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Review Article

Nitinol shape memory alloy spring

Tameshwer Nath* & Sunil Kumar Singh

Department of Mechatronics Engineering, Indian Institute of Information Technology, Bhagalpur, Bihar 813 210, India

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Manufacturing, over the years, has evolved through three revolutions brought out by the impact of mechanization, electricity and Information Technology. The update in manufacturing has its root of intelligence. Necessity of miniaturization is shifted the use of conventional actuators with smart actuators. Conventional actuators generally produce the power in proportion to their volume, which reduce their application in micro applications. A concise review of the recent developments within nearly ten years on shape memory alloys has been presented. Besides other available shape memory alloys, Nitinol(Ni-Ti) is preferred due to its array of characteristicslike light weight, high power to weight ratio, noiseless operation, ease of actuation and muscle like movement. Shape memory effect and pseudo-elasticity play a crucial role in smart materials. Various actuation modes (Joule heating, hot water, laser assisted) and cooling methods are tabulated for Ni-Ti. The different forms of Nitinolare commercially available, but spring is used specially, due to its coiled structure.

Keywords: Shape memory alloy, super-elasticity, Hysteresis, Modes of actuation, Reliability

1 Introduction

Shape memory alloys (SMAs) are also referred as "Smart Materials" since they show both sensor and actuator tasks with special properties such as shape memory effect (SME) and pseudo-elasticity (PE)[1-3]. These materials are successfully implemented in commercial fields such as; aerospace[4-9], automotive parts[10-17], medical/biomedical[18-26], actuators/sensors, industrial process control, robotics[27–29], electronic instrumentation and telecommunications[30], consumer products and industrial applications[31-33] structures and composites[34], mini actuators and micro-electrome chanical systems (MEMS)[36-37], and even in fashion[38] also. The importance of shape memory materials (SMMs) was not recognized until William Buehler and Wang revealed the shape memory effect (SME) in a nickel-titanium (NiTi) alloy in 1962[39-40], which is also known as nitinol (derived from the material composition and the place of discovery, i.e., a combination of NiTi and Naval Ordnance Laboratory). NiTi (or nitinol) is the most common composition because of its high recoverable strain (about 8%) and excellent performance compared to other SMAs[2]. Advantage and disadvantage of Ni-Ti (SMA) are also mentioned in Table 1.

Even iron-based and copper-based smart materials, such as Fe–Mn–Si, Cu–Zn–Al and Cu–Al–Ni, are commercially available and low-cost and, due to their instability, impracticability (e.g. brittleness)[41-42] and poor thermo-mechanical performance[43]; Ni-Ti-based SMA's are superior for most applications. Nitinol is the material used for the studied SMA helical spring, due to its several advantages: very large recoverable motion, great ductility, excellent corrosion resistance, stable transformation temperatures, high biocompatibility, and the ability to be electrically heated for shape recovery[56, 64-66]. Nickel-Titanium (Ni-Ti) shape memory alloys (SMAs) are used in the form of coil springs in most products because the coil springs generate a large stroke and a high recovery force. Another advantage of using the SMA springs is that they can function as actuators as well as sensors.

This paper also pointed some recent advances in the material processing of Ni-Ti spring and demonstrated the applications of Ni-Ti spring in various types of MEMS such as micro-valves, micro-pumps, micro-grippers, micro-positioners, micro-springs, micro-sensors, and micro-wrappers, etc.

2 Material and Methods

Detail description of it is given in section wise;

2.1 Engineering effects of SMAs

Devices made up of SMA's are completing the allotted tasks successfully due to their engineering behavior, i.e., Shape Memory Effect (SME) and Pseudo-Elasticity (PE) or super-elasticity (SE) phenomenon. The ability of SMA's to be severely

*Corresponding author (E-mail: tnath.mea@iiitbh.ac.in)

Table 1 — Advantages and disadvantages of Ni-Ti SMA

Advantage	Disadvantage
High mechanical performances	Low energy efficiency
High power to weight Ratio	Complex thermo-mechanical behavior
Large deformation	Complex motion control
Large actuation force	Expensive material
High damping capacity	Temperature dependent effect
High frequency response	Poor fatigue properties
High wear resistance	Low operational speed
High corrosion and chemical resistance	
Low operational voltage	
High specific strength	
Compactness and lightness	

deformed and then returned to their original shape simply by heating them is called SME, whereas super-elasticity is hysteresis behavior with total strain recovery during a mechanical loading-unloading cycle. Both properties are a result of underlying crystallographic phase transformations[1]. These noteworthy behaviors will be discussed in this part in more detail[44-47]. SMA's are available in two different phases with three different crystal structures (i.e., twinned martensite, detwinned martensite, and austenite) and six possible transformations[48-50].

