A simple solenoid valve: SMA-based

Suresh Kumar[1] M.L.Aggarwal[2] Lakhwinder singh[3]

[1] PhD student, Department of Mechanical Engineering, YMCA University of Science & Technology, Faridabad-121006, Haryana, India
[2]Professor, Department of Mechanical Engineering, YMCA University of Science &Technology, Faridabad-121006, Haryana, India
[3]Professor, Department of Mechanical Engineering, YMCA University of Science & Technology,Faridabad-121006,Haryana,India.

Abstract

In the last 10 years, shape memory alloys (SMAs) have been implemented in several high-performance applications requiring high competitive stresses, good biocompatibility, high work densities, high recoverable deformations, and high eco-friendly atmosphere. Nowadays shape memory alloys have become excellent candidates towards most general form i.e. MEMS/NEMS The minor application of 0.5mm SMA-based wire as a simple solenoid valve has been discussed in which SMA based conical spring in the helix form was employed. The advantageous purpose of valve to one way operated and can control the supply water, oil, liquid fuel and liquid refrigerant but choked by gravitational force/self weight, so It placed or installed anywhere in vertical position as per its limitations or reduction of cost. This solenoid valve can be called microelectromechicanical system (MEMS) because it is the integration of mechanical elements, sensors, actuators and electronics and fulfilled to small-scale precious requirements with high accuracy and precision. NiTi based thin film Shape Memory Alloys (SMAs) possess many desirable properties, such as high power density, large transformation stress and strain upon heating and cooling, superelasticity and biocompatibility. The actuation parameters included as average strain capacity, average running temperature avg. scale-load capability and wire-current and voltage during actuation were evaluated.

Keywords: Annealing, actuator, shape memory alloy and solenoid valve.

