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Comparative Study of Electrically and Hot Water Actuated Shape Memory Alloy using Developed Thermo-mechanical Cycletest Bench

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ABSTRACT

The optimal design and analysis of hot water actuated shape memory alloy spring is presented. Smart materials exhibit special properties that make them a preferred choice for industrial applications in many branches of engineering. The serviceable properties of a Ni-Ti piece can be improved by altering the energy source. With hot water actuation, as the temperature reaches 70 °C - 90 °C, spring gets fully compressed for the first few cycles followed by loss in actuation. The actuation loss is then studied with different characterisation methods such as thermo gravimetric analysis (TGA) and scanning electron microscopy (SEM). With SEM results, it can be strongly recommended that the energy source is sufficient for actuation (not affecting too much the structure). Results observed from TGA shows high oxygen content at lower temperature, suggest the need of conducting experiments in inert atmosphere. For the validation of hot water actuation, comparative analysis between electrical and hot water actuation is done. Graph shows that, there is a good agreement between both the methods. In addition to this, the application of hot water actuation is some micro-devices like micro-valve, drug delivery, directional control valve, also in engine in place of thermostat valve etc.

Keywords: Shape memory alloy; Thermo-mechanical cycling test bench; Characterisation technique; Hot water actuation

1. INTRODUCTION

Shape memory alloy (SMA) is an intelligent material that remembers its original shape, it does so upon heating. The conventional actuators are replaced by SMA since it is light weight and solid state alternative to it. In SMA these properties are achieved through solid-solid phase change (molecular rearrangement)[1]. These unique properties are achieved through a solid-state phase change (molecular rearrangement) that occurs in an SMA. High temperature parent phase is austenite and low temperature phase is martensite. When the phase transformation occurs between austenite to martensite, it is referred to as martensitic phase transformation and the property is known as the 'shape memory effect[3-5]. A simple SMA actuator has the potential to replace complex electromechanical systems, allowing for reductions in cost, size and weight. Compactness of SMAs allows easy incorporation into mechanical devices of small size and used as actuating elements[2]. There are some advantages of SMA such as high strain, silent operation and mechanical simplicity but the response time and energy efficiency limits its performance. SMA's are widely available in various forms such as sheet, spring and wire etc. SMA's are widely used in engineering industry, military, health, toys, aerodynamics, home appliances medical catheters, stents (thin wires, mesh form)[6-8], laparoscopic surgical tools (patterned tubing, wires)[9], and micro-robot actuators (coiled wires)[10,11]. As the field of smart materials evolves, it is vital to develop new technologies for better ways to actuate and control precisely to perform more knotty tasks. The methods available for the actuation of SMA are electrical current[12-16], laser[17-18], hot air, hot fluid, etc. Bo[24], *et al.* provide a comprehensive review of hysteresis modelling which forms a significant part of the SMA actuator modelling.

Christopher[12], *et al.* developed SMA wire based experimental setup to examine the thermo-mechanical behavior of the conditioned SMA wire. The SMA wire was clamped to a 100 N load cell. The heating cycle was obtained using an electrical resistive heating and natural convection was used for cooling to generate thermo-mechanical cycle. The thermo-mechanical behavior was imaged using a low power laser. The major limitations of this setup are (i) restricted to wire (ii) variable load cannot be applied. Saikrishna[13], *et al.* investigated the thermo-mechanical cycle on SMA wire through the transformation range under a constant or fluctuation load. The cycles were performed by resistive heating and forced cooling. The displacement of the wire during the thermo mechanical cycle was monitored using non-contact laser device which has a resolution of 10 µm. The recovery strain and the remnant deformation were recorded continuously throughout the experiment. However monitoring the true strain is limited with laser displacement sensor.

