THE DESIGN OF A Ni-Ti BASED SHAPE MEMORY ALLOY ACTUATOR

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Abstract

A simplified procedure for the design of SMA(Shape Memory Alloy) actuators is presented. The inter-relationship between the mechanical properties and the electrical properties that are relevant for the design of SMA actuators working under a constant load are clearly brought out. The different conditions that arise while using an SMA actuator against a constant load has been considered. The locus of SMA actuators in relation to conventional actuators has been clarified. The joule heating effects and power developed by the SMA actuator in relation to its weight has been also dealt with.

Nomenclature

D = diameter
δ = deflection
I = current
η = efficiency
N = Newton
m = meter
mm = milli meter
P_i = input power (watts)
Po = output power (watts)
Q = joule heating (I^2 Rt)
R = resistance
t = time
V = voltage
W,D = work done
Wt = weight

Introduction

The SMA actuation technologies have made significant strides in recent years. This is despite the fact that their efficiencies are low compared to other actuators due to factors such as high current density requirements to actuate these materials and their low time response characteristics. In fact in the area of micro-actuating devices, SMA based technologies are going to score well over many others. Even in applications other than micro-actuations (consider wire diameter in the range of 1 to $12x10^{-4}$ m (0.1 to 1.2 mm)), where larger forces are required, SMA is still very much in contention as an actuating element because of its compactness, simplicity, cleanliness and ease of operation compared to other actuating devices. This is particularly true in aerospace applications where the availability of space is often a severe constraint and silent and clean environments are desired. In such situations the use of SMA appears to be promising. Shape memory alloys are a unique class of materials, which remember their shape after large (about 4%) mechanical deformations. Once deformed in the cold shape (martensite) these materials will stay deformed until heated, whereupon they will spontaneously return to their original pre-deformed shape (hot shape i.e. austenite). In order to energize the SMA (for actuation) to bring about the thermally induced transformation the preferred mode of heating is electrical. This is because the electrical heating gives better control and is amenable for interfacing with the computer controls. Therefore, proper understanding of the mechanical and related electrical behavior of SMA is very important.

During the thermally induced phase transformation the desired changes in mechanical behaviour related parameters of the SMA actuating element, such as stress, strain, modulus etc, are achieved. As mentioned earlier, this is done by electrically energizing the SMA element.

The choice and selection of the geometry of SMA actuator element is dependent on the force and strain required, response time requirements and issues relating to power consumption.

For the successful realization of SMA actuation a whole range of material behavioural properties need to be thoroughly studied. Since electrical heating is the preferred mode of heating the SMA , the understanding of the mechanical, time response and related electrical properties

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of the SMA assumes paramount importance. Some work has been done in this area. G. Airoldi et. al. [1] reported on the electric resistance of shape memory in the pseudoelastic regime, Pavel. L. Potapov et. al.[2] presented a paper on the time response of nitinol ribbons. R. Stalmans and J.V.Humbeeck [3] reported the locus of SMA actuators in relation to other actuators with regard to the power developed and the weight of the actuator based on their work and on the work of other researchers. Papers are also available in the literature which detail the use of SMA spring actuator; Tom Waran [4], Richard F Gordon [5] explain the principles of SMA spring actuators. SMA spring actuators are used in several fields such as air conditioner baffles, ventilators in houses, fire protection devices and so on. J.R. Yaeger [6] reports on the selection, processing and evaluation of SMA wires. The mode of deformation in the spring actuator is shear. The maximum recoverable stresses in the shear mode is far less than in the tension mode. J.V. Humbeeck [7] lists the maximum stress in relation to strain and number of cycles for Ni-Ti alloys. Papers which extensively report on the inter relationships and interdependency of various parameters for thin wires in the tensile mode, such as power developed, power required, time response characteristics, efficiencies for SMA elements of the same chemical composition but varying cross-sections are very scanty in the literature [6]. By gaining proper insight and appreciation of these interrelationships one is better equipped to make the right selection of the SMA and properly design the SMA based actuation element for a given application. In this paper the design issues involved in the design of shape memory actuators are discussed.

