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A phenomenological constitutive model of characterization for the heating and cooling transformations process of nickel-titanium wires using Datastudio 1.9.8

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ABSTRACT

This paper presents a three-dimensional constitutive model for a shape-memory alloy that generalizes the behaviour of Nickel-Titanium transformation whilst subjected to heat, then cooling processes. This model is able to predict the behaviour of Shape Memory Alloys (SMAs) wires under complex thermo-mechanical loadings by curve-fitting heating and cooling curves sensed with the Data logger GLX using the DataStudio 1.9.8 package. The phenomenological model for SMAs was investigated to better model their behaviour in cases where temperature and stress states change simultaneously. This model was applied on a 3D printed artificial finger which mimics an actual human finger.

Keywords: Shape memory alloys, nickel-titanium, phenomenological model.

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INTRODUCTION

In the early 1960s, W. F. Buehler (Buehler et al., 1963), a metallurgist investigating nonmagnetic, salt resisting, waterproof alloys for the space programme at the Naval Ordnance Laboratory in Silver Springs, Maryland, USA, discovered the shape memory effect in an equiatomic alloy of Nickel and Titanium, which can be considered a breakthrough in the field of Shape Memory Alloys (SMAs). The alloy was named Nitinol, an acronym for the elements from which the material was composed; “ni” for Nickel, “ti” for Titanium and “nol” from the Naval Ordnance Laboratory. Nitinol is the name given to a family of inter-metallic alloys of Nickel and Titanium which have been found to have unique properties of shape memory and super-elasticity. The super-elastic behaviour of Nitinol wires means that on unloading they return to their original shape before deformation (Serene et al., 1995).

Since that time, intensive investigations have been made to explain the mechanics of its basic behaviour.

This paper provides an enhanced phenomenological model for SMAs, to better model their behaviour in cases where the temperature and stress states change simultaneously. The phenomenological models for SMAs, consisting of a thermodynamics-based constitutive and a phase transformation kinetics model are widely used models for engineering applications.

Previously, two approaches for constitutive modelling of SMAs were developed (Lagoudas et al., 2003). The first one being the direct approach: the evolution laws are obtained by either considering transformation micro-mechanisms (Tanaka, 1986) or by directly matching experimental results, that is, phenomenological approach. The first approach uses the thermodynamic approach, it starts with constructing a free energy and then, by utilizing a dissipation potential in conjunction with the second law of thermodynamics, evolution laws for the internal state variables, that is, the volume fraction of the various forms of martensite, are derived (Lagoudas and

Shu, 1997).

In the thermodynamic approach, the second law of thermodynamics applies constraints to material constitution, but these constraints are usually weak. Hence, if a constitutive model does not violate the thermodynamic constraints, usually it can also be derived from the thermodynamic approach (Lagoudas et al., 2003). A previous 3-dimensional constitutive model developed (Liang, 1990), based on the 1st and 2nd law of thermodynamics and was defined by three parameters namely: the equivalent strain, the absolute temperature and the martensitic fraction. They discovered that the constitutive equations were non-linear and therefore required large computational effort.

In this study, the phenomenological models developed by Tanaka (1986) and later refined by Liang (1990) are utilised to describe the behaviour of the SMA. These models are based on the experimental characterisation of SMA hence phenomenological. Here, we investigate phenomenological behaviours of the heating and cooling process of SMA wires actuating an articulated finger.

Micromechanical model

SMA wires heat transfer equation consists of electric (ohmic) heating and natural convection (Incropera and DeWitt, 2001):

$$mC_p\frac{dT}{dt} = I^2R - hA(T - T_\infty) \qquad (1)$$

The SMA wire that is used in the system is a 70 mm long Nickel-Titanium wire with a diameter of 1 mm. The parameters in the heat transfer equation are:

$m = \rho\pi\frac{d^2}{4}$ is mass per unit length of wire, ρ is density of wire, d is diameter of wire, *A* is the circumferential area of the unit length of wire, C_p is the specific heat, *I* is electrical current applied, *R* is resistance per unit length of wire, *T* is the temperature of the wire, T_∞ is the ambient temperature, and *h* is the heat convection coefficient.