Introduction

Shape memory alloys (SMAs) are a class of smart materials characterized by shape memory effect and pseudo-elastic behavior. They have the capability to retain their original form when subjected to certain stimuli, such as heat or a magnetic field. Shape memory alloys (SMA) are able to recover their original shape through the appropriate heat or stress exposure after enduring mechanical deformation at a low temperature. Numerous alloy systems have been discovered which produce this unique feature like TiNb, AgCd, NiAl, NiTi, and CuZnAl [9, 10].The TiNi-based thin films in MEMS applications: a review in which preparation of high performance shape memory TiNi films using sputtering methods and their MEMS applications were involved. In their review paper, some critical issues and problems in the development of TiNi thin films are discussed, including preparation and characterization considerations, residual stress and adhesion, frequency improvement, fatigue and stability, modeling of behavior as well as functionally graded or composite thin films. Different types of TiNi thin film based microdevices, such as microgrippers, microswitches, microvalves and pumps, microsensors, etc. are also described and discussed. They also suggested the future directions for TiNi films and micro-actuators, TiNi thin film processing and characterization MEMS requirements for TiNi-based thin films [2]. Fabrication and actuation mechanism of gripping device actuated by shape memory alloy (SMA) wire discussed. A SMA wire was used to close the gripper during operation and a torsion spring was integrated to open the gripper when the SMA wire relaxed. SMA wire diameter and the number of coils the SMA wire was wound had significant effects on the gripping device’s performance. The gripping force was adjustable by changing the driving current. The gripping device using one coil of Ø 100 μm SMA wire with a music wire spring produced good performance and the gripping device could withstand over 1.175 million opening and closing cycles without any deterioration in its performance. They also described the design of the gripping device, gripping force measurement and gripping forces vs. driving current measured [4]. A novel concept for in-plane actuators based on a thin free-standing shape memory alloy (SMA) film also described. A prototype actuator demonstrated a displacement of 45 μm related to 4.5% of the SMA film length and a force of up to 115 mN related to a stress of 230 MPa in the SMA film without plastic deformations. Integration of the stress with respect to the strain showed that the demonstrated actuator provided a work per volume of 8 × 106 J m−3, which are more than two orders of magnitude larger than the capabilities of the other MEMS actuation methods. The ability to induce large strokes and forces allows the demonstrated actuator to provide a motion against stiff springs (overall stiffness of 1500 N m−1) whereas several MEMS actuation principles other than the SMA have been demonstrated in the past for in-plane actuation, including electrothermal, piezoelectric, and electrostatic [3]. Y.Q. Fu, J.K. Luo and A.J. Flewitt discussed the Micro-electro-mechanical System (MEMS) applications by thin film shape memory alloys and microactuators. They focused on crystal nucleation and growth during annealing, film thickness effect, film texture, stress induced surface relief, wrinkling and trenches as well as Temperature Memory Effect (TME). They also considered microvalve and microcage for biological applications, micromirror for optical applications and data storage using nanoindentation method. Overall the microactuator applications of TiNi films, TiNi thin film processing and characterization were mainly explained [1]. The design of shape memory alloy coil spring actuator for improving performance in cyclic actuation was described by Je-sung Koh. The static two-state model of the SMA coil spring is modified in order to optimize the strain range of the SMA. The proposed model describes the nonlinear tensile behavior of the SMA coil spring actuator with material properties obtained by the experiment. They used the static two-state model of the sma coil spring actuator, validation of the static two-state sma coil spring model, lip sma coil spring design procedure, actuation performance experiments of the lip sma coil spring actuator. The cyclic actuation tests verify the improvement of the SMA coil spring actuators in frequency, mass and efficiency by comparing non-LIP and LIP (pitch angle) designs [5]. Mohammad Amri Zainal included fabrication of thin-films, manufacture of bulk SMA and most common method used to deposit thin-film SMA is sputtering deposition. Other methods included flash evaporation, pulsed laser deposition, filtered arc deposition, cluster beam deposition, and cathodic arc plasma ion plating. It was shown that Ti-rich films exhibit a transformation temperature near to or above ambient temperature. They also considered the different compositions of NiTi thin-film shape memory alloys (SMAs) and bulk micromachined SMA actuation methods [6]. Nicole Latrice Harris Odum described NiTi thin film processing and characterization techniques in his dissertation. NiTi thin film '1' µm thick were produced using sputter deposition techniques. Substrate bound thin films were deposited to analysis the surface using Scanning Electron Microscopy; the film composition was obtained using Energy Dispersive Spectroscopy. The phases were identified using X-ray diffraction and the transformation temperatures acquired using resistivity testing [9]. A crystallization study in which amorphous films are annealed by a scanning laser was performed experimentally and numerically. The nucleation and growth mechanisms in the laser annealing process were found to be the same as for furnace annealing. Uniform microstructure and shape memory properties were locally introduced in the films by the laser. A 3-D thermal model was developed to simulate the crystallization behavior of the laser annealing process of amorphous Ni-Ti thin films. The crystallization kinetics parameters determined in the furnace annealing study were included in the model to allow us predict the size of the crystallized region as a function of laser annealing parameters [10]. The biocompatibility of these alloys is one of their most important features. Different applications exploit the shape memory effect (one-way or two-way) and the super elasticity, so that they can be employed in orthopedic and cardiovascular applications, as well as in the manufacture of new surgical tools. They considered the point that why the main properties of shape memory alloy hold so many opportunities for medical devices and will review a selection of current applications [7]. The thermomechanical behaviour of SMA wires and, with a simple force balance, the resulting composite behavior including interfacial quality, internal stress distribution and reproducibility of the behaviour were also addressed. The following major steps are examined as selection and characterisation of the material constituents, development of manufacturing processes for the production of composites with prestrained SMA wires, analysis and modeling of the action of the SMA wires in the composite, the contribution of the SMA-resin interface, analysis and modeling of the functional, thermomechanical, impact and durability properties of SMA composites and the development of a simple, large-scale, aerodynamic model [8].

Problem statement: The thin flexinol wire of 0.020" or 0.5mm wire was considered for observations as a small actuator. The helix form of conical spring was employed based on NiTi shape memory alloy in this work. The advantageous purpose of this valve to one way operated and can control the supply water, oil, liquid fuel and liquid refrigerant but choked by gravitational force/self weight, so It placed or installed anywhere in vertical position as per its limitations or reduction of cost. Actually, this valve is microelectromechicanical system (MEMS) and the actuation parameters included as average strain capacity, average running temperature avg. scale-load capability and wire-current and voltage during actuation were evaluated. Basically, it is a minor application of small scale equipment based of NiTi intelligent spring.

