Shape memory alloys:
Properties, demands and opportunities in engineering applications

PART I

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Abstract

Shape memory alloys (SMAs) are a subclass of shape memory materials (SMMs), which are materials that, in response to a specific impact like thermal, mechanical, or magnetic changes, can "memorize" or hold into their prior form. This review addresses the properties, demands, and application prospects of SMAs, and provides a synopsis of recent advancements, as well as a historical background. Due to their special and exceptional qualities, SMAs have attracted a lot of interest and attention recently in a wide range of commercial applications; basic and applied research investigations have supported this commercial development. In order to shed light on design, issues faced by SMA developers, this paper explains the characteristics of these materials that make them perfectly suited for variety of applications, addressing also the accompanying constraints. This paper offers a pertinent overview of current SMA research.

Keywords: History; metal materials; ceramics; polymers, composites.

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1. INTRODUCTION

A smart material is a material with one or more properties that are susceptible to change with the impact of an external force or stimulus making them interesting engineering materials. This change has to be either tangible or visible for the material to qualify for 'smart' status and can be induced by electrical, chemical, thermal, magnetic, or mechanical impact. A very wide range of different materials could be considered as smart, such are piezoelectric materials, shape-memory materials, chromato-active, and magnetorheological materials. The shape memory materials (SMM) also include very different types of materials, such as metal materials, ceramics (piezoceramics), polymers, and different types of composite materials, as presented in Figure 1 [1-5].

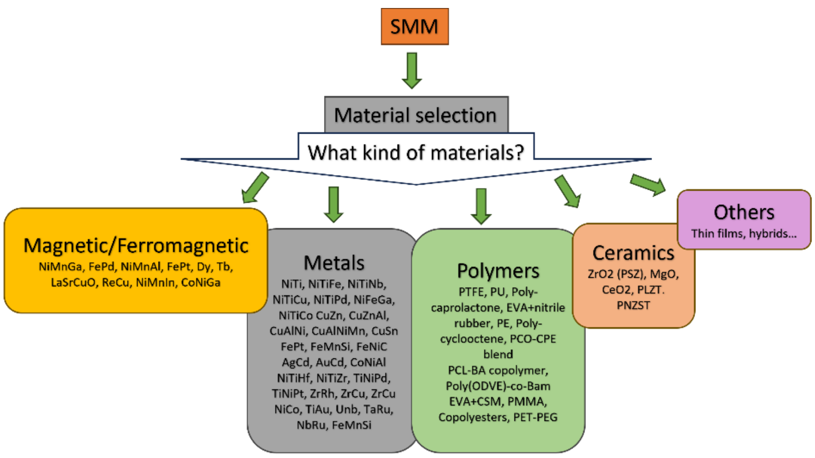

Figure 1. Materials selection for SMM materials

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Shape memory alloys (SMAs) possess special properties like superelasticity, thermomechanical properties, and a memory effect. Thermal and mechanical properties allow a smart material to return to its previous shape or size when it is subjected to significant plastic strain by heating or cooling [1-3]. The ability of a material to instantly return to its initial shape under nonlinear strain after stress or load is removed is known as superelasticity [1-4].

2. HISTORY OF SHAPE MEMORY ALLOYS

Gustav Arne Ölander, a Swedish scientist, discovered this type of alloys in the 1930s while working with a gold and cadmium alloy [1-2]. He discovered that the alloy could remember, or plastically deform, to its original dimensional structure when heated after cooling. Even though this provided advancements in the science of metallurgy, the shape memory effect was not as great as that of nitinol, a novel material that was found in the early 1960s [1-3].

The nitinol material is a mixture of titanium and nickel. US metallurgist William J. Buehler discovered the material's double-state, *i.e.* two distinct combinations of chemical energy within the solid. This observation occurred when he observed the difference in sounds when a cooled ingot was dropped on the floor landing with a dull thud as opposed to the metallic clang of a non-cooled one [1-5]. Superelasticity, the term used to characterize this capacity, is defined as an elastic or reversible response to an applied stress and it is sometimes compared to the stretching and releasing of a rubber band.

Subsequent research showed that nitinol could be bent and twisted indefinitely until the object lost all recognition of its original form. At this point, heat could be employed to accelerate a complete reversal to restore the original shape of the object. Before being employed in eyewear by a number of companies, including the sportswear major corporations, and then in dental and medical equipment, it took another twenty years or so of research to determine exactly how the shape memory effect occurred in nickel [1-5]. Discoveries related to SMA materials over decades are presented in Table 1 in order to point out how interesting, dynamic and how applicable SMA materials are.

