CORRELATION BETWEEN ELECTRICAL RESISTANCE AND STRAIN OUTPUT OF SMA ACTUATOR UNDER CYCLIC THERMOMECHANICAL LOADING CONDITIONS

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ABSTRACT

This paper presents a study on the correlation between electrical resistance (R) and strain output (ε) of Shape Memory Alloy (SMA) actuator. Characterization of the change in electrical resistance with respect to the strain output was performed for a selected Ni-Ti SMA material. The results indicate that such correlation, in general, is non-linear and hysteretic. Linear approximation can only be applied to a limited strain output range on the heating phase. The non-linearity of correlation on cooling path may be related to the complicated and two steps phase transformation involved. The influences of loading stress on R-ε correlations are specifically studied and the results show that the extent of non-linearity and hysteresis in the R-ε correlation is dependant on the loading stress applied to Ni-Ti SMA actuators.

Keywords: Shape memory alloy, SMA, actuator, position control, electrical resistance

1. INTRODUCTION

The SMA actuator possesses the highest power density of all types of actuators, and yet operates on a simple principle. Because of such unique characteristic, it has been under study in recent years for a variety of applications in the areas ranging from medical to industry and to space [1]. Typical examples are: the prototype of robot system using SMA, developed by Penney et al [2], and the studies to use the SMA for low frequency vibration control of flexible structures [3,4], aircraft wing shape control [5], and micro-system precision control [6]. A more recent work by Peng et al [7] deals with the use of SMAs for the active control of the flatness of membrane SAR antennas in potential variable space temperature environment. One of key requirements for those potential applications, however, is to achieve the precision control for SMA actuators with minimum system requirement, particularly in the case of space applications. A common approach over the last decade has been to incorporate various thermomechanical models [8-12] into the control algorithms. A main drawback is that the model parameters must be determined experimentally and control scheme tends to be very complex, which make the position control rather impractical. On other hand, feedback control using the position sensor, although demonstrated reasonably good precision and stability [13, 14], requires extra hardware and thus has a system penalty. Realization of SMA precision control without a position sensor is more desirable. One possible approach is to use the internal electrical resistance of SMA as feedback signal, as initially investigated by Raparelli et al [15] and Ma et al [16]. However, it appeared that, because of hyeteresis and non-linear characteristics, simple approximation of the correlation between electrical resistance (R) and strain output (ε) has so far resulted in fairly large error in control precision [15, 16]. More detailed study of such correlation is probably needed to provide data for better precision position control of SMA actuator. Of particularly is that such correlation or data needs to take into account of the influence of loading stress. This paper aims to conduct a detailed study in order to provide an insight to those questions.

2. EXPERIMENT DESIGN AND PROCEDURE

2.1 SMA material

A commercially available Ni-Ti SMA wire (Flexinol*) of diameter of 0.15 mm, is selected for this tudy. Its properties are listed in table 1. All samples used have length of approximately 150 mm with a phase transformation (A_f) temperature of ~90 ºC, which is determined experimentally by using the Differential Scanning Calorimetric (DSC) instrument. DSC is also used for characterization of phase transformation of Ni-Ti SMA wire during both heating and cooling processes.

Fig.1 shows the testing fixture for the SMA multi-actuation experiment, which includes a mechanical fixture, linear variation differential transducer (LVDT), data acquisition device, a PC, digital/analog converter and power amplifier. A reference resistor is introduced into the circuit of power supply to measure the internal electrical resistance of SMA. Characterization and control of SMA wire were conducted at both constant and bias loading conditions.