2. Material Descriptions

The thin flexinol wire of 0.020" or 0.5mm wire was obtained in drawn condition as prescribed by the seller. The smart intelligent helical spring was prepared from 0.5mm diameters wires with the help of fixture-cum-spring tool and clamping wire then heat treatment provided in the furnace at 550º C for 45 minutes and then cooled for 24 hours by switch-off the furnace. This is one way shape memory SMA's in the form of NiTi wire nominal composition of 49.2% (Ni) – 50.8 %(Ti) and purchased from USA vai 'LINT SEELS'[2ND Floor, 32/34, Room No. 17, Damodar Niwas, C.P. Tank Road Gulalwadi, Girgoan Mumbai, Maharashtra-400004 (India)]

Figure 1: Flexinol wires

The SMA material wire of 0.020" or 0.5mm obtained in drawn condition which initially produced by the vacuum induction melting technique as prescribed by seller.

Table 1: Specification as-received

Length of each wire	10 INCH.	Diameters	0.020"/0.5mm Flexinol
Thermal Expansion Coefficient (Austenite)	11.0x 10^{-6}/°C	Thermal Expansion Coefficient (Martensite)	6.6x 10^{-6}/°C
Density	6.45 g/cm^3	Specific Heat	0.2 cal/g * °C
Melting Point	2370 °F (1300 °C)	Thermal Conductivity	0.18 W/cm * °C
Latent Heat of Transformation	578 cal/g.	Composition	49.2% (Ni) – 50.8 %(Ti)

The Table 1 represents the various parameters values such as length of each wire, diameters, thermal expansion coefficient (Austenite), specific heat, thermal conductivity, thermal expansion coefficient (Martensite), density, melting point, latent heat of transformation and composition.

3. Main Components/parts/tools used: The solenoid valve comprised of the spring tool, clamping wire, acrylic box, core-parts (Fixed cylindrical part and sliding part), muffle furnace, temperature sensors, polystyrene foam sheets, thin plywood sheet and DPM's and basic electric-electronic parts etc.

3.1 Spring tool (mild steel): These are also called spring manufacturing tools which removed the fixtures and clamping devices. This mild steel tool was prepared with the help of lathe machine and drill machine basically used in engineering's workshops. The lathe machine (horizontal/3-jaw chuck) involved various operations as turning, facing, centering, thread-cutting and drill machine (230V/2200rpm) involved the drilling operation of holes by 2.0mm drill bit.

Figure 2 spring tool

3.2 Clamping wire (soften mild steel): These are also called spring holding wire which removed the fixtures and clamping devices also. This soften mild steel was obtained in drawn condition by seller and mentioned that it made of mild steel and softened by annealing at 500° to 650°C for several hours. This process is known as "close" annealing.

Figure 3 Clamping wire

3.3 Acrylic box: It can be seen from Figure 2, which is made with the help of Autocad software of Autodesk Company Version-2017, It includes base plate having dimensions: 84.9mmx83.6mmx5mm, top plate having dimensions:84.9mmx83.6mmx5mm, two side plates and each having dimensions: 75.8mmx83.6mmx5mm. The base plate had a hole of 24.5mm diameter which was centrally placed. Two small acrylic rough plates were also placed on the base plate for the support which can be seen in original pictorial view.

