Indian Journal of Pure & Applied Physics
Vol. 59, March 2021, pp. 216-222

Characterization and Behavior Study of Nitinol Shape Memory Alloy Wire for Effective and Efficient Use in Soft Robotics as an Actuator

Mithilesh Kumar Koiri & Anuj Kumar Sharma*

Centre for Advanced Studies, Dr A P J Abdul Kalam Technical University, Lucknow- 226 031, India.

Received 27 January 2021; accepted 17 February 2021

Soft Robotics is an emerging field due to high degree of freedom, their soft and delicate interaction, almost no vibration during operations *etc.* are some among many reasons, why scientists and researchers got attracted towards this field. Nitinol is commonly used in soft robotics and easily available Shape Memory Alloy (SMA) actuator. In present investigation, the authors attempted to understand the characteristics and behaviour of Nitinol SMA Actuator wire with change in various parameters such as length, diameter, current, and temperature. Moreover, it is investigated, how resistance, power consumption, force developed, hysteresis, and displacement changing takes place with current passing through the wire and corresponding temperature developed. Various experiments are performed and based on the results and findings related to the selection of wires for specific requirement have been discussed and suggestions were made for the use of the SMA actuator efficiently and effectively.

Keywords: SMA, Soft robotics, Actuator, Nitinol, Temperature

1 Introduction

Soft robotics is a field of robotics which mainly deals with the robots having no links, gears, and motors *etc.* as in the case of conventional robots. These robots have higher degree of freedom, and can interact with people softly and delicately and have almost no vibration during operations[1,2]. (SMA)[3-5] actuator based soft robots have been the domain of attraction for researchers working in the field of robotic and automation due to their unique properties over traditional rigid robots, like lightweight, higher flexibility, low cost, easy fabrication, and less sound and vibration[6]. Most of the soft robots work on the principle of muscle hydrostats. This special muscular organization forms the structures called muscular hydrostats, whose main property is their volume which remains constant during muscle contractions[7]. In soft robotics, the SMA is used widely and extensively due toits special characteristic of memorizing the predefined shape. Moreover, various types of robots and automatic machines can be developed using SMA actuator like underwater robots, micro-actuator and grippers, colonoscopy, self-re-configurable robots, autonomous and in-pipe walking robots, parallel manipulators *etc.*[8,9]. SMA are materials that can memories their original shape and return to its previous state when heated. The original shape can be set easily by doing heat treatment. The SMA crystallographic structure changes between two phases, *i.e.* between the low temperature (martensite) and the high temperature(austenite) phases. Nitinolis SMA material, which is analloyofnickel and titanium (discovered in Naval Or dance Laboratory in the sixties of the twentieth century)[10]. It can be used in a simple and complex robotic and automation system due to its simplicity and easy operations in minimum space. In present paper, the characterization and behavior study of Nitinol SMA Wire have been carried out for effective and efficient use of these wires in soft robotics, as an actuator. Various parameters and properties which are usually considered for the development of any robots such as force or torque developed by actuators, power consumption, voltage and current required, resistance, space requirement, response time have been discussed and analyzed. The measurements are performed on five SMA actuator wires with different diameter, length and spring coil diameter. For the ease of understanding, the wire of diameter 0.12 mm, length 8cm and coil diameter 3mm is named as “A”, the wire of diameter 0.3mm, length 8cm and coil diameter 4mm is named as “B”, the wire with diameter 0.5mm, length 8cm and coil diameter 5mm is named as “C”,

*Corresponding author (Email: sharmaanuj79@gmail.com)

the wire with diameter 0.5mm, length 14cm and coil diameter 5mm is named as "D", and the wire with diameter 1mm, length 8cm and coildia meter 10mm is name d as "E".

2 Experimental Setup

The experimental setup and schematic diagram for measuring displacement and temperature is illustrated in Figs. 1&2, respectively. The experimental setup for measuring force developed in SMA based spring type actuator and the corresponding schematic diagram is depicted in Fig. 3 and Fig. 4, respectively.