Table 1-Technical parameters of 0.15 mm diameter Flexinol wire

Electrical resistance (Ohms/in)	1.3
Maximum pull force (N)	3.3
Recommended current input (mA)	400
Contract time (s)	1.0
Off time (s)	1.2

* Supplied by Dynalloy Inc., USA

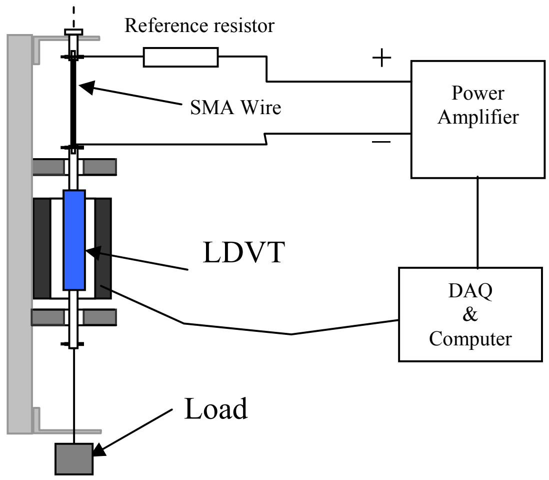


Fig.1 The illustration of the test fixture for the SMA multi-cycle actuation experiment

EXPERIMENT RESULTS

3.1 Differential Scanning Calorimetric (DSC) analysis of selected Ni-Ti SMA

Phase transformation is the fundamental mechanism for the actuation of SMA actuator. It is understood to be one of main reasons contributing to the change in electrical resistance of SMA actuator upon its actuation normally through thermal cycle [19]. Understanding of the phase transformation involved in SMA is thus of importance in understanding of potential correlation between the change in electrical resistance and its strain output. Fig.2 shows the DSC analysis of SMA actuator material chosen for this study. It can be seen that during the heating, the phase transformation is a simple one-step process from Martensite to Austenite. However, during the cooling, the phase transformation process is more complicated that it involves two steps, firstly from Austenite to R-phase and then from R- phase to Martensite, as indicated in Fig.2. Different phase transformation mechanisms involved in heating and cooling may subsequently influence the correlation between the electrical resistance and strain output of SMA actuator.

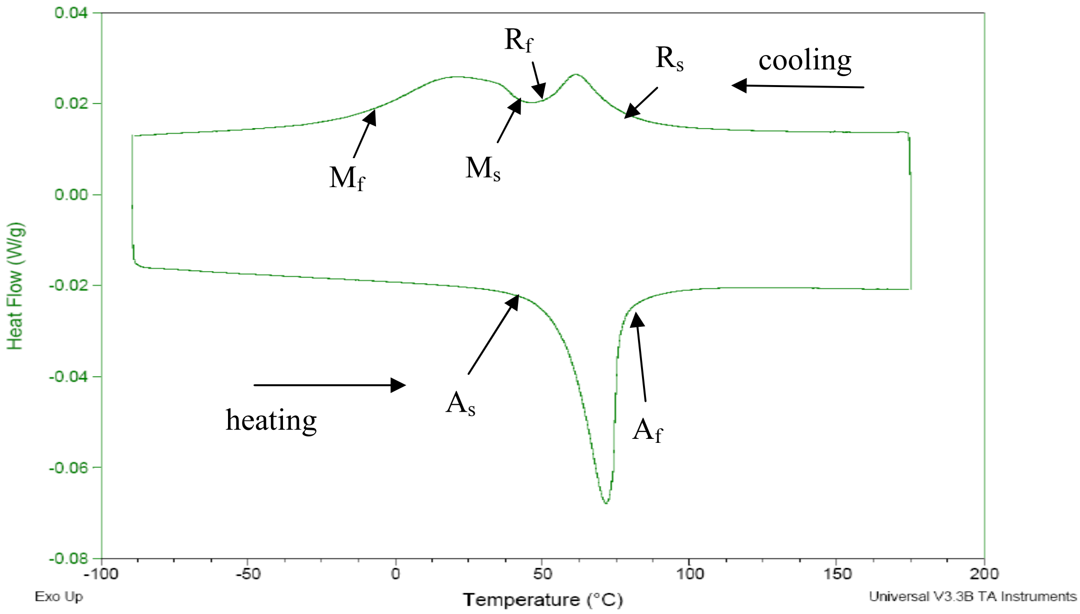
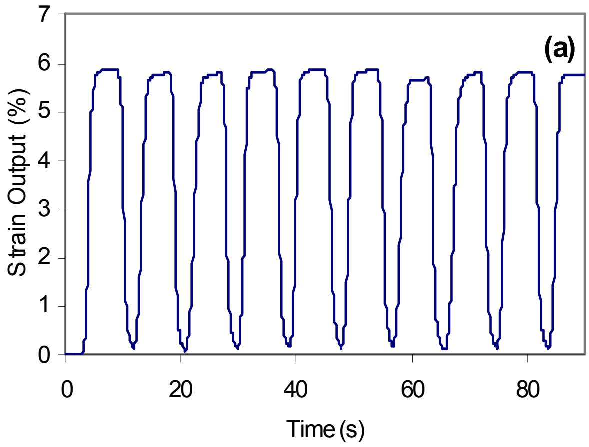