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Mammano[14], *et al.* introduced a set up to investigate the fatigue in SMA wire which is attached to a rigid clamp. The lower end of the SMA wire is constrained which is heated though an electrical resistance and the fan maintains a constant air flow across the wire. The equipment has a compatibility to apply constant stress, constant strain, constant stress with limited maximum strain and linear stress strain cycle. However the system is limited to measure the engineering strain and there is no provision to acquire the data for each and every cycle. In the previous setup a forced convection was applied through cooling fan whereas in the set up proposed by Olivier and his group[15], the forced convection is adopted by passing a chilled fluid, thus inducing a martensite transformation in the system and the wire is actuated through electrical biasing. Costanza[16], *et al.* developed one basic set up to investigate the thermo-mechanical behaviour of the SMA spring. The actuation is performed by electrical resistive heating, followed by natural cooling cycles in fully automatic manner. The system consists of a relay circuit actuated by a TTL signal coming from a function generator. A metallic base with a ceramic guide fixed inside has been adopted for the characterisation of the cyclic experiments of the spring. However the major limitation in this setup is the lack of online monitoring and the experiments are performed for the complete elongation of the springs and cannot be opted for small displacement. Nath[17], *et al.* proposed and actuated SMA sheet based micro-positioning stage using laser, in this study the requirement of optimum fluence for the actuation of SMA sheet is 100 mj/cm^2 which gives 7.25 mm displacement of it. When the same stage is actuated through electricity it requires 5 V (1.2 Ampere) supply and measured displacement is 6.10 mm. Nath[18], *et al.* developed SMA sheet based micro-valve, actuated using laser for investigating its flow rate which showed that the maximum deflection achieved for optimum LASER fluence of 25.48 mJ/cm^2 is 7.29 mm, The flow measurement was performed using an air meter at pressure difference ranging from 1 KPa to 5 KPa with minimum rate of flow 325 μL/s.

In order to validate the results for heating-cooling cycles and to investigate the cause for depletion in its actuation property, SEM and TGA were conducted. SEM gives the information about the sample's external morphology (texture) and TGA is a method of thermal analysis in which changes in physical properties of materials are measured as a function of increasing temperature and time. It is used to determine selected characteristics of materials that exhibits either mass loss or gain due to decomposition, oxidation. Some micro-structural observations performed has shown that SMAs are in fact very sensitive to overheating[19]. Since excessive electrical power has the capacity to overheat the SMA, causing thermal stress fatigue and a gradual degradation of its performance, so optimum time is calculated for heating and cooling[27]. Other techniques like laser, hot water can be chose but due to some drawback like non uniform heating, Clumsy joints, single pointed source, low energy capacity hot water is preferred over Electrical and laser actuation. Literature survey reveals that most of the authors focused their studies on SMA sheet. Here SMA spring is taken and showed its result.

Note: For actuation of shape memory alloy two methods has been done, electrical and hot water actuation. For investigating actuation time and temperature one important assumption is that structure has to follow continuity equation. ($m = \rho AV = \rho Q$, for which density is constant across a section)

2. EXPERIMENTAL SETUP

Test bench is developed to perform experiments based on the medium (Electrical and hot water) used. It comprises of an actuation unit and a displacement sensing unit with a load pulley arrangement. Especially Ni-Ti (Nitinol) spring (high resistive) which is an equiatomic (Ni-Ti 50 per cent - 50 per cent) and in nature, is used with specifications as described in Table 1. Heating-cooling cycle is defined based on the time when steady state is achieved. Laser displacement sensor (Model: HL-G-108-A-C5), supplied by Panasonic, with resolution 2.5 microns over a displacement range of 40 mm at a frequency of 664 nm is used to find the displacement. Data-acquisition system, Supplied by Agilent Technologies (Model 34970 A) is used to take the data from LDS in terms of voltage and thermocouple (K-type) in terms of °C. Spring is held fixed at one end and at the other end load is applied. A flapper arrangement is made that laser displacement sensor takes as reference for the calculation. The actuator is interfaced to a computer via a data-acquisition system (Agilent 34970 A). Data from LDS is measured in terms of voltage with the help of data acquisition system and then the reading can be seen on the system. To generate a displacement, electricity/hot water is poured in the container and then cooling is done through natural convection. During heating and cooling the martensite changes to austenite; the length of the spring reduces with mass movements upward and the austenite changes to martensite; the length of the spring increases with the mass movement downward, respectively.