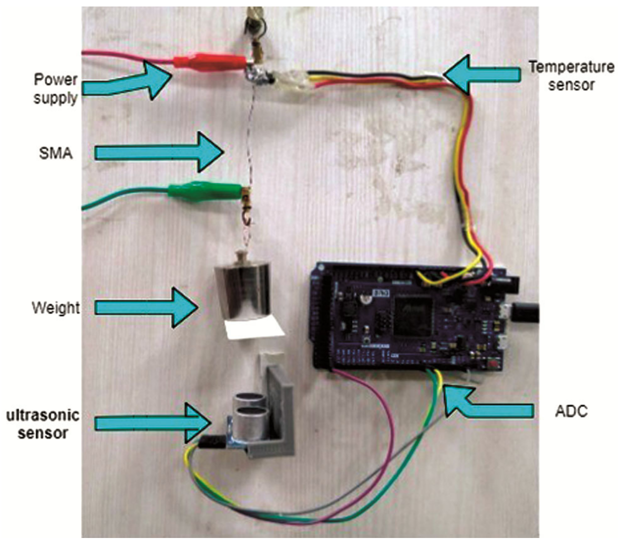

Fig. 1 — Experimental setup for measuring displacement and temperature

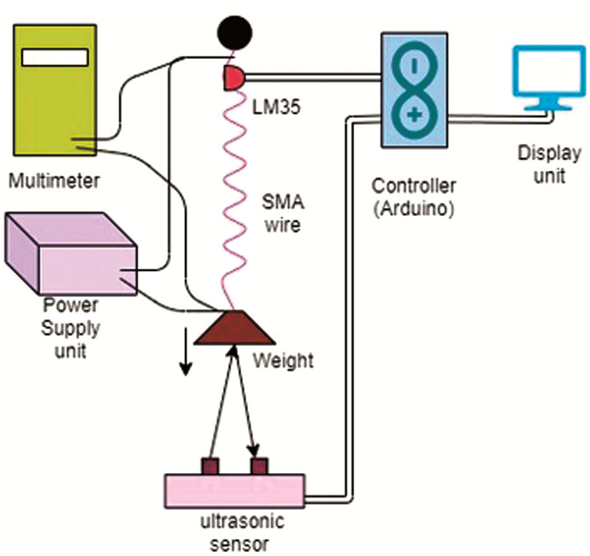

Fig. 2 — Schematic diagram of experimental setup for measuring temperature, displacement, Resistance for a wire carrying constant load.

3 Results and Discussion

Various experiments have been performed on SMA wires of different diameter and length. The characteristics and behavior of wires under different variables such as force developed in spring type SMA actuator, power consumption, resistance variation, displacement, response time with current and temperature have been investigated and analyzed.

3.1 Variation of Temperature withCurrent

From the microscopic point of view, the transformation consists of transition from a crystallographic phase stable at low temperature, *i.e.* martensite, to a different crystallographic phases table at high temperature, namely austenite. The critical temperatures at which transition occurs, mainly depends on the composition of the alloy, its thermo-mechanical history and the From the microscopic point of view, the transformation consists of transition

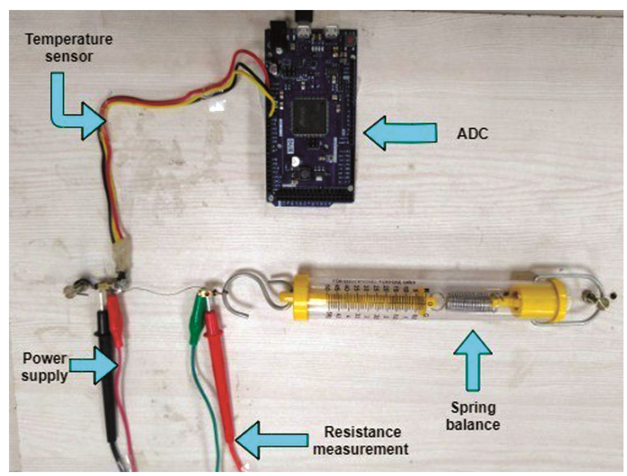

Fig. 3 — Experimental setup for measuring force developed in SMA based spring type actuator.