The constitutive behaviour of Nickel-Titanium shape memory alloy can be calculated by applying this micromechanical model numerically. The micromechanical model is based on calculations and formulae.

Incropera and DeWitt (2001) showed that we can predict the heating trend for the SMA wire with the following relation:

$$T = \frac{I^2R}{hA}\left(1 - e^{-hAt/\rho Vc}\right) + T_\infty \qquad (2)$$

Where T is the estimated temperature; I is the applied current; I is the wire resistance; V is the volume of the wire; ρ is the density; h is the convection coefficient; c is the specific heat; A is the surface area of the wire; T_∞ is the ambient temperature and t is the time.

Cooling of activation temperature to room temperature under free convection conditions was also analysed. The equation used to predict the cooling temperature of the SMA wire is given below (Incropera and DeWitt, 2001):

$$T = (T_i - T_\infty)e^{-(hAt)/(\rho Vc)} + T_\infty \qquad (3)$$

T_i is the surface temperature.

The heating and cooling relations are exponential functions.

Heating relation is a natural exponential function [2]. The general form of natural exponential functions is given by:

$$y(t) = \mathcal{A}e^{-\mathcal{C}t} + \mathcal{B} \qquad (4)$$

Where $\mathcal{A}$ is the coefficient of scale factor, $\mathcal{B}$: the y-offset coefficient, and $\mathcal{C}$: the exponent coefficient.

We can deduce from the heating relation the following:

$$\mathcal{A} = \frac{I^2R}{hA} \qquad (5)$$

$$\mathcal{B} = T_\infty \qquad (6)$$

$$\mathcal{C} = {-hA}/{\rho Vc} \qquad (7)$$

Cooling process follows the inverse exponential function with the general expression given by (Liang, 1990):

$$y(t) = \mathcal{A}(1 - e^{-\mathcal{C}t}) + \mathcal{B} \qquad (8)$$

Deducing from the cooling relation, we have:

$$\mathcal{A} = T_i - T_\infty \qquad (9)$$

$$\mathcal{B} = T_\infty \qquad (10)$$

$$\mathcal{C} = {-hA}/{\rho Vc} \qquad (11)$$

Phenomenological model

In order to further investigate the SMA phenomenological models, an SMA-actuated artificial finger was investigated.

MATERIALS AND METHODS

Commercially available Nickel-Titanium wires of 1 mm thick, 70 mm long were used in these experiments. The material was purchased from the supplier Dynalloy, Inc. USA.