Table 1. Specification of Ni-Ti SMA spring (supplied by dynalloy Inc.)

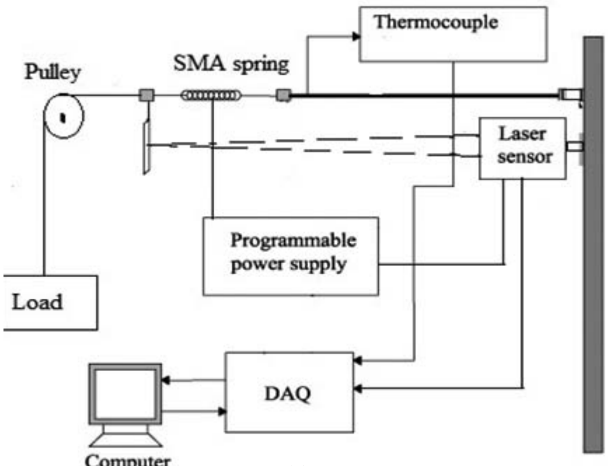
Parameter	Value
Solid length	13.86
Number of turns	18
Wire diameter (mm)	0.77
Coil Diameter (mm)	5.69

2.1 Electrical Actuation

An experimental set up for electrical actuation has been developed (Fig. 1). Because of their metallurgical composition shape memory alloys especially Ni-Ti can be heated and subsequently activated by passing a direct current through them, also called joule heating. The current value can be empirically evaluated for the specific ambient conditions on which the actuator must operate. Heating and cooling for five cycles were recorded and analysed for maximum displacement attained.

2.2 Hot Water Actuation

Ni-Ti Shape memory alloy spring is actuated using hot water. An immersion rod is used to heat the water kept in the container (Fig. 2) which in turn supply thermal energy to the spring. The temperature imparted to the spring with this thermal energy when reaches the transformation limit in turn actuates the spring. But the actuation was not linear indeed drastic.



(a)

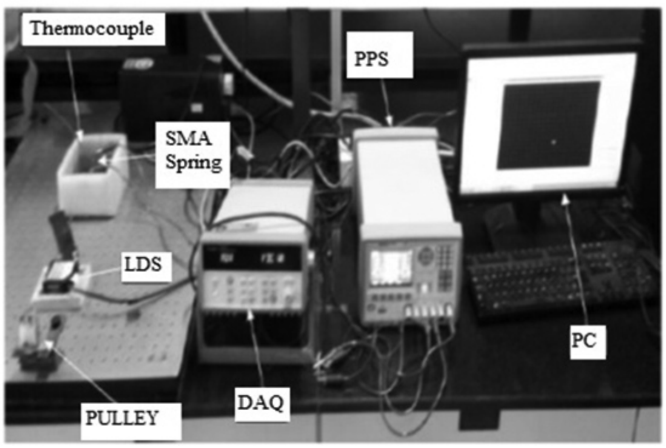


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Figure 1. (a) Schematic diagram for electrical actuation and (b) Experimental set up (actuator/sensor location) for electrical actuation.

2.2.1 Thermal Modelling for Hot Water

Since Heat is applied on SMA spring using hot water, so it is important to know the fluid temperature and flow rate which is function of SMA wire.

Assume SMA wire is considered as a cylinder. Parameters related to SMA wire are:

$Q =$ Heat flux

$D_i =$ Inside diameter

$D_o =$ Outside diameter

$T_w =$ Temperature of wire

$T_f =$ Temperature of fluid

$h_i =$ Heat transfer coefficient

$L_c =$ Characteristics length $= D_o - D_i$

$N_u =$ Nussult number

$A =$ Area

$K_f =$ Thermal conductivity of fluid

$P =$ wetted perimeter

$m_f =$ Mass of fluid

$C_p =$ Specific heat at constant pressure

$A_f =$ Area of SMA wire

$\rho_f =$ Density of SMA material

$u_f =$ Velocity of fluid

So, Heat flux from SMA wire is given by Newton's law of cooling which is valid only for small temperature[19]