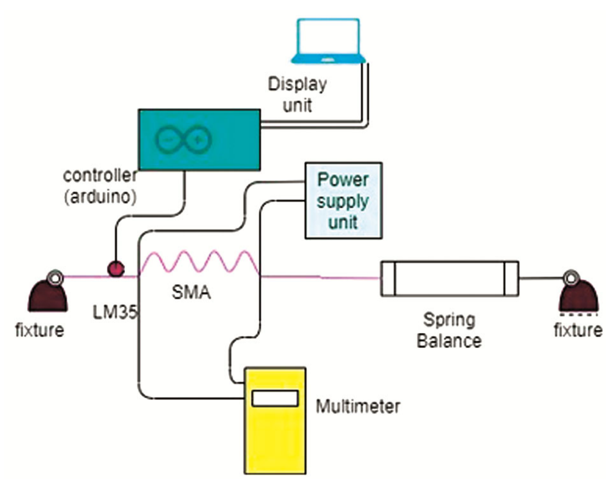

Fig. 4 — Schematic diagram of experimental setup for measuring force.

from a crystallographic phase stable at low temperature, *i.e.* martensite, to a different crystallographic phases table at high temperature, namely austenite. The critical temperatures at which transition occurs, mainly depends onthe composition of the alloy, its thermo-mechanical history andthe Heat developed in the wire is directly proportional to I^2 and t, therefore, it has parabolic nature. It is an established fact that with increasing heat, the resistance of the wire increases, and as a result, heat developed in the wire increases which further increases the resistance of the wire even at constant current.

The process of heat transfer in the wire is a vital factor to be considered. Considering uniform heating of the wire due to passes of current, heat loss by convection is given by:

$$\dot{q} = -hA\,(T_{sma} - T_{\infty}) \qquad \ldots (1)$$

Where h is the convective heat transfer coefficient that is to be determined, A is the lateral surface are a of the wire and T_{sma} is the temperature of the wire. It has been assumed that the temperature is uniform through out the wire. However, the wire's temperature changes rapidlyover time as a consequence of the heat loss. Therefore, the T_{sma} is given by

$$T_{sma} = T_{\infty} + (T_0 - T_{\infty})e^{\left(\frac{-hA_{sma}}{V_{sma}\cdot\rho_{sma}C_p}\right).\tau} \qquad \ldots (2)$$

Where V_{sma} is the volume of the wire and T_0 is the temperature at time t = 0, C_p is the heat capacity of wire, ρ_{sma} is the density of the wire material[11].

From Fig. 5, it is observed that in case of SMA wire "E", the heat developed is minimum with positive variation of current and the temperature of the wire can be increased only up to 30°C even the current through the wire has been increased above 1.5 Ampere. In Fig. 6, it is observed that the actual transformation of SMA actuator wire from marten site to austenite starts above 34°C up to 40°C and higher with rise in temperature.

3.2 Variation in displacement with temperature andload

Though the conversion of crystalline of the wire startsabove 27°C as crystal structure of twinned martensite shown in Fig. 7 (marten site without distortion) started to convertin to austenite, but initially it does not develop sufficient force. It can clearly be observed in Fig. 8 that for 0.3 mm spring

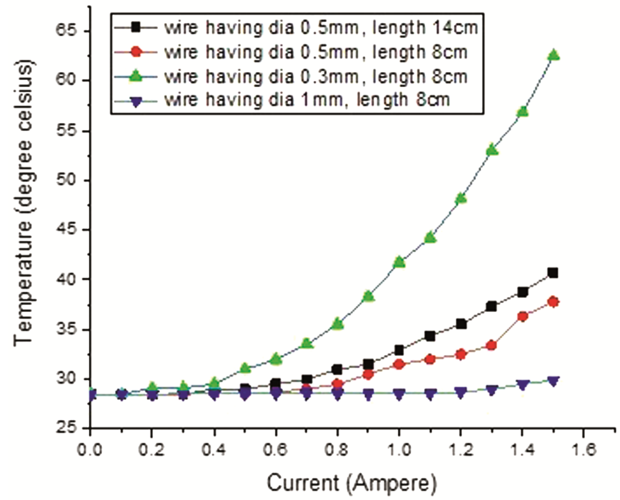

Fig. 5 — Variation of temperature with current in different wires.