Phases of SMA's: There are two phases of a shape memory alloy, namely: Austenite and martensite (Fig. 1), whose details are given below:

The austenite structure is stable at high temperatures, and the martensite structure is stable at lower temperatures (Fig. 2). There are four temperatures which are required for phase transformation, which is enlisted below:

M_S: The starting temperature of SMA transforms from austenite to martensite.

M_F: The ending temperature of SMA transforms from austenite to martensite.

A_S: The starting temperature of SMA transforms from martensite to austenite.

A_F: The ending temperature of SMA transforms from martensite to austenite.

Once an SMA is heated beyond as it begins to contract and transform into the austenite structure i.e., to recover into its original form. This transformation is possible even under high applied loads, and therefore, results in high actuation energy densities[50]. During the cooling process, the transformation starts to revert to the martensite at martensite start-temperature (Ms) and is complete when it reaches the martensite-finish-temperature (M_f)[54].

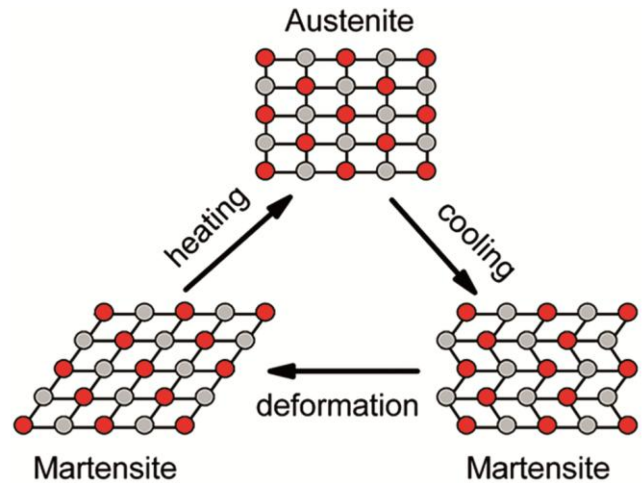

Fig. 1 — SMA phases with its crystal structures.

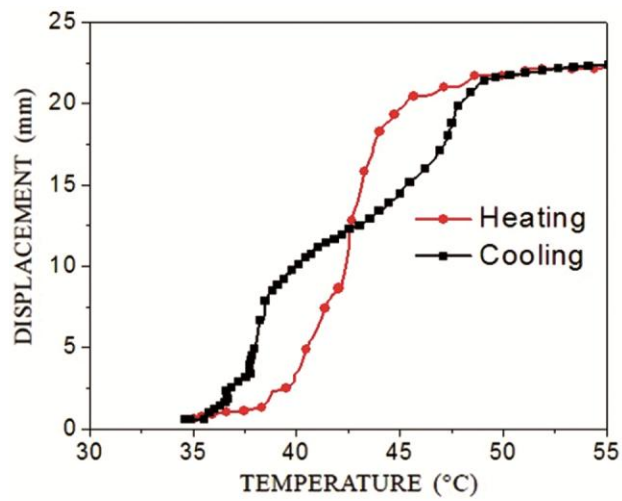

Fig. 2 — NiTi SMA phase Transformations.

Hysteresis is a measure of the difference in the transition temperatures between heating and cooling (i.e., $dt = A_f - M_s$), which is generally defined between the temperatures at which the material is in 50% transformed to austenite upon heating and in 50% transformed to martensite upon cooling[51]. This property is important and requires careful consideration during SMA material selection for targeted technical applications; e.g., a small hysteresis is required for fast actuation applications (such as MEMSs and robotics), larger hysteresis is required to retain the predefined shape within a large temperature range (such as deployable structure and in pipe joining)[52]. Various transition temperatures can be directly measured with various techniques such as differential scanning calorimetry (DSC), dilatometry, electrical resistivity measurement as a function of temperature, and can be indirectly determined from a series of constant stress thermal cycling experiments[53].