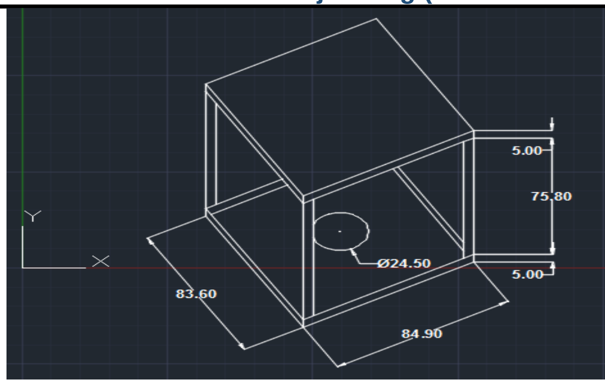

Figure 4 Acrylic box

3.4 Core-parts (Fixed cylindrical part and sliding part): The core parts basically consist of two parts, first one i.e. fixed cylindrical part and second part i.e. sliding part. The fixed cylindrical was a hollow cylindrical section of stainless steel having outside diameter: 24.5mm, inside diameter: 22.5mm, height: 60.0mm and thickness: 1.0mm respectively. The sliding part basically was 'cylindrical specimen' which having significant weight equal to 80gm. The dimensions included as height: 31.5mm, outside diameter: 24.0mm, inside diameter: 22.0mm and thickness 1.0mm respectively. The sliding part having a plastic wide knob (with hole) which was used for one end connections of NiTi based SMA spring.

Figure 5 sliding part

3.5 Muffle furnace (230 V/AC 1100 deg C): A muffle oven is a one type furnace in which the subject material is isolated from the fuel and inside coating made of glass wool. Muffle Furnace is a furnace with an externally heated chamber, the walls of which radiantly heat the contents of the chamber, so that the material being heated has no contact with the flame. It is operated at 230v upto 100deg C which managed by digital voltage regulator.

3.6 Polystyrene Foam Sheets: Two polystyrene sheet pieces has been used i.e. one for plywood sheet base and placed under it; another for base plate of acrylic box and placed also under it. The dimensions are 32.0cmx24cmx2.0cm (for main base), 90mmx88mmx2.0cm (for acrylic base) respectively.

Figure 6 polystyrene sheet

It has special features as lightweight, easily sandable, flat, smooth finish, laminated with tape or gum or paste and cuts with precision by knife so that it can provides additional Strength to plywood.

3.7 Plywood sheet (2.5mm thick): Plywood is a material manufactured from thin layers or "plies" of wood veneer that are glued together with adjacent layers or plywood referred to wood panels made of multi-layered veneer, bonded together with glue. (wood grain rotated up to 90 degrees to one another). These thin layers, also called plies, are glued together in alternating, perpendicular directions to create a cross-graining pattern. All plywood's bind resin and wood fibre sheets to form a composite material called plywood. it is ideal for applications in residential and light-duty construction .It have many forms as softwood plywood, medium plywood, hardwood plywood, marine type and cabinanet grade type etc. The medium type plywood and dimensions: 30.5cmx23.0cmx2.5mm has applied.

3.8 Temperature Sensor (LM35): Two LM35 temperature sensors (series are precision integrated-circuits which provide output voltage is linearly proportional to the celsius temperature) has been applied So temperature value measured with respect to volt (V) here. First one sensor for atmospheric temperature and another for actuation temperature has been applied. The proper connection has been used of LM-35 temperature sensor & indicated the digital value practically when body of active surface (black) glued or consistently touched within the working SMA.

3.9 DPM (2 pieces): Two digital panel meter with amplifier circuit (Operational type) and 5 volts supply output has been applied**:** A high performance and low power consuming integrated circuit (IC) 7107 that consists of seven segments decodes, reference voltage source, comparator and display drives as its internal circuiting It includes the IC7107 in which 0-2000 V digital panel meter using seven-segments display driver circuit seven light emitting diodes.

Additional parts/equipments used as:-

(i) DC Supply (15V/5A)

(ii) Electric cutter

(iii) Multimeter (digital)

(iv) Hot-air gun (2000W)

(v) Fixture holder

(vi) Digital caliper (stainless steel)

(vii) Ruler-scale (steel/30cm):

(viii) Two terminal connecters

(ix) Short connecting electrical wire

(x) Infrared Temperature sensor

(xi) Basic electrical-electronic components etc.

3 Manufacturing of SMA Helical Spring Specimens

The thin flexinol wire of 0.020" or 0.5mm wire was converted into conical spring (helix form) with the help of spring tool, clamping wire and muffle furnace to know the effect of unique parameters response for its actuation. The relation in the composition of this alloy as 49.2% (Ni) – 50.8 %(Ti) and phase transformation of SMA wire varies from 250-630°C. Wire was heated here above to its critical temperature as per required properties in strain recover rate for the applications in form of mechanics actuators to generate force or displacement. The fixture holder has been also applied for constant heating of SMA and placed inside the furnace can be seen in figure 7. We have also used Infrared Temperature sensor for the purpose of better accuracy in results.