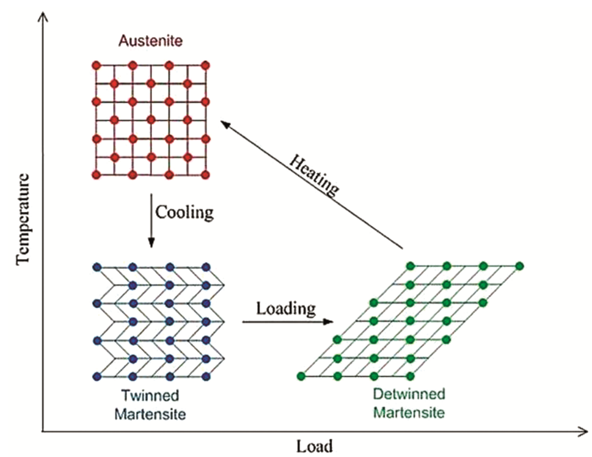

Fig. 6 — Variation of displacement with temperature and the hysteresis developed during operation for a wire with 0.5 mm diameter and load of 3N.

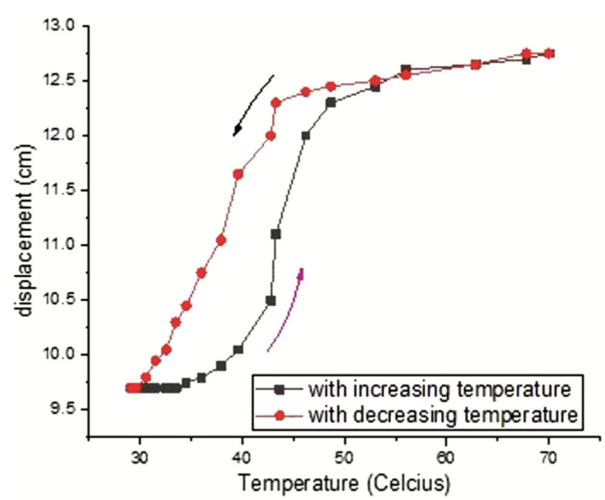

Fig. 7 — The process of transformation of crystal structure austenite to martensite formation[12].

wire carrying a load of 24gm needs a rise in temperature above 34℃ for a significant detectable change in structure. In Fig. 8 it can also be observed that the SMA wire with higher distortion due to higher load start regaining its previous state comparatively at early temperature than that of the same wire with low load. This is due to the conversion of wire material from detwinned martensite to twinned martensite followed by the conversion to austenite as shown in Fig. 7.

The hysteresis is a significant characteristic of the heating and cooling behavior of SMA. Hysteresis and non-linearity create problems with position control of SMA actuator. The heat loss during the phase transformation causes hysteresis behavior of SMA[13].

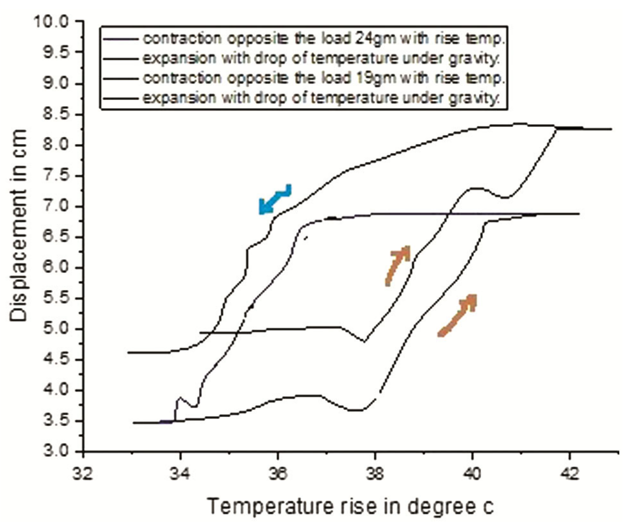

Fig. 8 — Variation of displacement with temperature and load.