SMA elements (as actuators) are used to do work either against a constant load such as a dead weight or against a bias spring as shown in Fig.1 . In this paper the experiments focus on SMA lifting a constant load. For the case of SMA lifting a constant load itself, two different sets of experiments were carried out. In one set of experiments the current was varied within a small range and the corresponding deflections were recorded. In the second set of experiments the current and time were both varied in a certain range, so that the deflection was constant. As mentioned earlier the interrelationships between mechanical and electrical properties that are relevant for the actuator design and sizing the electrical power requirements are brought out for Ni-Ti based shape memory round wires of identical compositions but varying diameters.

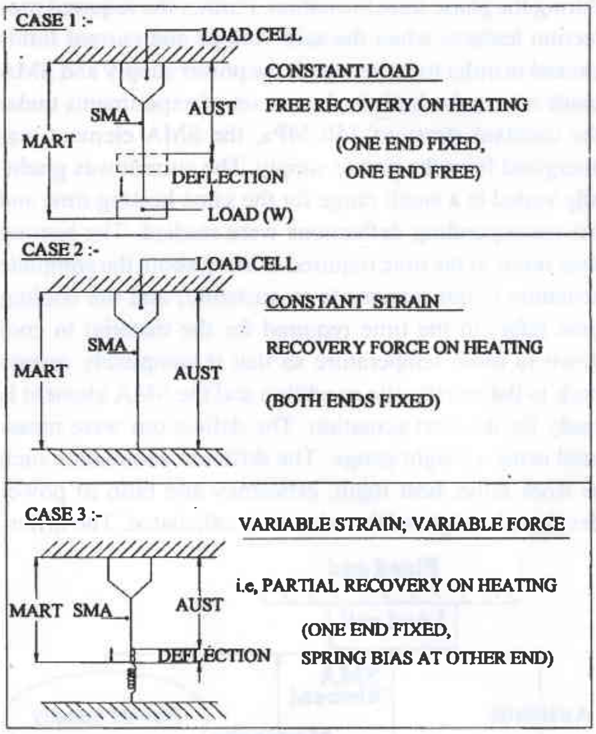

Fig. 1 Basics of SMA behaviour for different types of application

Experimental details

Ni-Ti round wires of 1.3 to 12×10^{-4}m (0.13, 0.3, 0.5 and 1.2mm) diameter and constant length of 0.26m were chosen. They were all supplied with an appropriate amount of cold work and heat-treatment so as to produce a recoverable strain of 4% under a constant stress of 150 MPa. The zero load martensite finish, martensite start, austenite start and austenite finish temperatures for these elements was around 25, 45, 55, and 75°C respectively. To simplify the experimentation a constant stress of 150 MPa was applied for the wires and two different experiments were carried out.

A variable voltage, variable current source was used to energize the SMA. The schematic of the experimental set up is shown in Fig.2.

The resistance of SMA decreases while the martensite to austenite phase transformation is being effected and therefore the resistivity decreases as the temperature increases. The power supplies that are used to energise the SMA has to take care of this and related effects. Also, the power supply has to have enough compliance voltage to take care of the entire range of load current which varies during the phase transformation. Further the required protection features when the said voltage and current limits exceed in order to protect both the power supply and SMA loads have to be built in. In one set of experiments under the constant stress of 150 MPa, the SMA element was energized from the power supply. The current was gradually varied in a small range for the same heating time and the corresponding deflections were studied. The heating time refers to the time required to bring about the complete actuation (from martensite to austenite) and the cooling time refers to the time required for the material to cool down to room temperature so that it completely reverts back to the martensitic condition and the SMA element is ready for the next actuation. The deflections were measured using a height gauge. The different parameters such as work done, heat input, efficiency and ratio of power developed/weight of the wire were calculated. The different readings and the calculated parameters for this set are listed in Table-2.