Table 1. Some of the significant points in history of SMA development [5,6]

Year	Discovery	Author	Application
1932	Discovery of SMA Au Cd alloy	Gustav Arne Ölander	
1949	The basic phenomenon of the memory effect governed by the thermoelastic behavior of the martensite phase	Kurdjumov and Khandros	
1951	Thermoelastic transformation	Chang and Read	
1958	Nitinol discovery	William J. Buehler	
1962 to 1963	Nitinol development and commercialization	Naval Ordnance Laboratory	
1968	Satellite Nimbus shutter actuation system	H. Schuerch	Demonstrations
1970	SMA couplings for F-14 fighter jets	U.S. Navy	Airframe application
1982	Pipe couplings on Salyut-7	Gutskov *et al.*	Space devices
1988	Propulsion system on the Soviet shuttle Buran	USSR	Space devices
1989	Large space structure-cargo spacecraft Progress-40	Mir space station (MIR)	Space experiments
1991	Sofora experiment- Mir station	Cosmonauts A. Artsebarsky	Space experiments
1992	SMAAC shape memory alloy adjustable camber	Beauchamp	Airframe application
1994	Release devices Frangibolt	Spacecraft Clementine	Space devices
1996	Mars pathfinder-materials adherence experiment	Material adherence experiment	Space devices
1996 to 1998	The smart wing program	Defense Advanced Research Projects Agency (DARPA), The Air Force Research Laboratory (AFRL), National Aeronautics and Space Administration (NASA), Northrop Grumman Wing twist & flexible leading and trailing edges	Airframe application
1999	SMA release device (SMARD)-MightySat, LFSA-lightweight flexible solar array, Reversible hinge for deployment	AFRL, STS-93, Moignier	Space experiments
2000	SAMSON program, The smart aircraft and marine project system demonstration F15 fighter engine inlet, fan cowling, inlet lip shaping, Miniature mechanisms for small spacecraft, SMA release mechanisms, FalconSat spacecraft	Navy's Office of Naval Research (ONR), DARPA, NASA	Engine application Space devices

Year	Discovery	Author	Application
2001	Active jet engines chevron, Pitch active shape - memory alloy wing UAV, Helicopter rotor blades	Turner, Barrett, Prahlad	Engine application Airframe application Helicopter
2002	Variable Stiffness Spar - Modified F-16 wing increase in roll effectiveness	Nam	Airframe application
2003	Shape morphing airfoil, Solar paddle actuator for small satellites, Cosmic hot interstellar plasma spectrometer spacecraft	Elzey, Iwata-Japan, CHIPSat	Airframe application Demonstrations Space devices
2004	ROSETTA-pinpushers, SMA actuated satellite valve	Murray	Demonstrations
2005	Active tip clearance control, REIMEI-frangibolts	DeCastro, Japan	Engine application Space devices
2006	VGC - variable geometry chevron, STEREO-rel. Dev.	Boeing, UC Berceley	Engine application Space Devices
2007	THEMIS program, Mars Phoenix-pinpuller deployment	25 SMA actuators flying on THEMIS, TiNiAero	Space Devices
2008	VAFN variable area fan nozzle, RRB - Reconfigurable rotor blade, Antagonistic flexural actuating cell	Mabe, Ruggeri, Sofla	Engine application Helicopter Airframe application
2009	Adaptive wing demonstration system, LCROSS-pinpullers, SMA spacecraft tribo-elements	Lv, NASA Ames, DellaCorte	Airframe application Space devices Demonstrations
2010	Attitude control of nanosatellites	Iai *et al.*	Demonstrations
2011	DTE - Divergent trailing edge, Juno two-way actuation	Boeing, JPL/Lockheed	Airframe application Space devices
2012	ATE-adaptive trailing edge, SIMPLE-single crystal SMA Shape memory composite hybrid hinge, Deployable auxetic SMA cellular antenna	Boeing, Japan, JPL, Jacobs	Airframe application Space devices Demonstrations
2013	AFB-adaptive fan blade, Slat-cove filler, MAVEN-pinpullers	NASA-GE, NASA-LaRC NASA/UC berckley	Airframe application Space devices
2014	SMA Interference coupling	Crane	Demonstrations
2015	Slat-gap filler, ATE-SMART-VG, SMARS-rock splitter, Spring Tire	NASA-LaRC, Boeing-NASA-AFRL, Benafan, Padula et al.	Airframe application Demonstrations
2016	Spanwise adaptive wing, AlBus CubeSat	NASA-Boeing-Area-I, NASA GRC	Airframe application Demonstrations