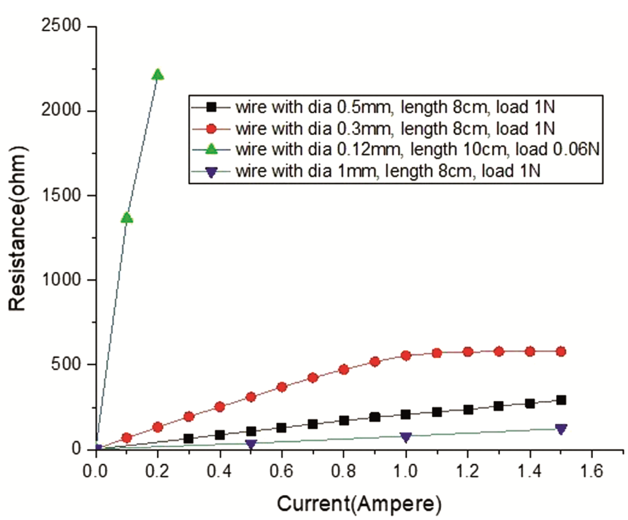

Fig. 9 — Variation of resistance of different wires carrying constant load, with current.

In Fig. 6 and Fig. 8 the above said behavior of hysteresis can be observed. The mathematical model has been presented in the given equation showing the behavior of SMA.

$$(dR/R) = \pi_e \, . d\sigma + K_\varepsilon . d\varepsilon + \alpha_t . dT \qquad \ldots (3)$$

Where, R is resistivity, π_e is piezoelectric coefficient, σ is stress, K_ε is coefficient of shape sensitivity, Ɛ is strain (deformation), α_t is coefficient of thermal expansion and T is temperature[14].

3.3 Variation of resistance with current

SMA wire is such an actuator that is directly used in an electronic circuit like a normal wire. Therefore, it becomes important to know the behavior change related to resistance with current, temperature and with the variation of loads. It is established fact that $R = \rho L/A$ that the resistance is directly proportional to length and inversely proportional to cross sectional area.

It is observed in Fig. 9 how change in resistance took place with current when a constant force of 1N is applied on it. It is opined from Fig. 10, how the

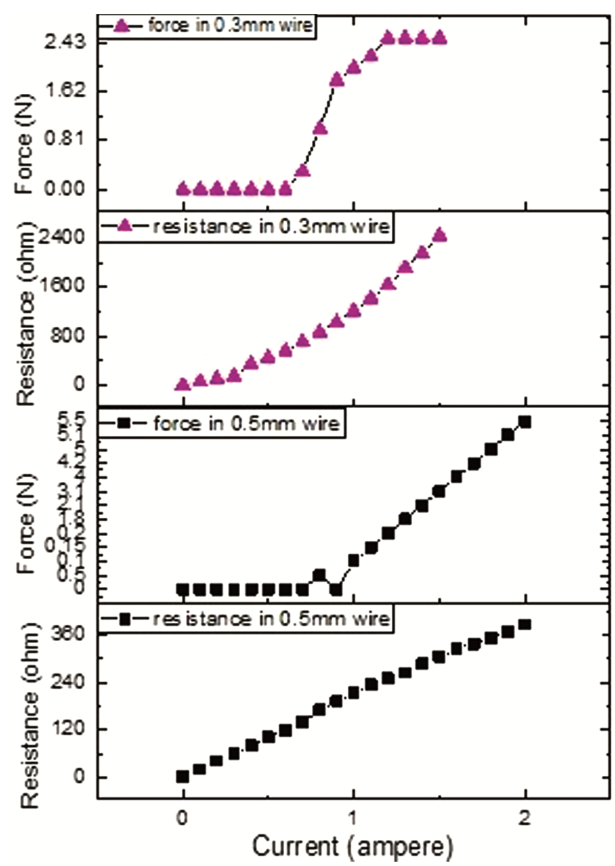

Fig. 10 — Variation of resistance with current in different types of wire and corresponding developed force.

resistance and developed force in the wires vary with current, when force carrying capacity is measured using spring balance. Furthermore, it is observed from Fig. 11 that, during resistance test, under the load carrying capacity of trained SMA wire, the displacement of the spring beyond which it does not return back to its original position, variation of load does not cause any variation in resistance up to certain maximum value of resistance. Here a testing have been performed on a wire with 0.5mm diameter carrying different loads that are 1, 2 and 3N respectively.

