted from [13], [14] is shown in figure 5 and it can be concluded that the SMAs are a better alternative to conventional actuators for biomedical and robotic applications considering their high power to weight ratio with added advantages of being lightweight, silent, spark-free and clean operation. Also since the SMA responds to the thermal stimulus it can be used as a sensing element too enabling it to be a bifunctional active element [9].

4. Modelling aspects of the SMA

Modeling will help in developing one to one relation between the input and output thus helping in predicting the material response. The strain or displacement versus temperature curve of the SMA shown in figure 4 displays hysteresis which is non linear [19] in nature and has been widely studied in literature [19], [20], [21]. Figure 4 depicts that at a particular temperature the SMA has two strain values and a proper strain has to be chosen depending on whether the SMA is in the heating state or cooling state. The different ways in which the SMA has been tried to model has been discussed in papers [22], [23] and [24]. The paper [24] discusses the advantage and disadvantages of most widely and commonly used modeling approaches for the SMA. The various ways in which researchers have tried to model the SMA can be broadly categorized into two types [22]:
A. Macroscopic modeling
B. Microscopic modeling

4.1. Macroscopic modelling
If the intention is to study the behavior and understand the underlying physics of the material then one has to choose macroscopic modeling [22]. All the empirical, phenomenological models based on the assumption that the thermodynamic laws fulfilled as pre-requisite and free energy-based models that need a good amount of thermodynamic framework to fall under this category [22].The papers [25], [26], [27], [28] present phenomenology based modelling of the SMA. The papers [26], [27], [28] discuss about the minor loops of operation of the SMA within the major loop formed by the heating and cooling curve shown in figure 4. The papers [29], [30], [31] discuss the free energy-based modelling of the SMA. The two main types of hysteresis models for the SMA namely Preisach type models and Duhem-Madelung models also fall under the phenomenological models [22]. These models have the advantage of being relatively simple and help in analyzing the behavior of the SMA and may aid the engineer or designer to build a good SMA based application.

4.2. Microscopic modelling
If the intention is to study the lattice structure and how varying the composition of the materials will tweak the SMA characteristics then one has to choose microscopic modeling [22]. The papers [32], [33], [34], [35] present the microscopic modelling of the SMA.These models may be relatively challenging in terms of time consumed and mathematical computations involved in comparison with the macroscopic modeling techniques [22].

5. Applications of the SMA
The SMA finds its applications in diverse fields out of which few are discussed below.

5.1. Field of robotics
The SMAs can be used to develop mini-actuator [14] which can be used in the field of robotics. The study of various driving principles for microactuators is presented in the paper [36]. A millimeter-sized joint actuator using SMA used to move small joints in a robot is presented in [37]. The use of artificial muscles that is SMA as robotic actuators discussed in [38] can be used to design a prosthetic hand [39]. A new actuator of a joint mechanism using nitinol which is a type of SMA discussed in [40] may aid the development of microactuator or micro-robots [41].

5.2. Marine applications
A hydrostatic robot designed using the SMA which can maneuver itself in areas that cannot be accessed by the conventional devices inside the ocean is presented in [42] which aids in marine studies and research. The bearings for rotary elements in water clad environment and applications that require a material that is stably non-magnetic in nature, for example, non-magnetic hand tools, can be made using nitinol-60 which has high hardness, strength and is marine corrosion resistant [43].

5.3. Automotive domain applications
The SMA actuators have the advantage of being compact, lightweight, simple, noise-free and hence has potential application in the automotive domain for operations such as mirror closing and opening, locking mechanism, engine temperature control and micro-valves [44] where conventional electromagnetic actuators are used [45], [46]. The use of the SMA for antiglare rear-view mirrors is presented in [47].

5.4. Aerospace applications

SMA couplers have been used in F-14 fighter jets because of their unique material properties [48]. To improve the aerodynamic performance, shape morphing of the aircraft wing is used which can be done using SMA [49]. The adaptive wings for small aircraft that aid in better control of the flight can be implemented using the SMA [50]. Applications in space prefer low-shock release devices for avoiding damage to sensitive equipment and can be designed using the SMA since it provides jerk-free actuation [51].

The small spacecraft needs components like micro and mini separation nuts, mini rotary actuators, micro burn wire release, linear actuator, and redundant release mechanism that can be developed using the SMA [52].

5.5. Biomedical engineering

Nitinol is a type of SMA which is biocompatible and hence finds its applications in biomedical devices [53]. Nitinol can be tailored and manufactured to respond to human body temperature [54]. An overview of nitinol in the field of dentistry for example, nitinol based root canal files [55], endodontic insturments [56], is presented [57] , [58]. Stents are devices that are inserted into the body to expand and reinforce the inner walls of blood vessels to ease the blood flow. These stents are made of nitinol exploiting its shape memory behavior [59]. Few other biomedical applications out of the vast list include use of titanium-nickel for intervertebral fusion [60], staples and bone anchors [61], stents[62]. It is also used to manufacture eye glass frames because of its superelastic behaviour [63].

6. Conclusion

A brief introduction to the unique class of active material SMA is given which throws light on the basic characteristics, behavior, bias force, and type of excitation required by the SMA. The SMA material properties of the most commonly used SMAs are discussed which will help in the selection of the SMA which will opt for a particular project under consideration. The advantages of using the SMA as an actuator and the modeling aspects of the SMA are discussed. The potential areas where the SMA finds its application is presented. Though the SMA has its advantages it is slow in comparison to conventional actuators like dc motor since it is associated with its own time constant. There will also be energy lost to the atmosphere in terms of heat reducing its efficiency. Hence there will always have to be a tradeoff between the weight and volume occupied by the actuator and the speed of response to a stimulus.

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