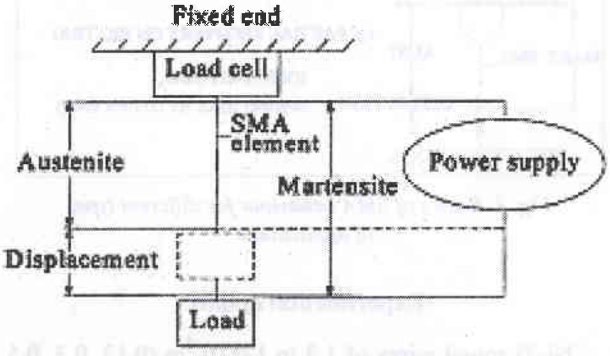

Fig. 2 Schematic of experiments setup

In the second set of experiments again under the constant stress of 150 MPa the current was again gradually varied but this time the heating time was decreased with increase in current such that the amount of deflection was always constant at approximately 4% recoverable strain. Again, the different parameters such as work done, heat, input, efficiency and ratio of power developed to weight of wire was calculated, as shown in Table-3.

Observations

As mentioned earlier the SMA linear actuators are used in many cases against a bias load, in which case the design strain is normally in the range of 2-3% depending

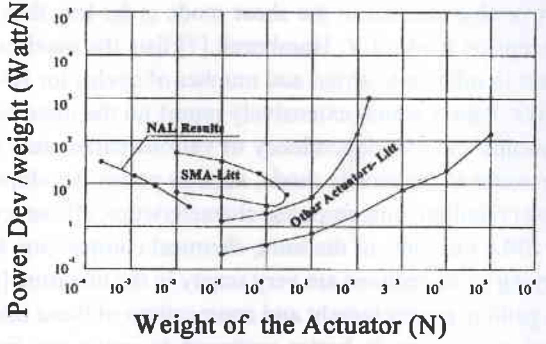

Fig. 3 Locus of SMA and other actuators

Table-1 : Summary of Data from Figs. 4, 5 and 6 Plotted for 4% Strain

Sl.No.	Parameters	Fig.4	Fig.5			Fig.6
1	Heating time in secs.	9				
2	Cooling time in secs.	25				
3	Diameter (m)	$5x10^{-4}$	$5x10^{-4}$			5x10-4
4	Length (m)	0.1	0.1	0.5	0.5	
5	Displacement (m)	0.004	0.004	0.02	0.02	
6	Force (N)		30	30	210	
7	No. of wires	1	1	1	7	
8	Input power density (Watt/m2)					$4.364x10^6$
9	Voltage-V (Volts)	0.611	0.611	3.055	3.055	
	This leads to					
1	Input power (Watt) - VxI		0.08554	4.277	30	
2	Current - I (Amps)		1.4	1.4	9.8	

Note: Figs. 4, 5 and 6 have been plotted for L=100 mm for convenience and other figs are plotted for L=260mm

Table-2 : Heat Input and Workdone for Different SMA Elements (Varying Deflection)