One-way shape memory effect (SME) can recuperate a large amount of strain (about 8%) in low-temperature mechanically due to the de-twinning phenomenon, while two-way shape memory effect (TWSME) is considered as a spontaneous phenomenon based on thermal cycling in a particular range of martensitic transformation. In fact, TWSME can be returned to the original shape without any application of external force[57-59]. Another process is to make the SMA as a two way is the implementation of biased spring against SMA spring. Recovery force and strain of SMA springs decreased by 30% after 1000 cycles and by 60% after 10,000 cycles[60]; in addition, the SMA springs deflection against the bias force degraded by at least 20% after aging at 95 C for 2000 h[61]. Parameter of Ni-Ti is compared with other shape memory alloy and is tabulated Table 2:

There are many possibilities regarding the shape of an actuator. Preferred configurations are:

a) straight tensile wires (high force, small motion)
b) helical compression or extension springs (large motion, less force)
c) Cantilever Springs (Bending)
d) Belleville type disc springs (High force small motion)
e) Wave washer springs (High force small motion

The design of shape memory elements for sensor-actuators is based on the different stress/strain curves of the austenite and the martensite as well as the change in modulus during the transformation. Transformation temperatures can be varied between approximately -100°C and + l00°C and the width of the hysteresis between approximately 2°C and 150°C[95]. As per its application, SMA spring can be used successfully. It can be used in various configurations and shapes such as helical springs, torsion springs, straight wires, cantilever strips, and torsion tubes[16, 56]. Here only SMA-based spring is reviewed because spring is reliable as a comparison to other shapes. Performance of various actuators has been compared and tabulated in Table 3.

Plenty of proposed actuator designs are based on the SMA spring as the active element, where large macroscopic displacements can be generated out of a relatively small microscopic strain. However, the stress distribution over the cross-section of the SMA spring is not constant and therefore requires greater material volume to generate the same force, which has a negative effect on the efficiency, and the bandwidth of the actuator means for the same output larger material has to be thermo-cycled[62-63]. The properties of commercially available Ni-Ti is tabulated in Table 4.

2.2 Heating and cooling medium

The medium required for heating is different modes i.e., Electrical heating (Joule heating)[91], Hot water medium[92], Laser medium[94], and cooling criteria for Ni-Ti has been clearly mentioned in various studies[70-72]

Table 2 — Parameters of Ni-Ti w.r.t. other SMA's[91-94]

Parameters	Ni-Ti	Cu-Zn-Al	Cu-Al-Ni
Melting Temperature	1300	950-1020	1000-1050
Density	6.45	7.64	7.12
Resistivity	70-100	8.5-9.7	11-13
Thermal conductivity	18	120	30-43
Young Modulus	Austenite: 83	Beeta Phase: 72	Beta phase: 85
	Martensite: 26-48	Martensite: 70	Martensite: 80
Yield Strength	Austenite: 195-690	Beeta Phase: 350	Beeta Phase: 400
	Martensite: 70-140	Martensite: 80	Martensite: 130
Ultimate tensile strength	895	600	500-800
Shape memory strain	8.5	4	4
Transformation range	-200-100	<120	<200
Transformation hysteresis	30-50	15-25	15-20

Table 3 — Comparison of actuator performance[67-69]

Actuator Type	Stress (MPa)	Strain (%)	Efficiency (%)	Bandwidth (Hz)	Work per volume (J/cm^3)	Power per volume (W/cm^3)
Ni-Ti SMA	200	10	3	3	10	30
Piezo-ceramic	35	0.2	50	5000	0.035	175
Single crystal piezo-electric	300	1.7	90	5800	2.55	15000
Human Muscle	0.007-0.8	1-100	35	2-173	0.035	0.35
Hydraulic	20	50	80	4	5	20
Pneumatic	0.7	50	90	20	0.175	3.5

Table 4 — Commercial Ni-Ti SMA physical properties[1,42]

Property	Symbol	Units	Value	
			Austenite	Martensite
Corrosion resistance	-	-		Similar to 300 series SS or Ti-alloy
Density	ρ_D	Kg/m^3		6450–6500
Electrical resistivity	ρ_R	μΩ/cm	82–100	76-80
Specific heat capacity	c	J/kg-K	836.8	836.8
Thermal conductivity	k	W/m-K	18	8.6-10
Thermal expansion coefficient	A	W/m-K^{-1}	11 X 10^{-6}	6.6 X 10^{-6}
Ultimate tensile strength	σ_{UTS}	MPa	-	895 (Fully annealed)/1900 (Hardened)
Young's Modulus	E	GPa	75-83	28-41
Yield strength	σ_Y	MPa	195–690	70–140
Poisson's ratio	υ	-		0.33
Magnetic susceptibility	γ	μemu-g	3.8	2.5