The Nickel-Titanium wire actuator associated with a

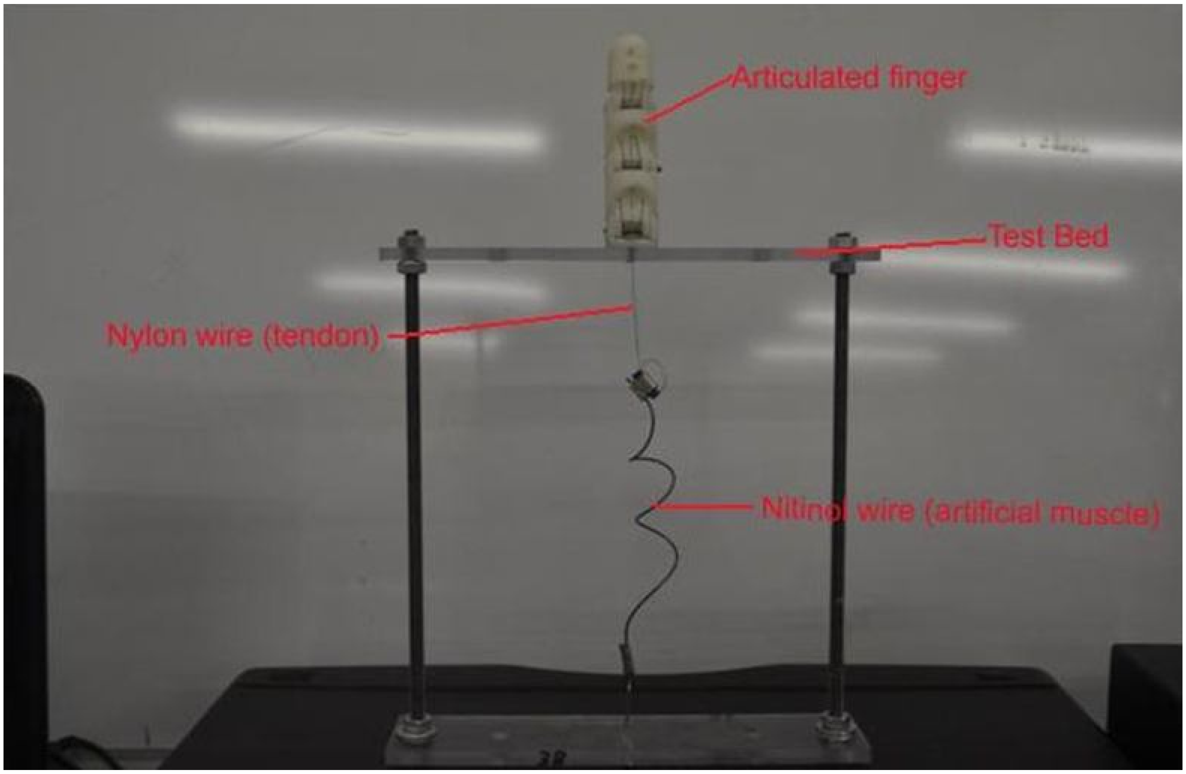


Figure 1. Articulated finger mounted on the test bed.

spring was used to control the flexion-extension of joints of an artificial 3D printed finger mounted on a test bed as shown in Figure 1.

Nylon cables (1 mm in diameter and 200 mm long) passed through the finger. When pulled, the cable drags the finger to bend. Once heated, the SMA wire can contract, thus pulling the cable anchored inside the finger; this causes the finger to clench. Subsequently, when cooled off naturally, the SMA wire softens then expands and the springs inside finger playing the role of bias force pull back the finger to its normal position.

Experimental set-ups

The experiment was conducted on one finger mounted on a support or a test bed such as shown in Figure 1.

Measurements were made with the following apparatus (Figure 2): 1. Data logger GLX: real-time data visualization, graphing and data analysis; 2. HP computer (2GHz processor); 3. Thermometer (noncontact infrared sensor, Range: -30 to 900°C) and; 4. DC power supply (Input: 220/240 V, 50 Hz~, Output: 3 to 15 V/ 18 amp DC).

Measurements were conducted on the above mentioned SMA wire specimen in order to determine the heating and cooling graph; from this graph, the heating and cooling relations will be deducted.

Heating and cooling process measurements

Fifteen tests were run at different voltage (five tests at 1.5 V, five tests at 5 V and five others at 10 V) for 100 s as shown in Figure 3. For each run, heating and cooling parameters ($\mathcal{A}$, $\mathcal{B}$ and $\mathcal{C}$) were determined. The data logger GLX recorded and calculated the parameters for heating and cooling relations by curve fit functions. After finding the average of each parameter, the phenomenal heating and cooling functions can be written easily. The heating and cooling parameters are found by curve-fitting each plotted curve as shown in Figure 4 for heating curves and in Figure 5 for cooling curves.

RESULTS

Heating tests results

The heating tests results are shown in Table 1.

Cooling tests results

The cooling tests results are shown in Table 2. Considering the data in Table 2, we can find out the average value of each coefficient (Table 3).