Sl	D (m)	V (volts)	I (amp)	R (ohm)	Pi(watt)	δ(mm)	t(sec)		W.D	Q	η(%)	Po(watt)	Wt(N)	Po/Wt
No		L=100mm					On	off	N-m	Joules				watt/N
1	0.13×10^{-3}	0.075	0.01	19.5	~~~~	0	~~~~	~~~~	~~~~	0.508	~~~~	~~~~	22×10^{-5}	~~~~
2	0.13×10^{-3}	1.796	0.3	15.567	1.401	11	3	3	0.021	4.203	0.518	0.0072		32.367
3	0.13×10^{-3}	2.03	0.4	13.2	2.112	11.7	3	3	0.023	6.336	0.364	0.0077		34.329
4	0.13×10^{-3}	2.638	0.5	13.72	3.43	12.1	3	3	0.024		0.232	0.0079		35.488
1	0.3×10^{-3}	0.018	0.01	5	~~~~	0	~~~~	~~~~	~~~~	~~~~	~~~~	~~~~	118×10^{-5}	~~~~
2	0.3×10^{-3}	1.0384615	0.7	3.86	1.89	12	6	6	0.11	11.17	0.98	0.018		15.254
3	0.3×10^{-3}	1.3076923	1	3.4	3.4	10	6	6	0.09	20.4	0.44	0.015		12.711
4	0.3×10^{-3}	1.4615385	1.1	3.45	4.18	11	6	6	0.102	25.04	0.4	0.017		14.406
1	0.5×10^{-3}	0.008	0.01	2.1	~~~~	0	~~~~	~~~~	~~~~	~~~~	~~~~	~~~~	338×10^{-5}	~~~~
2	0.5×10^{-3}	0.611	1.4	1.135	2.2246	9	9	9	0.2646	20.021	1.3215	0.0294		8.6982
3	0.5×10^{-3}	0.678	1.7	1.037	3	11.8	9	9	0.3469	27	1.2848	0.0385		11.39
4	0.5×10^{-3}	0.792	2	1.03	4.12	12	9	9	0.3528	37.08	0.9514	0.0392		11.5976
1	1.2×10^{-3}	0.005	0.01	1.3	~~~~	0	~~~~	~~~~	~~~~	~~~~	~~~~	~~~~	1910×10^{-5}	~~~~
2	1.2×10^{-3}	0.396	5	0.206	5.15	6.53	20	60	1.107	103	1.074	0.055		2.8796
3	1.2×10^{-3}	0.415	5.5	0.196	5.94	8.3	20	60	1.406	118.8	1.183	0.0703		3.6806
4	1.2×10^{-3}	0.434	6	0.188	6.768	9.51	20	60	1.613	135.36	1.191	0.0806		4.22

Table-3 : Heat Input and Workdone for Different SMA Elements (Varying Time)

Sl	D(m)	V (volts)	I(amps)	R(ohms)	Pi(watt)	δ(mm)	t(sec)		W.D	Q	η(%)	Po(watt)	Wt(N)	Po/Wt
No		L=100mm					On	off	N-m	Joules				watt/N
1	0.13×10^{-3}	1.765	0.3	15.3	1.377	11	3	3	0.021	4.131	0.508	0.007		31.818
		2.15	0.4	13.975	2.236	11	2	3	0.021	4.472	0.469	0.01	22×10^{-5}	47.727
		2.611	0.5	13.58	3.395	11	1	3	0.021	3.395	0.618	0.021		95.454
2	0.3×10^{-3}	1.115	0.7	4.14	2.02	11	6	6	0.115	12.12	0.94	0.018		15.254
		1.0076	0.7	3.74	1.83	10.5	6	6	0.11	10.98	1.001	0.018	118×10^{-5}	15.254
		1.057	0.8	3.43	2.19	10.5	5	6	0.11	10.95	1.004	0.022		18.64
		1.165	0.9	3.36	2.72	10.5	4	6	0.11	10.88	1.011	0.027		22.88
		1.3	1	3.38	3.38	10.5	3	6	0.11	10.14	1.084	0.036		30.508
3	0.5×10^{-3}	0.607	1.4	1.12	2.195	9	9	9	0.2646	19.755	1.339	0.0294		8.6982
		0.619	1.5	1.073	2.414	9.5	9	9	0.2793	21.726	1.2855	0.031	338×10^{-5}	9.1814
		0.665	1.6	1.081	2.767	10.5	9	20	0.3087	24.903	1.2396	0.0343		10.1479
		0.719	1.7	1.1	3.179	10.5	8	20	0.3087	25.432	1.2138	0.0385		11.4164
		0.742	1.8	1.072	3.473	10.5	7	20	0.3087	24.312	1.2697	0.0441		13.047
		0.796	1.9	1.089	3.931	10.5	6	20	0.3087	23.586	1.3088	0.0514		15.221
4	1.2×10^{-3}	0.442	6	0.1916	6.897	9.5	20	60	1.6102	137.94	1.1673	0.0805		4.2146
		0.511	6.5	0.2046	8.644	10	20	90	1.695	172.88	0.9804	0.0847	1910×10^{-5}	4.4371
		0.523	6.6	0.206	8.973	10	19	90	1.695	170.49	0.9941	0.0892		4.6707
		0.534	6.7	0.2074	9.31	10	18	90	1.695	167.58	1.011	0.0941		4.9301
		0.546	6.8	0.2088	9.654	10	17	90	1.695	164.13	1.03	0.0997		5.2202
		0.419	5.5	0.1981	5.992	9	20	60	1.525	119.84	1.272	0.0762		3.9921

on the load and on the number of cycles. However, for our experiments a constant load has been chosen in the results reported here and as mentioned earlier all the graphs have been plotted only for the cases of approximately 4% strain at a constant stress of 150 MPa for a wire length of 0.260m. Fig.3 shows the locus of SMA actuators in relation to other actuators and also the results of our experiments.