Figure 7 (Muffle furnace)

The NiTi wire was wounded upon the threaded provided surface of spring tool and then clamping wire was used as to sustain its position over the NiTi wire.

3.1 Final SMA Springs: The annealing done by temperature of muffle furnace for preset-condition by muffle regulator and the temperature maintain at 550°C. Although tolerance of ±2° was also considered due to the fluctuation exist by auto cut supply for an instant of time with the help of regular. The process of annealing was done on 0.5mm NiTi wire i.e. SMA wire continuously heated at 550° C (constant temperature) for 45minutes then switched-off furnace and specimen remained for 24 hours inside it. The dimensions which were obtained as:

Figure 8 (final SMA Spring)

No. of turns of NiTi SMA wire for 0.5mm diameter obtained as '8' and mean coil diameter of 0.5mm SMA helical spring = 7.7 mm, outer coil diameter of it = 9.8mm(Base-End) and inner coil diameter =5.5mm (Apex-End) and the Spring Index of 0.5mm NiTi SMA Spring $\frac{D_1}{d_1}$ =7.7/0.5 =15.4 respectively.

4. Results and discussion

The main data obtained in table 2, the data inclues the values of Voltage (V), Average current (Ia), Average Wire Temp. (Tavg.), Atmospheric Temperature (Ta), Measured load (gm) and Sliding displacement (Xs).

Table 2: Observation data

Sr. No.	Voltage(V)	Avg. current (Ia)	Avg. Wire Temp. (Tavg.)	Atm. Temp. (Ta)	Measured load (gm)	Sliding displacement (Xs)
1	0.8	0	16.9	18.8	80	0
2	1.2	0.03	18.9	18.9	80	0
3	1.64	0.08	20.6	19	80	0
4	1.99	0.09	24.4	18.9	80	0
5	2.4	2.1	29.2	19	80	12.5mm
7	2.8	3.6	30.2	18.9	80	12.5mm

The variation of Voltage (V), Average current (Ia) and Average Wire Temp. (Tavg.) can be seen in figure 9. Green sketch in graph represents the variation of Average Wire Temp. (Tavg.), blue sketch in graph represents the variation of Voltage (V), red sketch in graph represents the variation of Average current (Ia).

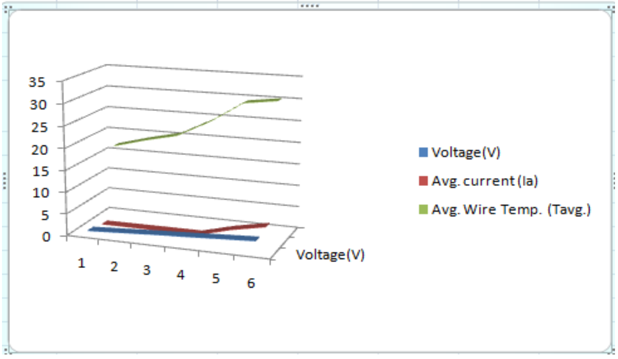

Figure 9: variation of V, Ia and Tavg.

The variation of Average Wire Temperature (Tavg.) and Voltage (V), can be seen in figure 10.

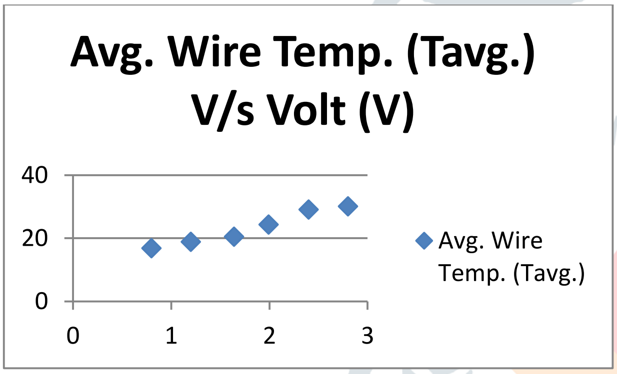

Figure 10: variation of Ia and V

The variation of Average Wire Temperature (Tavg.) and Average current (Ia) and can be seen in figure 11.