$$Q_i = h_i(\pi D_i)(T_w - T_f) \qquad (1)$$

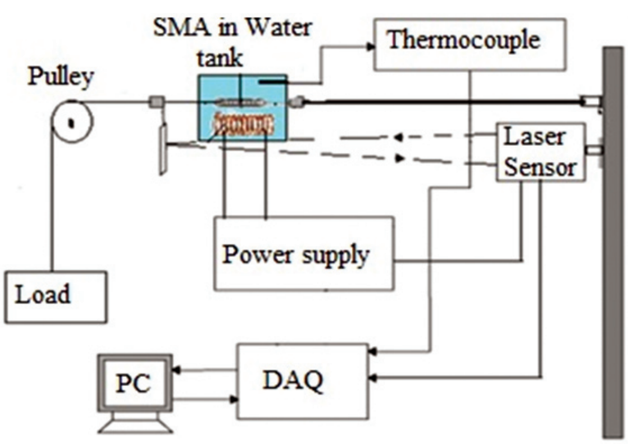
Nusselt number is required for free convection so,

$$N_u = \frac{h_i L_c}{k_f}$$

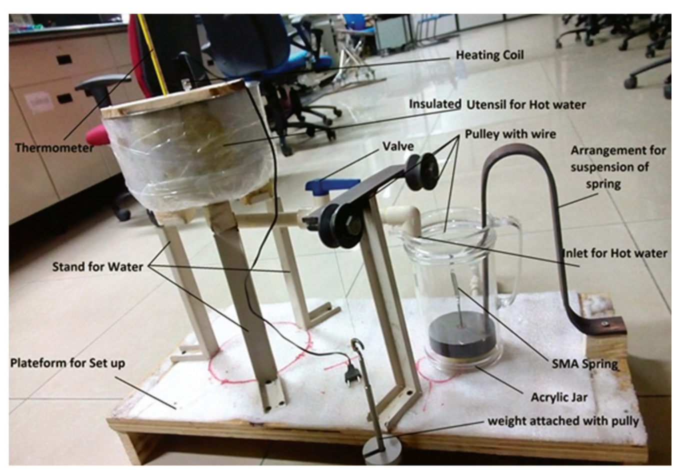
For cylinder, $L_c = \dfrac{4A}{P}$

So, $h_i = \dfrac{N_u . k_f}{D_o - D_i}$

Now by putting value of h_i into Eqn. (1):



(a)



(b)

Figure 2. (a) Schematic diagram for hot water actuation and (b) experimental set up for hot water actuation (actuator/sensor location).

$$Q_i^{'} = \frac{N_u k_f}{D_o - D_i} \times \pi D_i \left(T_w - T_f\right)$$

$$\left(T_w - T_f\right) = Q_i^{'} \frac{D_o - D_i}{N_u k_f \pi D_i} \quad (2)$$

Now $Q_{LOSS} = Q_{Gain}$

$$\dot{Q}_1 = m_f C_p \Delta T_F$$

$$\dot{Q}_1 = m_f C_p (T_{in} - T_{out})$$

$$\frac{d\dot{Q}_1}{dx} = m_f C_p \frac{dT_{Final}}{dx}$$

So, for fluid:

$$Q_1^{'} = m_f C_p \frac{dT_F}{dx} \quad (3)$$

$$\frac{Q_1^{'}}{m_f C_p} = \frac{dT_F}{dx}$$

$$\dot{m}_f = \rho_f A_f u_f$$

$$\dot{m}_f = \rho_f \frac{\pi}{4}\left(D_o^2 - D_i^2\right) u_f C_p \frac{dT_F}{dx}$$

To avoid overheating flow rate of fluid must be too much fast.

$$u_f = \frac{4Q_1^{'}}{\pi C_p \rho_f (D_o^2 - D_i^2)} \left(\frac{dT_F}{dx}\right)^{-1} \quad (4)$$