In Fig.4 and 5, the variations of heating time, cooling time, force and voltage Vs. area of cross-section of the wire is shown. It can be seen that assuming a more or less linear relationship between the heating / cooling curves with respect to diameters, the heating curve is changing at a far lesser rate than the cooling curve. This indicates that cooling becomes a concern as the diameter of wire increases. The cooling is absolutely essential for the SMA to re-transform back to the martensite condition completely, so that it is ready for the next actuation. Without adequate cooling the expected strains will not be obtained.

The decrease of voltage and input power density with area of cross section clearly indicates the relatively lower requirement of power at high diameters although it is at the cost of response time as shown in Fig.5 and 6. The efficiency increases till about 0.5mm dia. from 0.13mm and beyond 0.5mm diameter it decreases gradually as can be seen in Fig.6.

From the second set of experiments it is clear from the Fig.8 that the input power is higher for smaller time as the current is increased with decrease in time of heating for the same deflection. However, the heat input (Joule heating) remains more or less a constant for most cases, even though the time is decreasing as the current is increased in a certain range such that the deflection is a constant at 4% strain. This shows that for most cases there is a current-time equivalence for the joule heating in a certain range. A decrease in time is equivalent to an increase in current. In other words, the same amount of heat can be supplied to the SMA element for two different combinations of current and time values and identical amounts of deflection can be obtained under the constant loads.

In Fig.7 for the second set of experiments the ratio of power developed to weight of the wire decreases as the diameter of the wire goes up. From Fig.9 for the second set of experiments it is seen that the power developed/weight of actuator decreases as the time increases for the same diameter. The ratio of power developed/weight of actuator is higher for smaller diameters. This again proves the point that SMA actuators are good for micro-actuation involving short times. In Fig.10 the results of power output versus time is plotted. It is also seen here that the power output decreases as the time increases for the same diameter.

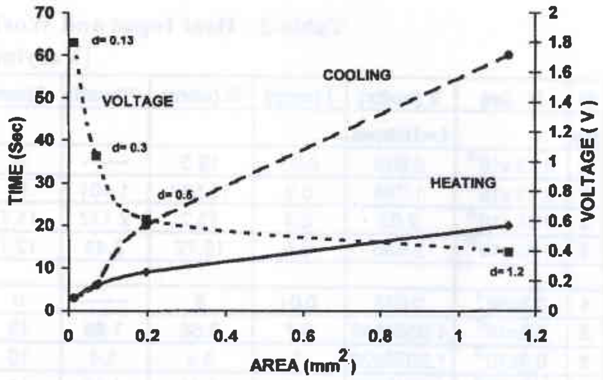

Fig. 4 Voltage$_{(L=100mm)}$ and heat and cool time Vs Area

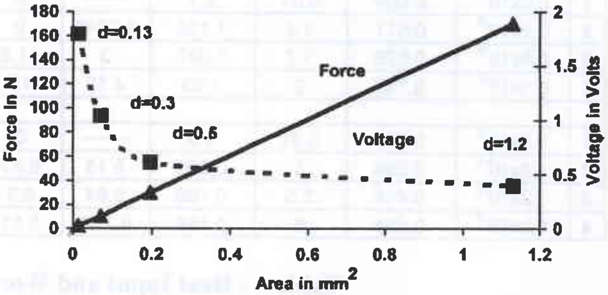

Fig. 5 Force development and Voltage$_{(L=100mm)}$ Vs Area (4% Strain)