Fig.2 DSC analysis of Ni-Ti SMA actuator material selected for this study.

3.2 Establishment of R-ε Correlation of SMA Actuator

As mentioned in the introduction, for SMA actuator position control with internal electrical resistance feedback, detailed correlation between strain output (*R*) and electrical resistance (**ε**) (so-called *R*-**ε** correlation) needs to be established. To serve this purpose, experiments were conducted to specifically characterize the changes in electrical resistance of SMA with respect to the change in its strain output during a typical multi-cycle actuation under constant load of 2.3 N (equivalent loading stress of 131 MPa), as shown in Fig.3(a). A pulsed power supply of electrical current was used to heat the SMA for duration of 1.5 seconds followed by a cooling period of 6 seconds to complete a full cycle of actuation and reset. It can be seen clearly in Fig.3(b) that the *R*-**ε** correlation are reasonably repeatable for a number of cycles. However, it is significantly hysteretic and non-linear. Linear approximation may only be applied to the heating path in the range where the strain output is greater than 0.6 mm. A close to linear *R-ε* correlation during the heating path is probably due to relatively simple and one step phase transformation (from Marteniste to Austenite). Whereas significant non-linearity of *R-ε* correlation on the cooling path is probably due to the complicated phase transformation involving two steps from Austenite to R-phase and then from R-phase to Martensite. From this point of view, to reducing the non-linearity of R-ε correlation, one possible way is potentially looking at the SMA material of relatively simple phase transformation.



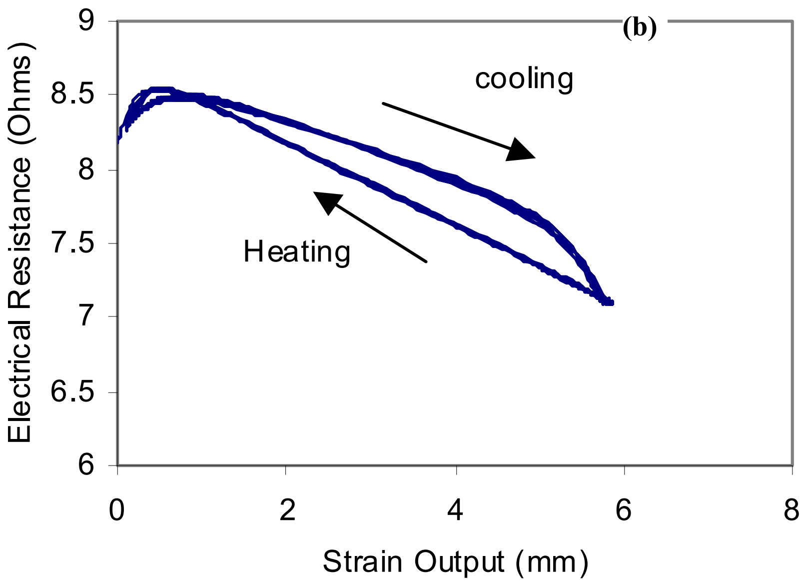


Fig.3 Characterization of correlation between electrical resistance and strain output of SMA (sample A) during multi-cycle actuation under loading stress of 131 MPa; (a) Profile of strain output of SMA over the time; (b) R-ε correlation.