3. RESULT

3.1 Electrical Actuation

Figure 3(a) shows the maximum displacement obtained .Three different loads are selected i.e. 2.5 N, 3.5 N and 4.5 N. Figure 3(b) shows displacement versus time for the load of 2.5 N, 3.5 N, and 4.5 N at 2.0 V. It can be observed from the Figs. 3(a)-3(e) that the maximum displacement for 2.5 N were 14 mm, 18 mm for 3.5 N, and 22 mm for 4.5 N, respectively. Time taken to complete one cycle was 100 s (30 s for heating and 70 s for cooling) and the applied voltage was 2.0 V. Minimum voltage was taken to measure the maximum displacement and precise temperature preciously. The speed of actuation with different loads was not studied as it is beyond the scope of this paper. Figure 3(b) shows the time *vs* temperature plot. The maximum temperature to actuate the spring was approximately 60 °C, which was achieved for all the loads. There was a rather homogeneous temperature profile for all the loads and the loads did not have considerable influence. For one of the cycle, hysteresis (dynamic lag between heating and cooling cycle) graphs were plotted as depicted in Figs. 4(c), 4(d) and 4(e) at 2 V with 2.5 N load. During heating and cooling the displacement varies drastically approximate 40 °C - 50 °C, which might be the temperature transformation. As a result, there is intersection as seen in Fig. 3(e), moreover there is significant change which can be observed from Figs. 3(c) and 3(d) in the mentioned temperature region. Furthermore, once the spring compresses, the displacement clearly reduces more rapidly after 12.5 mm. However, the hysteresis loop was compact in all the three instances. The resistivity of TiNi is approximately 80 microhm cm, and is suitable for joule heating (electrical actuation)/hot water which provides a simple means of actuation. Efficiency is low because of the small temperature difference in which the transition takes place, and removal of heat is slow. SMA wire has not replaced electric motors for many applications[25].

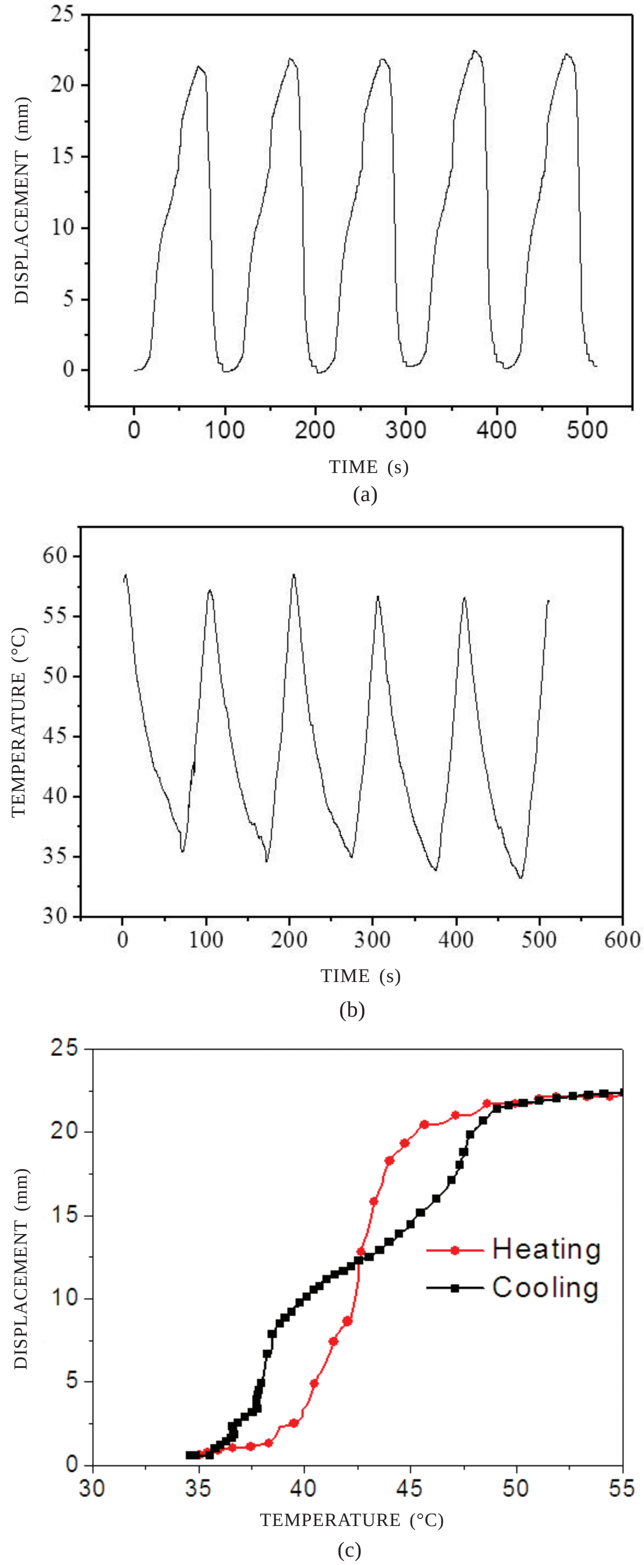
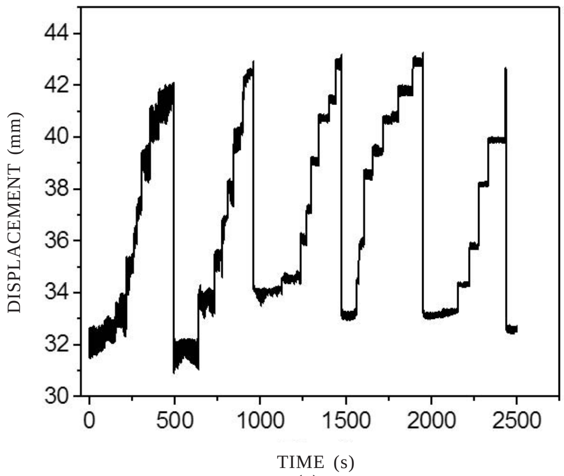