Thus, as shown in Table 3, the average equations of

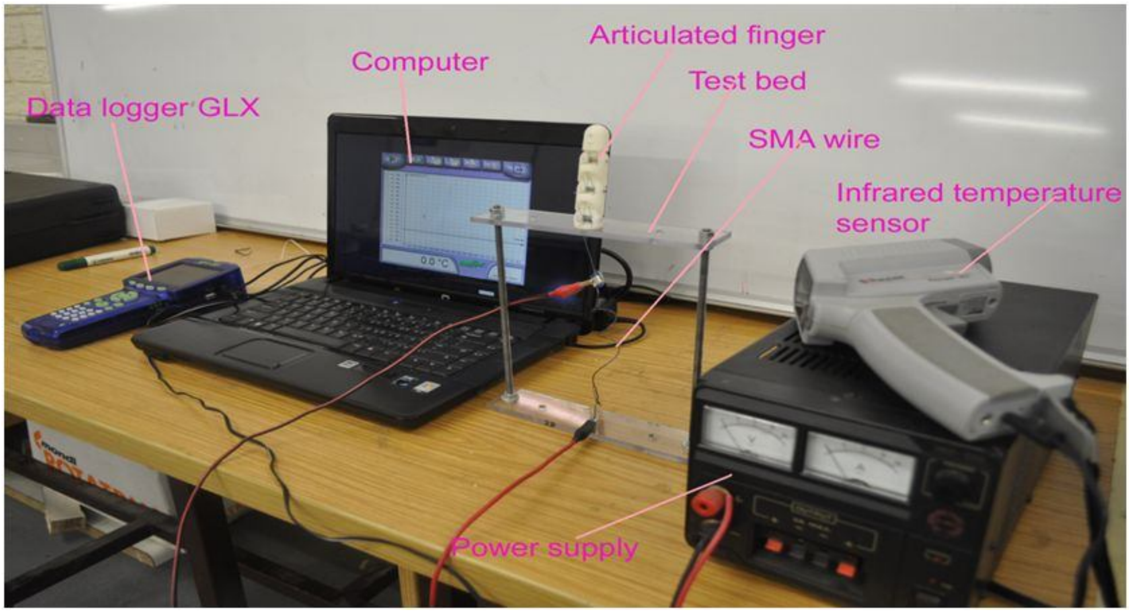


Figure 2. Equipment set up.