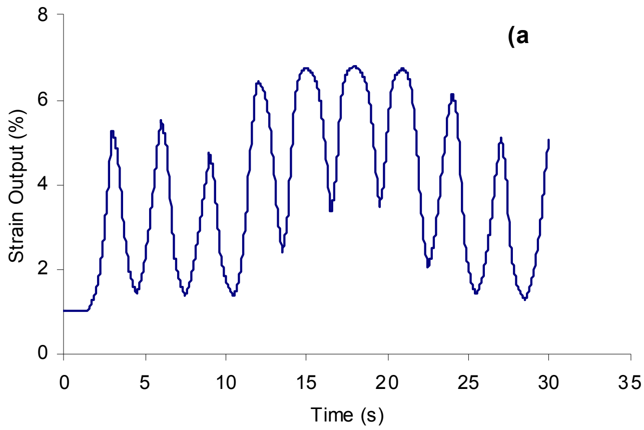
In a normal situation of position control, however, the SMA actuation may not go through full cycle (unconstraint cycle) each time. To understand the R-ε correlation in this case, test of SMA with different amplitudes of actuation was conducted. Fig.4 shows the profile of strain output over the time and the corresponding R-ε correlation. Data analysis indicates that three linear approximations may be used to describe the whole S-R correlation involving different sub-cycles:

$$\varepsilon = 28.66 - 3.145R \tag{1}$$

$$\varepsilon = 41.54 - 4.638R \qquad (2)$$

$$\varepsilon = 17.11 - 1.443R \qquad (3)$$

Here, ε and R are respectively the strain output and the internal electrical resistance of SMA actuator. The data analysis also indicated that the R-ε correlation during the transfer from heating path to cooling path or from cooling path to heating path, can also be approximated, as expressed by Eq.(3).



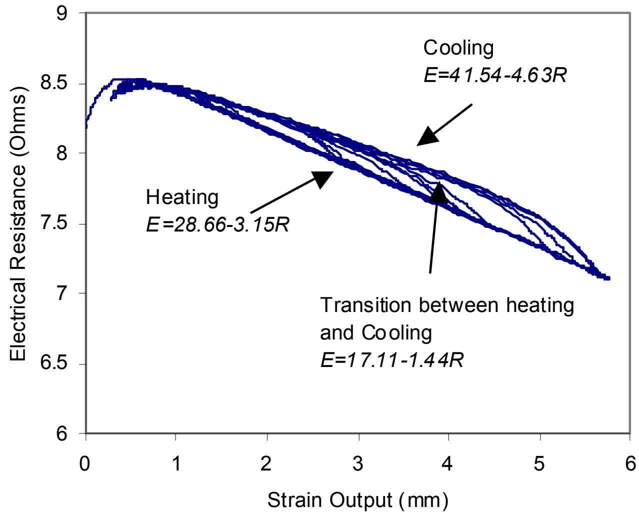


Fig.4 shows (a) the profile of strain output over the time, and (b) R-ε correlation during a multi-cycle actuation involving different sub-cycles