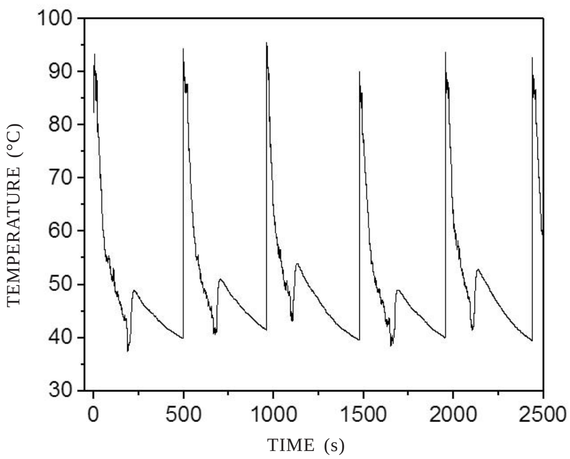
Figure 3. (a) Displacement versus time for 4.5 N load, (b) Temperature versus time for 4.5 N load, and (c) Displacement versus temperature for 4.5 N load.

3.2 Hot Water Actuation

Figure 4 (a) shows displacement versus time graph when spring is loaded with 4.5 N. Heating time (25 s) is very less compared to cooling time (20 min). The graph is plotted between displacement and displacement which shows the hysteresis nature i.e. dynamic lag between input and output stage. As the temperature reached 83 °C, a deflection of 4.3 mm can be seen from Fig. 4(c). Data from LDS is measured in terms of voltage with the help of Data acquisition system and reading is transferred to the system. For the same cycle temperature versus time curve Fig. 4(b) is plotted, in that fluctuations in gaining the temperature can be seen which may be due to release/absorption of latent heat and heat transfer with the ambient condition[20-21]. The transformation range for the one cycle (heating and cooling) is approximate 45 °C - 85 °C. Hot water actuation is gained when the temperature is reached stated above and then cooling happens through natural /forced convection[26]. SEM and TGA was performed over samples which are subjected to 5 cycles of Heating-cooling. Figure 5(a) shows scanning electron microscopy images of non-treated spring whereas Figs. 5(b) and 5(c) shows SEM images for electrical and hot water activation. Hot water actuated sample is more dense than Electrical actuation. Here it is observed that



(a)