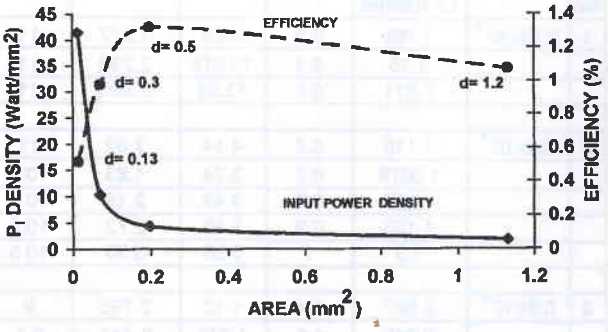

Fig. 6 Input power density and efficiency Vs Area (4% Strain)

Typical Calculations for Computing Number and Length of SMA Elements for the following Requirement

Force	200 N (20 kg. approx)
Displacement	0.02 m
Total cycle time	35 sec
Heating time	10 sec
Cooling time	25 sec

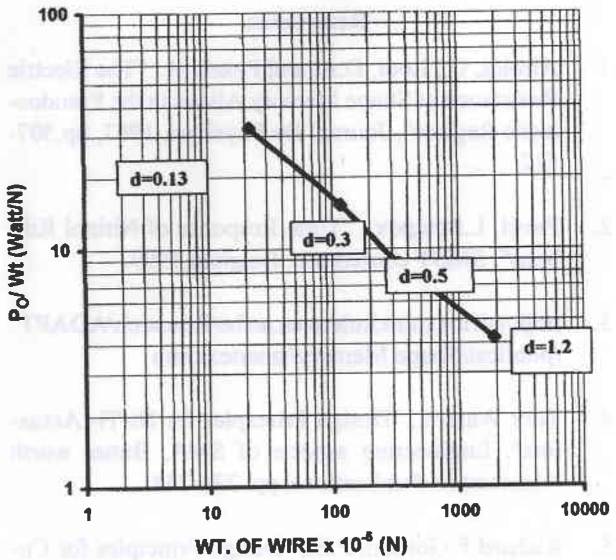

Fig. 7 Power output/weight Vs weight of wire (From Table 3)

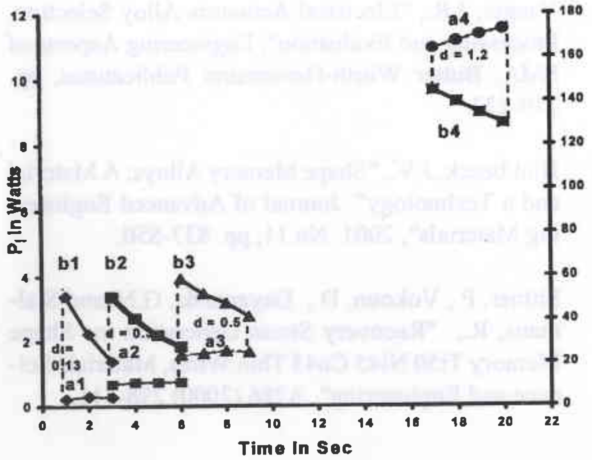

Fig. 8 Input power and heat (Joules) Vs time

Legend:

Curves a1 - a4 represent heat energy

Curves b1 - b4 represent input power

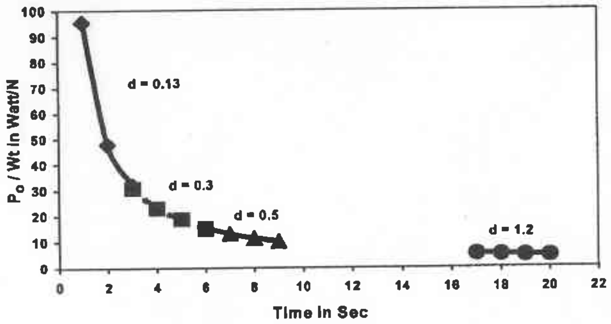

Fig. 9 Power output/weight Vs time

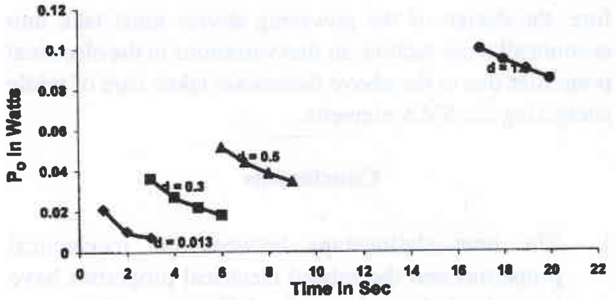

Fig. 10 Power output Vs time

From the Fig. 4, the heating time for a SMA wire of diameter 5 x 10-4 m (d=0.5mm) is 9 sec. which is almost nearer to 10 sec., therefore select 0.5mm dia wire. It is also seen in Fig.4 that a cooling time of 25 sec. is sufficient for the diameter of 0.5mm wire. Fig.5 gives the force and voltage values and Fig.6 gives the input power density. All the data from Figs. 4, 5 and 6 for computing the number and length of SMA elements is shown in Table-1.

Total energy (Joule heating) for 7 wires = I^2R(or V x I) x No. of wires x t, where t is the time of heating.

To summarize 7 wires of 500 mm length and 0.5 diameter will be necessary to generate a force of 200 N, displacement of 0.02 m involving heat and cool times of 10 and 25 seconds respectively. The voltage required will be about 3 volts and the current about 9.8 amps and the power requirement is 30 Watts.

However, when SMA actuators are used against a bias spring, which is the case in many practical situations the strain is generally limited to about 2 - 2.5%. For instance, when the design strain is 2% for the same force of 200 N if one were to use the same power of 30 Watts and the same number of identical diameter and length wires then the displacement is only 10mm. In designing powering devices for SMA elements, several factors have to be taken into account. For instance, if one considers the actuating current of 1.4 amps for the 0.5 mm diameter wire, this current is for a specific composition of Ni Ti base alloy and changes in some range depending on the chemical composition. Further the increase in stress (the constant load for the set of experiments described) increases the temperature required to bring about the martensite to austenite transformation. The rate of increase of stress with temperature is in the range to 6-8 MPa / °C [8] for Ni Ti based alloys. Also, the length of the SMA element is directly proportional to the voltage requirement. Therefore, the design of the powering device must take into account all these factors, so that variations in the electrical properties due to the above factors are taken care of while energizing the SMA element.

Conclusions

1. The inter-relationships between the mechanical properties and the related electrical properties have been clearly brought out for different conditions.
2. There is a current-time equivalence for the joule heating for a certain range of current.
3. This procedure significantly simplifies the design of SMA actuators under constant load. Typical design calculations have also been shown.
4. With the data and the graphs generated it is possible to calculate the diameter, number of SMA elements and the power and energy requirements for a given application.

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References

1. Airoldi, G., Lodi, D.A. and Pozzi, M., "The Electric Resistance of Shape Memory Alloys in the Pseudoelastic Regime", Journal De Physique, 1997, pp.507-512.
2. Pavel, L.Potapov., "Time Response of Nitinol Ribbons", SMST conference, Belgium,1999.
3. http://sirius.mtm.kuleuven.ac.be/Research/ADAPT /publicat/Shape Memory/smartext.htm
4. Tom Waram., "Design Principles for Ni-Ti- Actuators", Engineering aspects of SMA, Butter worth -Heinemann Publications, pp. 234-244.
5. Richard F.Gordon, P.E., "Design Principles for Cu-Zn-Al Actuators", Engineering Aspects of SMA, Butter Worth-Heinemann Publications, pp.245-255.
6. Yaeger, J.R., "Electrical Actuators Alloy Selection, Processing and Evaluation", Engineering Aspects of SMA, Butter Worth-Heinemann Publications, pp. 219-233.
7. Humbeeck, J.V., "Shape Memory Alloys: A Material and a Technology", Journal of Advanced Engineering Materials", 2001. No.11, pp. 837-850.
8. Sittner, P., Vokoun, D., Dayananda, G.N. and Stalmans, R., "Recovery Stress Generation in Shape Memory Ti50 Ni45 Cu45 Thin Wires, Materials Science and Engineering", A286 (2000) 298-311.