3. SHAPE MEMORY EFFECT

When exposed to an external influence, a shape memory alloy exists in two distinct phases with varying crystal structures. The basic function of SMAs is to deform under applied force and then to return to the original shape by applying heat or a magnetic field. Four phase transition temperatures from low to high are possible for SMAs: martensite transition finish temperature Mf, martensitic transition start temperature Ms, reverse martensitic transition start temperature As, and reverse martensite phase transition finish temperature Af (Figure 2).

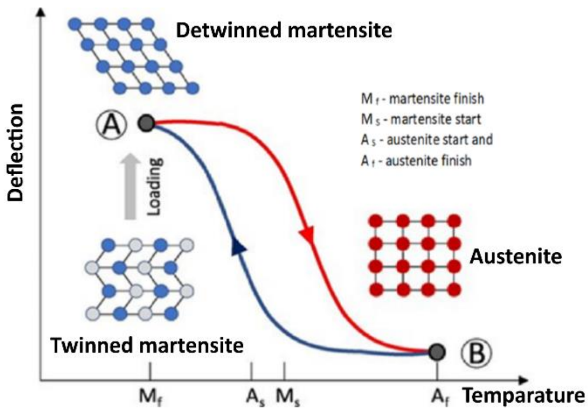

Figure 2. Schematic plot of SMA phase transformation: (A) maximum deflection at a 100 % martensite (detwinned) state, (B) maximum deflection at a full austenite state [2,6-9].

Shear lattice distortion is the method of transformation. The temperature of a SMA rises with heating, and beyond a certain point, the martensite structure starts to change into an austenite structure. The opposite process (*i.e.* austenite to martensite structure) occurs naturally when the alloy is cooled down without the help of an external force. Forward transformation is the term used to describe the phase transition from martensite to austenite, while for the opposite process (i.e. austenite into martensite) the term reverse transformation is used [2,6-9]. A schematic representation of this transformation with characteristic temperatures is shown in Figure 2.

4. PROPERTIES OF SHAPE MEMORY ALLOYS

There are several classes of shape memory alloys that are currently developed and [7-11], as follows.

- NiTi or nitinol is the most developed SMA, with excellent mechanical properties. It is pretty much the only commercially viable SMA [13].
- Cu-Al-Ni, Fe-Mn-Si, and Cu-Zn-Al systems have poorer mechanical properties than NiTi and are still in development, although they may one day offer advantages over NiTi such as higher transformation temperatures [14-17].
- Ni-Mn-Ga is a magnetic shape memory alloy, which is affected by magnetic fields rather than temperature. Magnetic shape memory alloys are also in the developmental stage [18].
- Other alloys also exist, which are even less commercially viable. Alloys with gold, silver, platinum, and palladium have made good SMAs in the laboratory, but they will probably never be worth the cost of the raw materials.

Mechanical and thermal properties of some of the mostly used SMAs are presented in Table 2.

Table 2. Properties of selected SMA alloys [10]

Property	Nitinol (Ni-Ti)	Cu-Zn-Al	Cu-Al-Ni
Melting temperature, °C	1300	950-1020	1000-1050
Density, g cm^{-3}	6.45	7.64	7.12
Resistivity, μΩ cm	70-100	8.5-9.7	11-13
Thermal conductivity, (W cm^{-1}) °C^{-1}	18	120	30-43
Young's modulus, GPa	83 (austenite) 26-48 (martensite)	72 (beta phase) 70 (martensite)	85 (beta phase) 80 (martensite)
Yield strength, MPa	195-690 (austenite) 70-140 (martensite)	350 (beta phase) 80 (martensite)	400 (beta phase) 130 (martensite)
Ultimate tensile strength, MPa	895	600	500-800
Maximum shape memory strain, %	8.5	4	4
Transformation range, °C	-200-110	<120	<200
Transformation hysteresis, °C	30-50	15-25	15-20

Advantages of shape memory alloys can be summarized as follows:

1. **Shape memory effect** as the most significant advantage of SMAs, which allows them to recover their original shape after deformation
2. **High energy density** so that SMAs can undergo large strains and stresses, making them useful for actuators and sensors
3. **High strength** makes SMAs useful in applications that require high load-bearing capacity
4. **High corrosion and wear resistance** making SMAs useful in harsh environments
5. **High power to weight ratio**
6. **Large deformation**
7. **Large actuation force**
8. **High damping capacity**
9. **High frequency response and low operation voltage**
10. **Compactness**

Still, SMAs have some disadvantages such as:

1. **High cost** of SMAs compared to other materials, which can limit their use in some applications
2. **Limited deformation range**, which can limit the use of SMAs in some applications
3. **Temperature sensitivity**: as the shape memory effect is temperature-dependent, this can limit the use of SMAs in applications that require high-temperature resistance
4. **Complex thermal and mechanical properties**

5. **Low energy efficiency**
6. **Poor fatigue properties**

Sometimes additional properties, or much frequently combination of properties is required for specific application, and these demands could include thermal shock conditions or cavitation erosion for monitoring the damage level and changes in morphological characteristics many investigations were performed in order to propose the approach and models of monitoring these changes and resulting effects on mechanical properties. These attempts are closely related to the estimation of the lifetime of investigated materials, as they are used for construction of many parts of equipment applied in engineering and influence the reliability of the parts or equipment [19-25].

5. APPLICATIONS OF SHAPE MEMORY ALLOYS

SMAs find applications in diverse fields out of which few are discussed below.

5. 1. Automotive domain applications

Because of the advantages over conventional electromagnetic actuators, such as compactness, lightweight, simplicity, and noiselessness, SMA actuators have potential applications in the automotive industry for tasks like engine temperature control, locking mechanisms, mirror opening and closing, and micro-valves [1,26]. In literature [29], the SMA application for antiglare rear-view mirrors is described.

5. 2. Aerospace applications

Due of special material qualities of SMA couplers, they were employed in F-14 fighter jets [30]. Shape morphing of the aircraft wing, which can be accomplished by an SMA, is utilized to increase aerodynamic performance [31]. The SMA can be used to install the adaptable wings for tiny aircrafts, which help with improved flying control [32]. Since SMAs offer jerk-free actuation, low-shock release devices are preferred in space applications to prevent damage to delicate equipment [11].

SMAs can be used to develop components for small spacecrafts such as micro- and mini-separation nuts, mini rotary actuators, micro burn wire release, linear actuators, and redundancy release mechanisms [11].

5. 3. Marine applications

A hydrostatic robot designed using an SMA, which can manoeuvre itself in areas that cannot be accessed by conventional devices in the ocean is presented in literature [11,33]. Bearings for rotary elements in water clad environment and in applications that require a material that is stable and non-magnetic in nature, for example, non-magnetic hand tools, can be made using nitinol-60 which exhibits high hardness, strength and is marine corrosion resistant [11,32-37].

5. 4. Field of robotics

Robotics can benefit from the development of miniactuators [37] made possible by SMAs. The work [38] presents the investigation of different driving concepts for microactuators. Application of a millimetre-sized joint actuator made of an SMA is applied for moving very low size joints in a robot [39]. A prosthetic hand can be designed using SMA artificial muscles that were previously addressed in [40] as robotic actuators [41]. Nitinol, could be used as a novel actuator for a joint mechanism that could assist the creation of microactuators or micro-robots [42,43].

5. 5. Field of mining

The Alliance for the Advancement of Additive Processing Technologies (ADAPT) at the Colorado School of Mines was part of an international research team that developed a new elastocaloric cooling material that is highly efficient, environmentally friendly, and easily scalable for commercial use [44].

Due to its characteristics, it can be applicable for difficult and complex conditions of various structural systems in the construction, mechanical and mining industries exposed to high stresses and temperature changes through the seismic response control system. It would be feasible to seismically monitor changes in ground deformation with sensor models of the SMA type. This will be made feasible by rheological changes in the mechanical rock material or on the surface of the terrain during the mining of mineral raw materials through boreholes. In addition to landslides on the final and working slopes of surface mines and landfills, as well as on geotechnical works of infrastructural, hydrotechnical, and other engineering facilities, the formation of excavated submerged caverns, exceptionally deep surface mines, and the construction of underground rooms for the needs of underground exploitation of mineral deposits or their stockpiling [45].