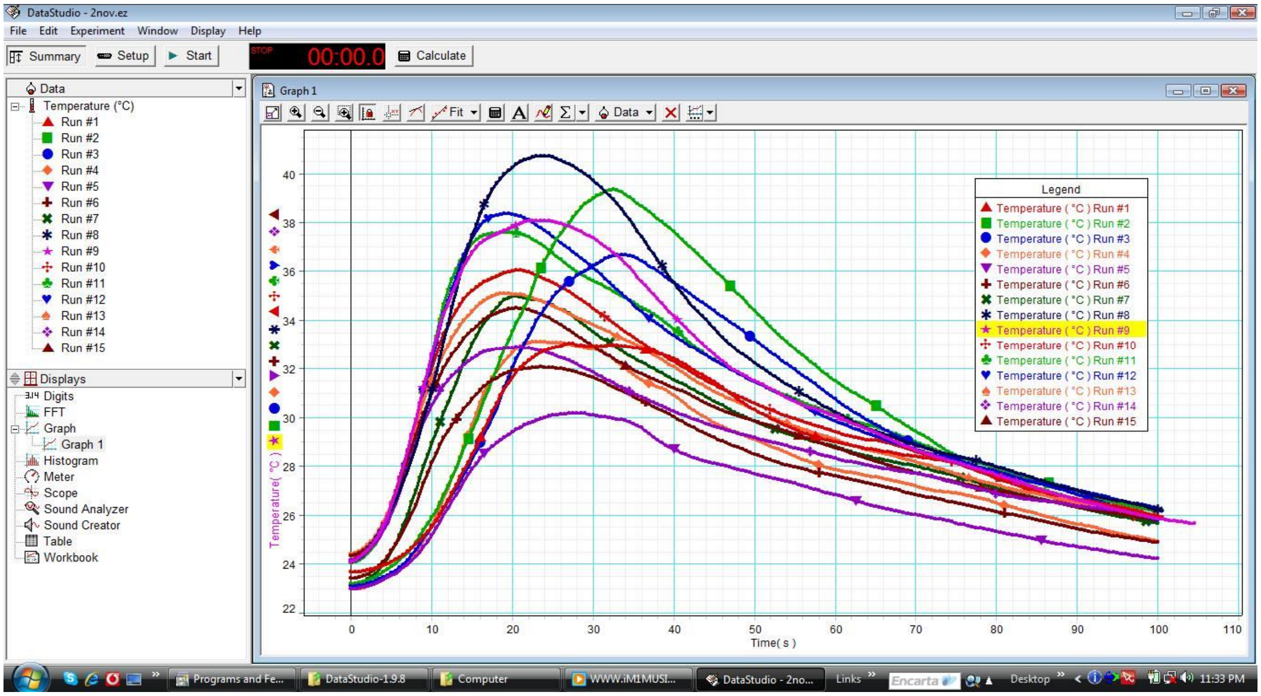


Figure 3. Overview of heating curves with DataStudio®.

heating and cooling are written.

$$T_{1.5V,heat} = 1.215e^{0.1252t} + 21.7 \quad (12)$$

$$T_{5V,heat} = 2.348e^{0.1472t} + 21.12 \quad (13)$$

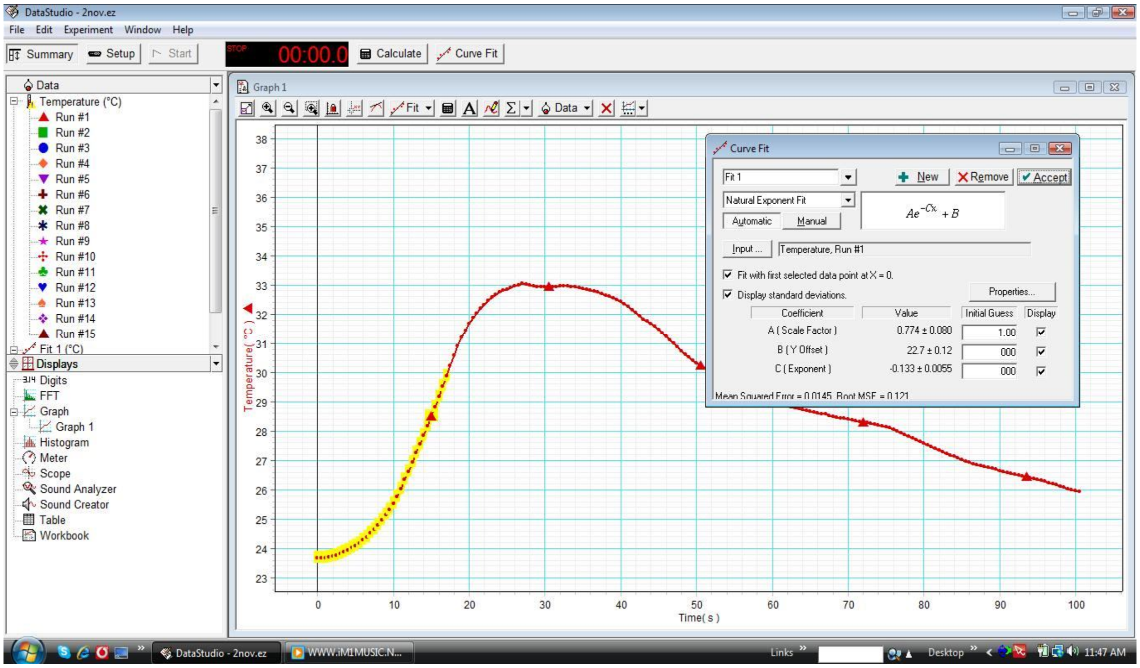
$$T_{10V,heat} = 2.2282e^{0.1516t} + 21.6 \quad (14)$$