that quick heating of SMA actuators can be attained easily with several methods, such as applying large electrical currents (Joule heating) to increase the heating rate. However, without proper examination and control, this may damage the actuator due to overheating. On the other hand, the most significant concern in bandwidth limitation is the very relaxed cooling process, where the heat energy removal rate is limited by the mechanisms of heat transfer mode, i.e., conduction and convection. The shape of the SMA actuator affects the actuator response time, where actuators with smaller diameter heat faster due to their higher resistivity, and cool sooner due to their higher surface-to-volume ratio[35, 55]. Therefore changing the wire diameter could change the application bandwidth dramatically. In addition, loading conditions and amplitude of activation potential also influence the response time of SMA actuators[73]. Several strategies have been developed to improve the control of the heating process[43, 74] and to expedite the cooling process with active cooling such as forced air[74-76] (large Reynolds number), flowing liquids[74,77-79], thermoelectric modules (i.e., Peltier or semiconductor heat pumps)[80-85], heat sinks[72-73,86] and conductive materials[87-89]. Table 5 shows the ratio of actuation speed improvement with several cooling methods[55].

Higher cooling rates are obtained when cooling with a fluidic medium, but this requires a special design to prevent any leakage to the environment. A small amount of air circulation around the wire is sufficient to obtain a substantial improvement compared to the natural convection case. However, several studies have also indicated that increasing the air flow would only produce a minor effect on cooling performance and has several drawbacks, such as higher energy consumption and noise production[63]. Therefore, active cooling is not practical in numerous situations since it contributes to increases in cost, weight, physical volume, as well as the mechanical and control complexity[50,74]. Alternatively, bandwidth improvement with passive cooling is also achievable via improvements in mechanical design and control systems, such as the application of an agonistic-antagonistic system[90-91], high surface-to-volume ratio design (e.g., thin film SMA), and controller optimization (e.g., gain optimization[74]). An assessment of transient cooling opportunities has been completed by Huang *et al.*[67]. NiTi SMA is the preferred choice for designers for actuators that provide significant displacement and forces, with no critical requirements for short response time or high efficiency. Due to this reason, Ni-Ti SMA an attractive candidate for a variety of industrial and MEMS applications. Table 6 shows material constants for Ni-Ti.

Table 5 — Cooling methods[55]

Cooling methods	Improvement in speed
Increasing stress	1.2:1
Using higher temperature wire	2:1
Using solid heat sink material	2:1
Forced air	4:1
Heat conductive grease	10:1
Oil immersion	25:1
Water with Glycol	100:1

Table 6 — Material constants for a Nitinol SMA

Gpa		°C				MPa/°C			%
D_M	D_A	M_s	M_f	A_s	A_f	C'	C	θ	e_l
26.3	67.0	9	18.4	34.5	49.0	2.0	10.3	0.55	6.7

2.3 Design of Ni-Ti spring

The design of shape memory alloy spring is essential because it will affect its stroke, reliability as well as application. Reliability analysis has also be done for SMA Ni-Ti spring[80, 94]. Conventional springs are designed to perform within the elastic region where Hooke's law is obeyed. This allows the easy design of the spring since the shear modulus and spring constant do not change within the elastic region. On the other hand, the relation between the deflection and load is not linear for the SMA.

Spring since both shear modulus and spring constant change with strain. However, for the design of an SMA spring, the formulae of conventional springs are used by assuming the shear modulus is constant if the strain is small. It can be designed on two criteria: The design of conventional springs is standard and can be found in most machine design textbook (Shigley, 1914)[68]. A simple review is briefly given here. The maximum shear stress of a linear elastic spring is

$$\tau_{\max} = K\frac{2FR}{\pi r^3} \quad \ldots (1)$$

where, K is the Wahl correction factor, F is the external force, R the mean spring radius, and r is the radius of the spring wire. For simplicity of discussion, the Wahl correction factor (K) is assumed to be unity in this paper.

The deflection of a linear elastic helical spring can be derived by considering the deformation of an element of length, dx, cut from a wire of radius r as shown in Fig. 3.

Consider a line ab on the surface of the wire element, which is parallel to the spring axis. After deformation, it will rotate through an angle γ, and occupy the new position ac. The angle γ, from the Hook's law for torsion, given by

$$\gamma = \tfrac{\tau}{G} = \frac{2FR}{\pi r^3 G} \quad \ldots (2)$$

The angle $d\alpha$, through which one section of the element rotates with respect to the other, is

$$d\alpha = \gamma\frac{dx}{r} \quad \ldots (3)$$

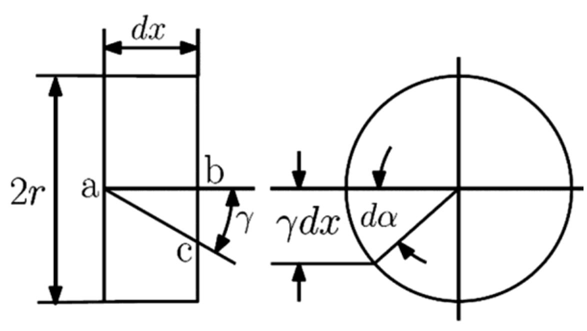

Fig. 3— Cross-section element of Spring.