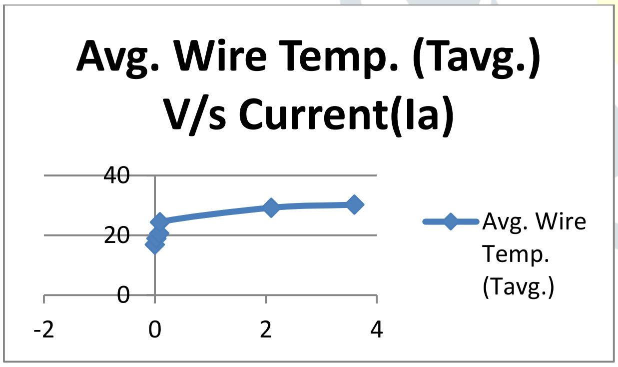

Figure 11: variation of Tavg. and Ia

The load measurement was obtained for the sliding specimen was obtained from the outside equal to 80gm and the displacement taken by the NiTi based equal to 12.5mm at the initial voltage of 2.4(V) ,initial current 2.1(Ia) respectively.

Conclusions

Mainly the minor application of 0.5mm SMA-based wire as a simple solenoid valve has been discussed in which SMA based conical spring in the helix form was employed. The advantageous purpose of valve to one way operated and can control the supply water, oil, liquid fuel and liquid refrigerant but choked by gravitational force/self weight. The obtained results shows that displacement taken by the NiTi based equal to 12.5mm at the initial voltage of 2.4(V) , at initial current 2.1(Ia) respectively. It is evidently clear from the results that the actuation of NiTi based SMA start after 1.99 voltages, so we can be considered this wire as a thin or slender SMA wire.

This work helps the researchers in the field of NiTi based SMA slender wire or thin wire about the initial voltage which significantly high.

References

[1] Y.Q. Fu, J.K. Luo and A.J. Flewitt, thin film shape memory alloys and microactuators, Int. J. Computational Materials Science and Surface Engineering, Vol. 2, Nos. 3/4, pp.208-226, 2009.

[2] Yongqing Fu, Hejun Du and Weimin Huang, TiNi-based thin films in MEMS applications: a review, Elsevier, pp.395–408, 2004.

[3] M Kabla, E Ben-David and D Shilo, A novel shape memory alloy microactuator for large in-plane strokes and forces, IOP Science, Smart Mater. Struct. 25, 075020 (8pp), 2016.

[4] Z.W. Zhong and S.Y. Chan, Investigation of a gripping device actuated by SMA wire, Sennsors and Actuators (A 136), Elsevier, pp.335-340, 2007.

[5] Je-sung Koh, Design of Shape Memory Alloy Coil Spring Actuator for Improving Performance in Cyclic Actuation, department of mechanical engineering, Ajou University, Suwon 16499, Korea, 2018.

[6] Mohammad Amri Zainal, Shafishuhaza Sahlan and Mohamed Sultan Mohamed Ali, micromachined shape-memory-alloy microactuators and their application in biomedical devices, Micromachines, vol.6, pp.879-901, 2015.

[7] Daniela tarnita, D. N. tarnita and N. Bizdoaca, properties and medical applications of shape memory alloys: Review, Romanian journal of morphology and embryology, 50(1), pp.15–21, 2009,

[8] Jan Schrooten, Ve´ronique Michaud and John Parthenios, progress on composites with embedded shape memory alloy wires, special issue on smart materials-fundamentals and applications, Materials Transactions, 43(5), pp. 961-973, 2002.

[9] Nicole Latrice Harris Odum, the characterization of thin film nickel titanium shape memory alloys, doctor of philosophy dissertation, Materials Engineering Department, Auburn University, Auburn, 2010.

[10] Xi Wang, crystallization and martensitic transformation behavior of niti shape memory alloy thin films, doctor of philosophy dissertation, The School of Engineering and Applied Sciences, Harvard University, Cambridge, 2007.