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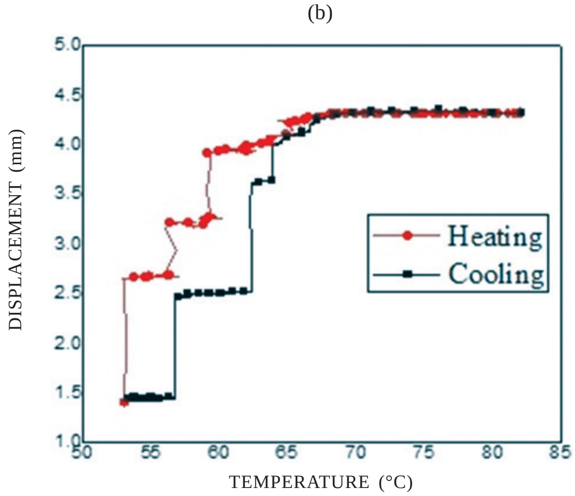
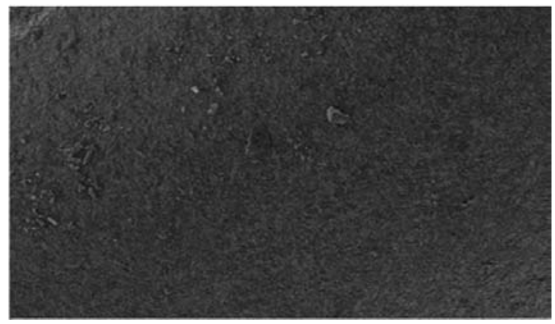
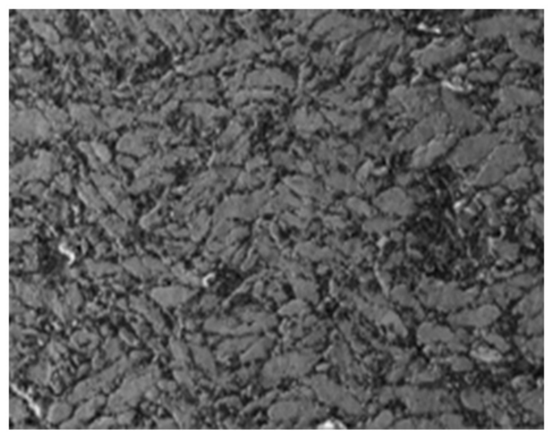


(c)

Figure 4. (a) Displacement *vs* time for 4.5 N load, (b) Temperature time for 4.5 N load, and (c) Displacement *vs* temperature for 4.5 N load.



(a)



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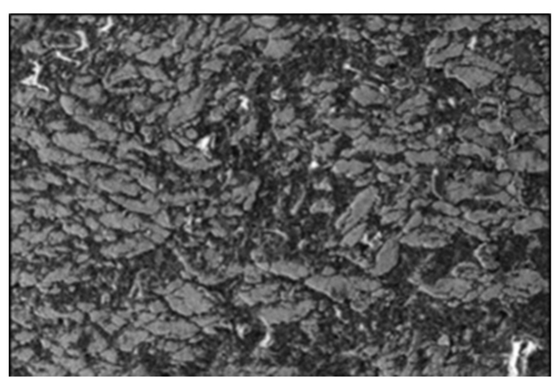
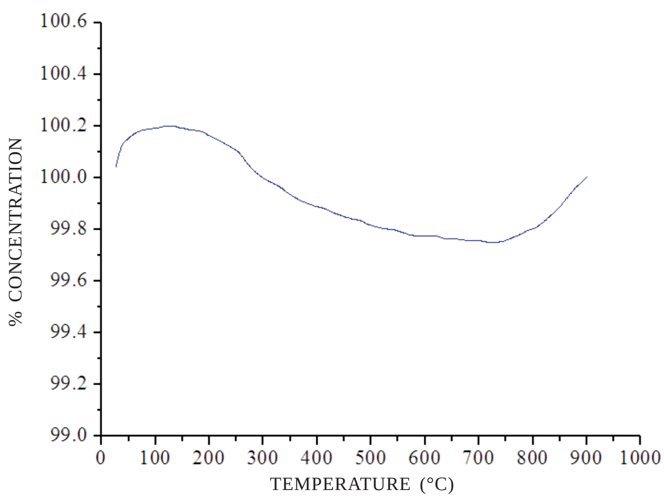