$$T_{1.5V,cool} = -10.052(1 - e^{-0.0216t}) + 32.68 \quad (15)$$

$$T_{5V,cool} = -10.432(1 - e^{-0.0220t}) + 33.38 \quad (16)$$

$$T_{10V,cool} = -10.260(1 - e^{-0.0225t}) + 33.54 \quad (17)$$

These functions were plotted with Matlab as shown in



Fit 1

Natural Exponent Fit

$Ae^{-Cx} + B$

Temperature, Run #1

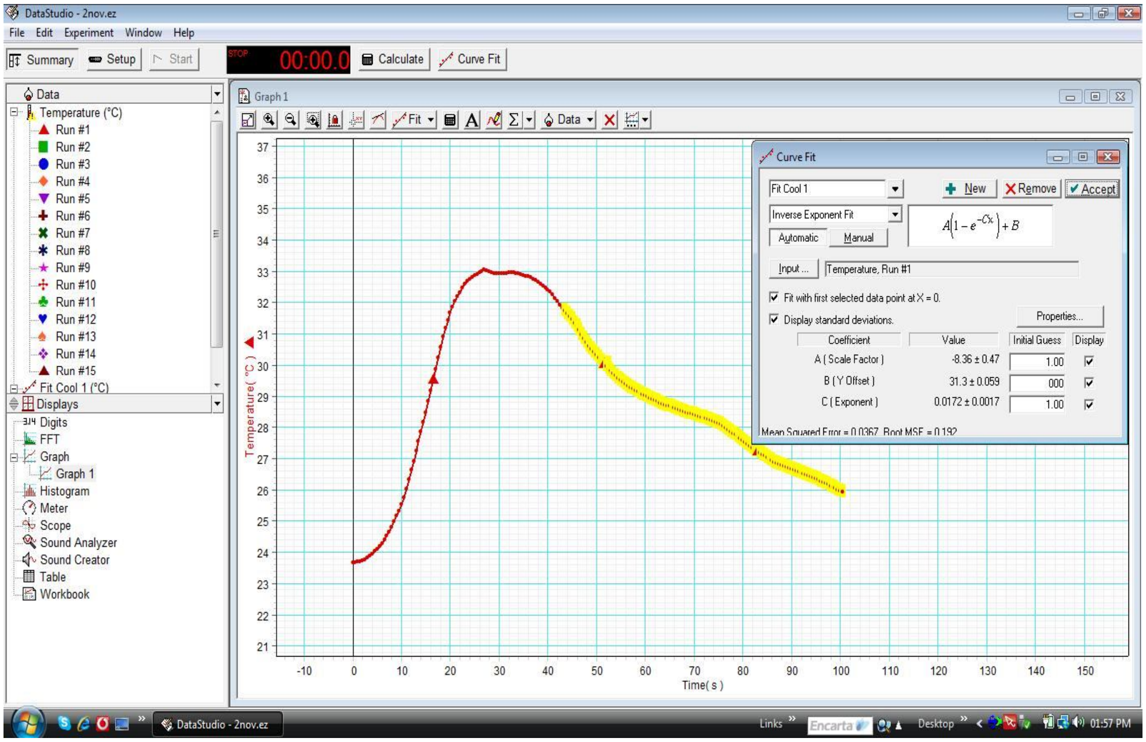
☑ Fit with first selected data point at X = 0.

☑ Display standard deviations.

Coefficient	Value	Initial Guess	Display
A (Scale Factor)	0.774 ± 0.080	1.00	☑
B (Y Offset)	22.7 ± 0.12	000	☑
C (Exponent)	-0.133 ± 0.0055	000	☑

Mean Squared Error = 0.0145 Root MSE = 0.121

Figure 4. Heating curve fit with DataStudio®.



Fit Cool 1

Inverse Exponent Fit

$A\left(1 - e^{-Cx}\right) + B$

Temperature, Run #1

☑ Fit with first selected data point at X = 0.