5. 6. Seismic monitoring systems

Seismic monitoring systems are widely used in mines with underground exploitation to monitor seismic changes caused by mining operations, especially those at great depths due to high loads or in neglected, so-called old pit operations. In addition, one could monitor ground tremors and seismic changes caused by extraordinary unfortunate circumstances in mines, caused by explosions of coal dust, methane, or due to mountain shocks, as well as earthquakes with known devastating effects on all objects. Also, application in the splitting of seismic waves is also possible due to drilling and blasting in all mining works and methods of excavation, tunnelling, and construction of the entire underground construction.

A possible system of seismic monitoring with SMA sensors of large vibrations and dynamic shocks on the working organs of mining and loading, disposal equipment and auxiliary machinery and transport systems in discontinuous and continuous exploitation, both surface and underground exploitation and in the mineral processing, should also be taken into account where we are dealing with large mechanical dimensions of machinery and huge capacities and volumes of overburden, interlayer tailings and useful raw materials [46,47].

5. 7. Fields of civil engineering and architecture

SMA materials also find their place in the field of building construction materials. For example, adaptive composite panels with surface-bonded shape memory alloy strips are used as building construction materials due to their excellent thermal and mechanical properties [48]. Some of the applications were related to the use of SMA materials for dampers, because for this purpose the material has to have a suitable structure with a very high resistance to external forces, as well as having the ability to self-repair after an applied external force [49,50]. Research and application of SMAs in the active management of structures gave rise to the smart concrete beam [50,51] and the SMA concrete beam, i.e. concrete beam with superelastic wire made of a shape memory alloy as the main reinforcement [50,51].

By using new design methods, such as 3D printing, new possibilities arise in the field of architecture accompanied with new materials and methods of construction. Several papers attempted to find design and construction methods, which will be reliable, but at the same time low cost and flexibly adaptive in building design. Some of the papers focused on using 3D-printed kinetic shading devices. This attempt is focused on a selective actuator by a switch between a geared DC motor and a thermomechanical shape memory alloy actuator [52].

5. 8. Textile industry

Using SMAs in textile industry was expected due to the unique properties and behaviour of these materials. Their use as part of a material for protective clothing was reported [53,54]. Also, some of the research attempts were related to the development of active textile systems with SMA elements for protection against the cold [55-57].

5. 9. Biomedical applications

SMA materials have found the irreplaceable place as biomedical materials due to their mechanical properties, anticorrosive behaviour, as well as biocompatibility of many alloys, which is crucial for biomedical implementations. A large number of investigations are related to using SMAs as biomedical material, which will be discussed in more detail in Part II of this paper. Some of the studies related to this wide group of materials were reported in many papers [3,5,58-62].

6. CONCLUSION

Smart materials draw attention as very interesting being utilized also as engineering materials. One of the mostly used class among smart materials are shape memory alloys. In this paper some of the relevant properties and behaviour of these materials are presented with the aim to understand possibilities for variety of applications.

Also, a wide range of fields utilizing SMAs, were discussed, including automotive, aerospace, marine, robotics, mining, civil engineering, and textile engineering.

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Legure sa svojstvom pamćenja: Osobine, zahtevi i mogućnosti u inženjerskoj primeni

Prvi deo

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Izvod
Legure sa svojstvom pamćenja (engl. shape memory alloys, SMA) su podgrupa velike familije „pametnih" materijala, koji predstavljaju materijale koji posle spoljašnjeg uticaja koji može biti termički, mehanički i/ili magnetni, imaju osobinu da „memorišu" ili zadrže prethodno stanje. U okviru ovog rada predmet interesovanja su svojstva, zahtevi za specifične primene, pregled skorašnjih istraživanja, kao i istorijski razvoj ove grupe materijala. Zahvaljujući svojim posebnim i izuzetnim svojstvima memorijske legure su u poslednje vreme privukle veliko interesovanje i pažnju u širokom spektru komercijalnih primena. Osnovna i primenjena istraživanja su podržala ova komercijalna interesovanja. Da bi se pojasnili izazovi sa kojima se suočavaju inženjeri koji se bave dizajnom ove grupe materijala, u okviru ovog rada su date karakteristike ovih legura koje ih čine veoma prikladnim za različite primene ali se rad istovremeno bavi i ograničenjima koja idu uz njih.

Ključne reči: Istorijat, metalni materijali; keramički materijali; polimeri, kompoziti