3.2 Factors influencing the R-ε Correlation of SMA Actuator

It is known that thermal cycle induced phase transformation gives rise to the change in electrical resistance of Ni-Ti SMA alloy [19]. However, because current testing condition involves both thermal cycling and mechanical loading, it is not clear if the mechanical mechanical loading is a significant factor in influencing correlation between electrical resistance and strain output of SMA. As the first step, experiment was conducted on the change in electrical resistance of SMA with respect to the change in strain of SMA under mechanical loading without thermal cycling as one may argue that elongation of SMA wire may also change the electrical resistance. Fig.5 shows the change of electrical resistance of SMA wire actuator with respect to the change in its strain output under purely mechanical loading condition (approximately 220 MPa) at the room temperature, at which the SMA is expected to be in a stable Martensite phase. Under such loading condition, change in mechanical strain of SMA up to 0.8% does not give rise to evident change in electrical resistance. This experiment demonstrates that mechanical loading, thus the mechanical elongation, alone would not cause evident change in electrical resistance of SMA. Change in electrical resistance during the multi-cycle actuation is thus mainly due to the phase transformation of Ni-Ti material. However, the question that remains is if loading stress influence R-ε Correlation of SMA Actuator when it is involved in thermal cycling of SMA actuator since it is well known that loading stress is a significant factor in influencing the phase transformation of SMA [1].

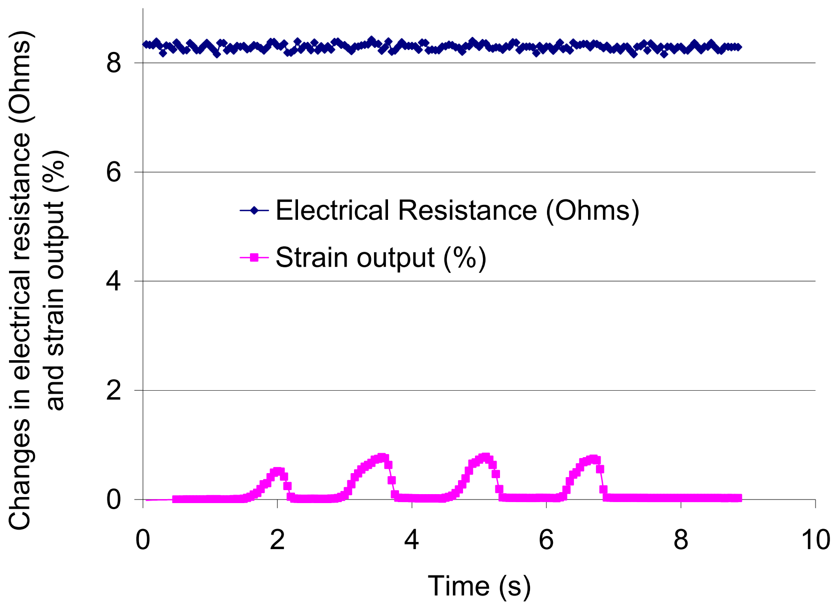


Fig.5 Change in electrical resistance of Ni-Ti SMA with respect to the change in its strain output under pure mechanical loading condition

To answer this question, further experiment is conducted to characterize the R-ε Correlation of SMA Actuator under different loading stress involving multi-cycle actuation. Fig.6 shows the R-ε correlations of same SMA actuator under the constant load of 0.5 N (equivalent loading stress of 28 MPa). It can be seen that when the loading stress is reduced from 130

MPa to 28 MPa, the hysteresis in the *R-ε* correlation is significantly increased and, comparatively, the non-linearity is also increased (see Figure 2 for comparison). Further experiment is certainly needed to understand the mechanism how the loading stress is influencing the R-ε Correlation of SMA Actuator.