☑ Display standard deviations.

Coefficient	Value	Initial Guess	Display
A (Scale Factor)	-8.36 ± 0.47	1.00	☑
B (Y Offset)	31.3 ± 0.059	000	☑
C (Exponent)	0.0172 ± 0.0017	1.00	☑

Mean Squared Error = 0.0367 Root MSE = 0.192

Figure 5. Cooling curve fit with DataStudio®.

Figures 6 and 7.

The speed of the actuators varies with electric current that heat the spring above transition temperature: the higher voltage applied to an SMA wire, the fastest it will contract but the slower its temperature will decrease (https://www.youtube.com/watch?v=DRO0yVodFR8). Also, using lower voltage (1.5 V) helps to prevent any loss the shape memory effect of the Nickel-Titanium wire;

Table 1. Heating process results.

Voltage (V)	Test number	Coefficient of scale factor $\mathcal{A}$	Y-offset coefficient $\mathcal{B}$	Exponent coefficient $\mathcal{C}$
1.5	Run #1	0.774	22.7	0.1330
	Run #2	1.960	20.8	0.0969
	Run #3	1.950	20.8	0.0891
	Run #4	0.661	22.1	0.1650
	Run #5	0.731	22.1	0.1420
5	Run #6	0.739	22.5	0.2060
	Run #7	2.330	20.4	0.1270
	Run #8	3.100	20.7	0.1200
	Run #9	2.990	20.7	0.1370
	Run #10	2.580	21.3	0.1460
10	Run #11	2.340	21.3	0.1560
	Run #12	2.660	21.1	0.1460
	Run #13	2.290	21.8	0.1500
	Run #14	1.820	22.1	0.1620
	Run #15	2.300	21.7	0.1440

Table 2. Cooling process results.

Voltage (V)	Test number	Coefficient of scale factor $\mathcal{A}$	Y-offset coefficient $\mathcal{B}$	Exponent coefficient $\mathcal{C}$
1.5	Run #1	-8.360	31.3	0.0172
	Run #2	-13.50	37.5	0.0316
	Run #3	-11.40	35.1	0.0281
	Run #4	-8.14	30.7	0.0192
	Run #5	-8.86	28.8	0.0120
5	Run #6	-7.36	30.7	0.0199
	Run #7	-9.33	32.5	0.0193
	Run #8	-11.00	36.3	0.0355
	Run #9	-11.20	34.4	0.0229
	Run #10	-12.80	33.0	0.0126
10	Run #11	-13.80	35.3	0.0166
	Run #12	-11.10	35.4	0.0380
	Run #13	-9.28	33.0	0.0214
	Run #14	-7.68	31.5	0.0184
	Run #15	-9.44	32.5	0.0181

Table 3. Heating and cooling results.

Voltage (V)	Heating			Cooling		
	Average Coefficient of scale factor $\mathcal{A}$	Average Y-offset coefficient $\mathcal{B}$	Average Exponent coefficient $\mathcal{C}$	Average Coefficient of scale factor $\mathcal{A}$	Average Y-offset coefficient $\mathcal{B}$	Average Exponent coefficient $\mathcal{C}$
1.5	1.215	21.70	0.1252	-10.052	32.68	0.0216
5	2.348	21.12	0.1472	-10.432	33.38	0.0220
10	2.282	21.60	0.1516	-10.260	33.54	0.0225