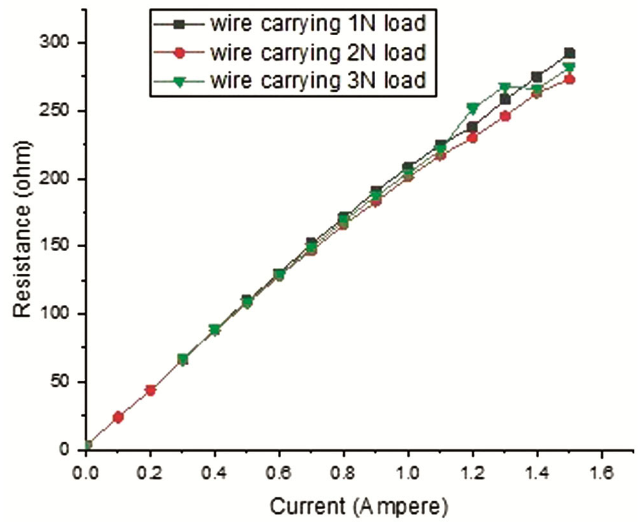

Fig. 11 — Variation of resistance 0.5mm wire with current with variation of load under load carrying capacities of wire.

3.4 Variation of power with current.

Power consumption is a very important factor to be considered for developing any automatic system. It is required for any system to be developed so that it consume power as low as possible. The variation of power is illustrated in Fig. 12. The electric power is the energy required or consumed by a system per unit time. Mathematically it is given by-

$$P_e = I^2.R = \left(\frac{I^2 \rho_n l}{S_n}\right) \quad \ldots (4)$$

Where, I=current, R=Resistance, ρ_n = Resistivity of Nitinol, l= length of the wire, S_n= Cross sectional area of wire.

Here power is the heat developed in the wire per second. Out of this heat, some part is used to perform the work but most of the heat is lost in the surrounding environment.

$$Heat\ of\ wire = Heat\ developed - Heat\ lost$$

$$H_w = I^2Rt - h_a A_s(T_w - T_\infty) \quad \ldots (5)$$

Where, h_a= Convective heat transfer coefficient of surrounding air or water, A_s=surface area of wire, T_w = Temperature of wire, T_∞ = Temperature of surrounding.

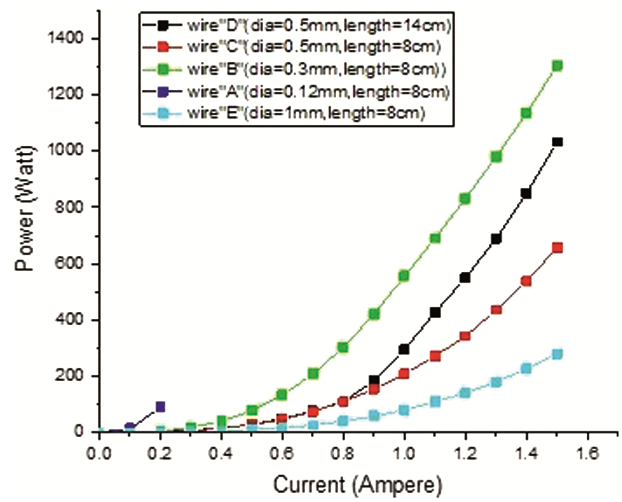

Fig. 12 — Variation of power with current.

3.5 Variation of force developed with current.

Force is important factor to be measured, as it is developed in the wire with current for moving the object. This force varies with diameter and length of the wires. There are various force test which are performed using spring balance as depicted in Fig. 13.