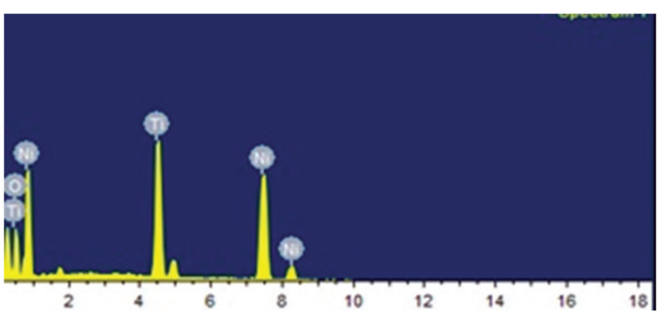
(c)

Figure 5. (a) SEM images for Non-Treated Ni-Ti, (b) SEM images for electrically actuated Ni-Ti, and (c) SEM images for hot water actuated Ni-Ti.

the structure shows elongated grains where black part is for Titanium and grey ones for Nickel. Figure 6(a) and 6(b) is for TGA analysis which explains that Nickel content is more than Titanium content though elongated grains results an increase in strength and hardness but it is also observed that the alloy becomes more brittle and more liable to fracture due to this actuation. The spring over which SEM is conducted is actuated with hot water for five cycles (1 cycle is equal to heating + cooling) Fig. 6(b) shows Thermo gravimetric analysis[22] which is done to find kinetics of oxidation. Upon cooling the Ni-Ti becomes weaker and the spring easily deforms the actuator while it closes tightly in the structure[28]. The loss or gain of material can be because of decomposition or oxidation. Here, it is shown that an increase in per cent weight concentration is observed at temperature range of 0-100 °C, which may be due to the oxide formation of Ni-Ti alloy. This is further verified with EDX data which shows 52.46 at per cent of oxygen content in the sample. Between 100 °C - 200 °C, Ni-Ti spring is severely oxidised and then decomposes after this limit. At about 800 °C, there is an increase of Ni-Ti per cent weight concentration (Fig. 6(b)) which may be because of nitridation in Ni-Ti alloy[23].



(a)



Element	Weight%	Atomic%
O	12.79	52.46
Ti	12.56	17.20
Ni	27.14	30.33

(b)

Figure 6. (a) TGA performed on hot water actuated spring and (b) EDX data performed on hot water actuated spring with its elemental percentage.

Finally it can be concluded that in case of electrical actuation, maximum displacement for the force of 2.5 N were 14 mm, 18 mm for 3.5 N and 22 mm for 4.5 N respectively, based on this displacement with focused load, assume flow rate is 350 µL/s at a varying pressure ranging from 5 KPa - 15 KPa, whereas in case of hot water actuation, maximum displacement is 11 mm for 4.5 N and based on this combination flow rate is 200 µL/s at a varying pressure

4. CONCLUSION

Here hot water media for shape memory alloy has been proposed. It has been found that actuation gained by hot water is good enough to use in practical applications. It is capable of actuating the spring once the temperature reached transformation limit. Thermo gravimetric results shows weight gain i.e. oxidation till 100 ^{0}C and then decomposition starts. Oxygen content is further validated with Electro dispersive X-ray spectroscopy (EDX), also weight gain after 800 ^{0}C can be because of Ni-Ti nitridation phenomenon. Results showed high oxygen content in the samples with about 50 per cent of oxygen by atomic weight and rest is Nickel and titanium. By changing thermal source, we can control the displacement for different load values. Hot water can be used at places where we cannot go for electrical connections, as it makes the setup clumsy. Applications can be micro valves for drug delivery; also in engines it can replace thermostat valve. The present study could represent the vital observations and results when actuated with Hot water.

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In the current study, he gave the idea for developing this set up and full work has been completed under his supervision.