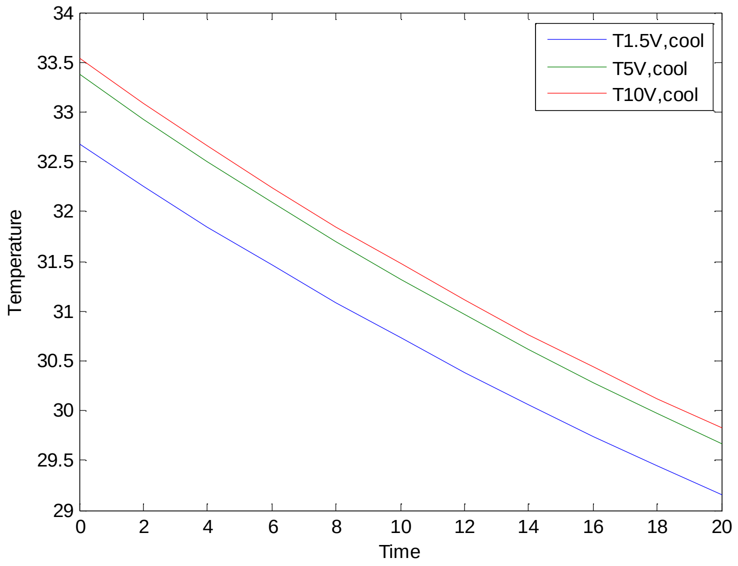


Figure 6. Cooling curves at different voltages (Temperature, °C; Time, s).

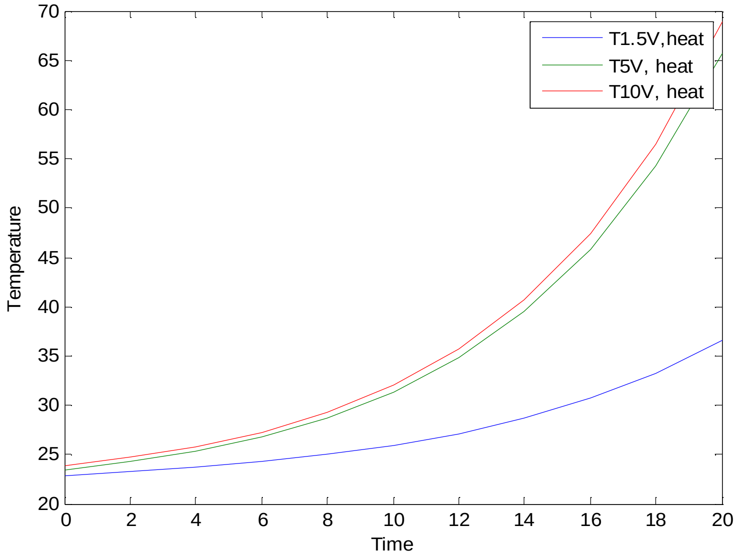


Figure 7. Heating curves at different voltage (Temperature, °C; Time, s).

though its heating and cooling curves revealed to be longer than those of higher voltages.

DISCUSSION

This study describes mathematically the behaviour of Nickel-Titanium upon electrical heating and cooling used as an actuator to articulate an artificial finger. When subjected to an electric current, heating by Joule effect occurs leading to the contraction of the finger, whereas, flexing happens when this electric current is removed. Based on different assays run, we were able to write mathematical models of equations behind heating (equations 12, 13 and 14) and cooling (equations 15, 16 and 17) of Nickel-Titanium wires depending on its length, internal resistivity and the electric current applied. From an experimental point of view, we found out that using lower voltage (1.5 V) was required to keep the Shape Memory Effect longer though it's heating and cooling curves revealed to be longer than those of higher voltages.

From this study, we emphasized the use of Nickel-Titanium as actuators to power an artificial finger mimicking a real human finger.

This application can be used for further research on biomimetic limbs as well as on robotic applications.

CONCLUSION

A model of the Nickel-Titanium actuator has been developed that includes the change in free length of the spring due to phase transformation. By using this model, Nickel-Titanium wires can be well designed according to the force and displacement requirements. This greatly expands the positive potential for Nickel-Titanium actuators. Normally, actuators need gears or transmissions to match the impedance of the load, frequently making the actuator system bulky and cumbersome. But Nickel-Titanium actuators can be tuned to match the load by changing the shape and the annealing temperature of the wires.

The speed response of the actuators varies depending on the electric current applied to the shape memory alloy wires. This phenomenological model is able to predict the behaviour of SMA wires under complex thermo-mechanical loadings.

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