The angular deflection of one end of the spring wire with respect to the other is

$$\alpha = \int_0^{2\pi RN}\frac{\gamma}{r}dx = \frac{4FR^2N}{r^4G} \quad \ldots (4)$$

where, N is the total number of active coils. The total deflection is expressed as

$$y = \alpha R = \frac{4FR^3N}{r^4G} \quad \ldots (5)$$

The spring constant, from Eq. (v), is

$$k = \frac{r^4G}{4R^3N} \quad \ldots (6)$$

where, D, D_A, and D_M are the Young's modulus in any state, the austenitic phase, and the martensitic phase, respectively. This linear relation of D — ξ can nicely fit most D-T relations if the relation of ξ vs. T is substituted into Eq. (vii). The shear modulus is given by

$$G = \frac{D}{2(1+\mu)} \quad \ldots (7)$$

where, μ is the Poisson's ratio and for most SMAs is about 0.3 in the elastic range. When the temperature is lower than M_S the shear modulus is the martensite shear modulus, G_M When the temperature is higher than A_f the shear modulus is the austenite shear modulus, G_A. The ratio of G_A. to G_M is three to four for nitinol SMAs.

Since elastic stress limit of shape memory alloys is a function of phase transformation so shear stress can be expressed as:

$$\tau = \frac{\sigma_e}{\sqrt{3}}\frac{F}{F_e} \quad \ldots (8)$$

The force-displacement expression of Eq. (viii) is very convenient in the design and application of shape memory alloy springs as actuators and other control elements.

Some SMA actuator has been given in detail with its Remarks in Table 7.

3 Results and Discussion

3.1 Application

A micro-actuator is a microscopic servomechanism that provides and transmits a required amount of energy to operate another mechanism/system. As a general actuator, the following standards have to be

Table 7 — SMA spring actuator[85-90]

Actuator and motor description	Remarks	Year	Inventor
An actuator with multiple SMA wires arranged around a resilient member (such as spring) to increase bandwidth	Linear Type	1986	Hosoda et al.[110]
A linear actuator to translate an object from one position to another by the action of a SMA flat spring attached at one end to a heating device and tothe object at the otherend	Linear Type	1999	Foss and Siebrecht[111]
A SMA linear actuator with a SMA wire, two moving bodies and two bias springs positioned in a cylinder	Linear Type	2009	Takahashi[112]
A linear actuator designbased on MSMAcomposites (A hybridelectromagnet and a permanent magnet to activate FSMA spring)	Linear Type	2010	Taya et al.[113]
An actuator consists ofSMA strips (coiled intosprings) and SMAsprings that produce aconstant force fromapplied heat. Canrotate either aclockwise or anti-clockwise depending on which spring is activated	Rotary Type	2000	Weems[114]
A rotary actuator composed of a SMAtorque tube connected with a bias superelastic return spring	Rotary Type	2006	Jacot et al.[115]

met: (1) large travel, (2) high precision, (3) fast switching, (4) low power consumption, and (5) power free force sustainability. The analyzed configuration is frequently used for SMA Latching Mechanisms, for SMA Bell Crank Mechanisms, and for SMA Controlled Valves developed in our laboratory and used in the robotic field[96-98]. Other applications are some micro devices like, Micro-valves[74] Micro-gripper[75], Micro-pumps[76-77], Micro-sensors[95], Micro-mirror[96], Micro-positioner and micro-wrapper[97-98], Tip Articulation Mechanism, Fiber-optic actuator for tip articulation, latch mechanism and fiber-optic sensor for microscopic observation, Tube type tip articulator, joint mechanism[74], Forward looking Active catheter[76], Medical (Bending actuator and mirror actuator for endoscopy, zooming system, micro-muscle fibre)[77-78], Robotic system[88], Micro-positioning stage[91], Directional flow control valve[94], Micro-damper[96], In vibration control[98] etc.

4 Conclusion

Shape memory alloys represent a very encouraging material to be used as active elements for actuator and/or sensor applications in numerous technical fields. In this review paper, the main features of Ni-Ti shape memory alloys with its design parameter and actuation technique with its reliability, were enlisted with proper reference. SMA's are a unique class of intermetallic materials with the ability to regain their initial shape at certain characteristic temperatures (shape memory effect) or to undergo large strains without plastic deformation or failure (super-elasticity). Brief discussion about SMA Ni-Ti spring has been done.

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