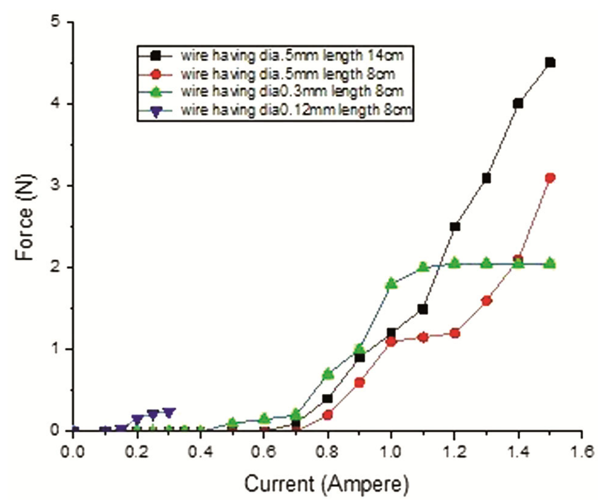

Fig. 13 — Variation of force with current in constant time gap.

3.6 Variation of maximum force carrying capacity with repetition of force measuring test.

During the force measurement using spring balance the same testing have been performed on the same wire under similar outer environment as shown in Fig. 14. It is observed that with repetition, the

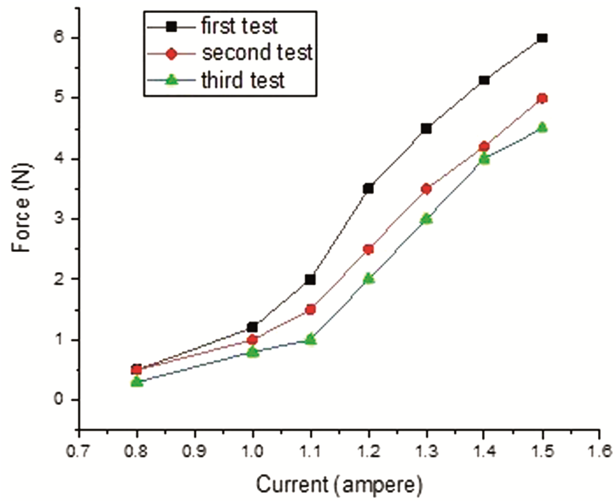

Fig. 14 — Variation in load carrying capacity with current over repeated force tests.

maximum force developed by wire "D" is found to be reduced after each testing. That is over certain load, with each cycle or stroke of repetitions the designed actuator lose its properties. So, certain actuator must be chosen according to the specific requirement or need of load to be carried. Because if load will cross a certain value for given actuator, the wire will lose its properties over cycles of repetitions.

3.7 Variation of different parameter with time gap among each inputscurrent

In robotics, the time is a vital factor. It varies according to the types of robots and its applications. Activation time can be described as ratio of the energy required for heating and electric power consumption used for actuating the actuator[15].

$$T_a = \left(\frac{E_h}{P_e}\right) \quad \dots (6)$$

Where energy required for heating is E_h and electric power consumption used for actuator activation is given by P_e . Again we know,

$$E_h = m\,C_p\,dt = C_p \rho_{sma} S_n\, l\, dt \quad \dots (7)$$

So, finally we have.

$$T_a = \left(\frac{C_p \rho_{sma} {S_n}^2\ dt}{I^2 \rho_n}\right) = \left(\frac{A_{material} {S_n}^2 dt}{I^2}\right) \quad \dots (8)$$ [14]

It has been discussed that heat is the only reason which causes the transformation of the SMA crystal structure from martensite to austenite and vice-versa. Also by joules law of heating $H = I^2Rt$. Therefore, for given resistance and current, heat (H) is directly proportional to the time (t) bywhich current is passing through the wire. If t_h is the heating time and $t_c$is the cooling time of the wire, the working frequency f_w of the wire will be given

$$f_w = \left(\frac{1}{t_c + t_h}\right) \quad \dots (9)$$

3.8 Effect of Shape and Size of SMA actuator

The outstanding quality characteristics of SMA are shape memory effect (SME) and super elasticity (SE). The SME allows the deformed material to recover a memorized shape upon heating above the transformation temperature[16]. Only about 5% of the total length of wire can be used for displacement using super elastic property, but by using the property of SME the actuation capacity of SMA based actuators can largely be amplified. That is why the researchers have designed SMA in various shapes and sizes according to the required position and applications. Among all, the spring type of SMA based actuator got more attention and popularity. Deflection of spring is givenby

$$\delta = \left(\frac{8PD^3n}{Gd^4}\right) \quad \dots (10)$$

and stiffness of spring is given by

$$K = \left(\frac{P}{\delta}\right) = \left(\frac{Gd^4}{8D^3n}\right) \quad \dots (11)$$

where G= modulus of rigidity, P= applied load, D= coil diameter, d= wire diameter, n=number of turns of spring. here for given designed spring G varies with temperature.

$$\delta = constant \times \left(\frac{P}{G}\right) \quad \dots (12)$$

and

$$K = constant \times (G) \quad \dots (13)$$

But it is established fact that modulus of rigidity (G) increases with temperature. So for given axial load, deflection decreases and stiffness increases with increasing temperature of the wire.

4 Conclusion

In the present work, various experiments are performed on the Nitinol wire with different diameter, length and coil diameter with different loads and current. Based on the results, optimal SMA based actuators having definite shape and size can precisely be selected according to requirements. Among the chosen samples the "E" types wire of diameter 1mm, length 8cm and coil diameter 10mm cannot be used in soft robotics due to almost no measurable displacement, and therefore, exerts no force even at higher current. "C" and "D" types Wires of wire diameter 0.5mm, coil diameter 5mm but length 8 and 14cm respectively can be used, in the situations, where higher force with lesser response time is required at the current more than1ampere."B" type's wires of diameter 0.3mm, length 8cm and coil diameter 4mm can be used where higher force with higher response time at the passes of current less than 1 ampere is required. "A" types wires of diameter 0.12mm, length 8cm and coil diameter 3mm can be used where it require less force with highest response time. It has also been observed that the actual transformation of SMA actuator wire from marten site to austenite starts above 27℃upto 50℃. "B" types wires of diameter 0.3mm, length 8cm and coil diameter 4mm consumes more power among all selected wires as shown in Fig. 12. With the repetition of measurement of maximum load carrying capacity testing, the tested wire loses their characters of memorizing the predefined shape as shown in Fig. 14.

References

1 Kim S, Laschi C & Trimmer B, *Trends Biotechnol*, 31 (2013) 287.
2 Trivedi D, Rahn C, Kier W & Walker, *Appl Bionics Biomech*, 5 (2008) 99.
3 Ahmad M R, Yahya M H M, Ahmad W Y W, Salleh J & Hassim N, *Indian J Fibre Tex*, 38 (2013) 193.
4 Taya M, Liang Y, Namli O, Tamagawa H & Howie T, *Smart Mater Struct*, 22 (2013).
5 Nespoli A, Besseghini S, Pittaccio S, Villa E & Viscuso S, *Sensor Actuat A-Phys*, 158 (2010) 149.
6 Majidi C, *Soft Robot*, 1 (2014) 5.
7 Laschi C, Cianchetti M, Mazzolai B, Margheri L, Follador M & Dario P, *ADV Robotics*, 26 (2012) 709.
8 Sreekumar M, Nagarajan T, Singaperumal M, Zoppi M & Molfino R, *Ind Robot*, 34 (2007) 285.
9 Mikov´a L'L, Medveck´a S, Kelemen B M, Trebu˜na F & Virgala I, *Metalurgija*, 54 (2015) 169.
10 MohdJani J, Leary M, Subic A & Gibson M, *Mater Des*, 56 (2014) 1078.
11 Brinson L, Bekker A & Hwang S, *J Intel Mat Syst Str*, 7 (1996) 97.
12 Daudpoto J, Dehghani-Sanij A & Richardson R, *Meas Control*, 48 (2015) 285.
13 Lara-Quintanilla A & Bersee H, *J Intel Mat Syst Str*, 27 (2015) 403.
14 Dovica M, Kelemenov´a T & Kelemen M, Mechatronics : Recent Technological and Scientific Advances, (2011) 187.
15 Song G, Ma N & Li H N, *Eng Struct*, 28 (2006) 1266.
16 Ma J, Huang H & Huang J, *Adv Mater Sci Eng*, 2013 (2013) 1.