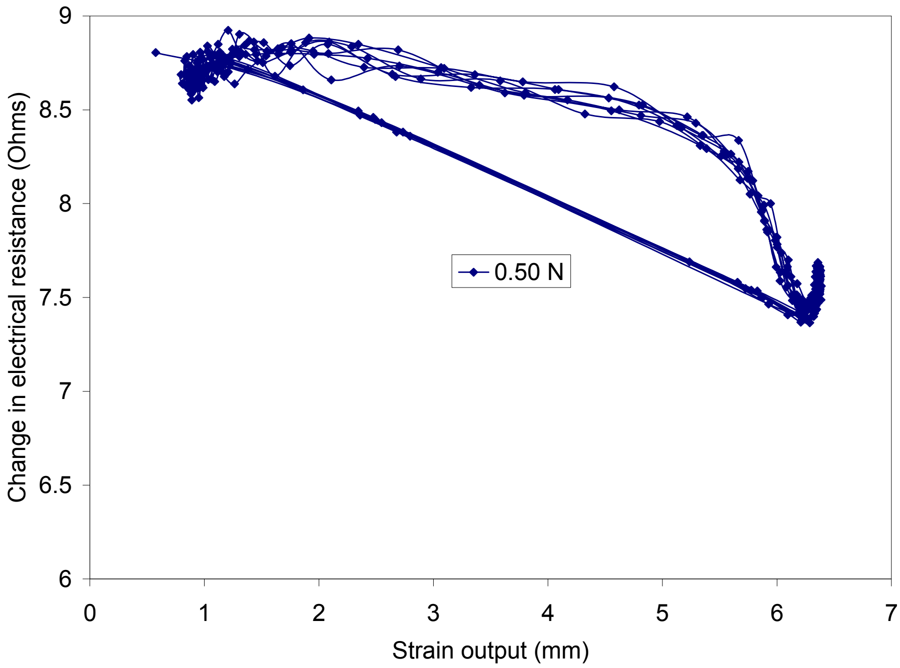


Fig.6 shows the *R-ε* correlations of same SMA actuator under the constant load of 0.5 N.

4. CONCLUSIONS

In this study, experiment is conducted to examine the correlation between the change in electrical resistance (R) of SMA and its strain output (ε). The results indicate that mechanical stress caused elongation alone would not cause evident change in electrical resistance of SMA. Phase transformation is the primary reason for the change in electrical resistance. Detailed experiments demonstrated that R-ε correlation, in general, is non-linear and hysteretic. Linear approximation can only applied to the R-ε correlation of SMA upon the heating path. Whereas significant non-linearity of R-ε correlation on the cooling path is probably due to the complicated and two steps phase transformations involved. The influence of loading stress on R-ε correlation is furthermore studied. The results show that the extent of non-linearity and hysteresis in R-ε correlation increases with the reduction of the loading stress.

5. REFERENCES

[1] Razov, A. I., “SMA applications and design principles” in “Shape memory Alloys: Fundamentals, modelling and applications”, edited by V. Brailovski , S. Prokoshkin, P. Terriault, F. Trochu, Published by University of Quebec, 2003, Montreal, Canada, pp686-723
[2] Penney, N; T A. Barr, G. Song, "Design of a robotic fish using shape memory alloy (SMA) wires", in Proc. Of Intl. Conf. On Adaptive structures and material systems, 11-16 Nov. 2001, New York, NY, pp. 419-424.
[3] Jiang, X. X., M. Mullavey, D. Xu, A. Yousefi-Koma and D. Nikanpour, "Application of shape memory alloy for the vibration control of cantilever beam", Proceedings of 1st Canada-US workshop on Smart Materials and Structures, edited by G. Akhras, Montreal, Canada, Oct. 2001, pp33-38
[4] Moallem, M, "Deflection control of a flexible beam using shape memory alloy actuators", Smart Mater. Struct. 12 (2003) 1023–1027
[5] Kudva J N, Sanders B, Pinkerton-Florance J and Garcia E, "2001 Overview of the DARPA/AFRL/NASA smart wing phase 2 program", in Smart Structures and Materials 2001: Industrial and Commercial Applications of Smart Structures Technologies (Newport Beach, CA, 2001); SPIE **4332** 383–9
[3] Kuribayashi K, "Micro SMA actuator and motion control", in Proc. 2000 Int. Symp. on Micromechatronics and Human Science (Nagoya, Japan, 2000) (Piscataway, NJ: IEEE) pp 35–42
[7] Peng, F., Y. Hu, A. Ng, "Experimental Study of Active Shape Control of Membrane Structures Using Genetic Algorithm", Proc. of the 55th International Astronautical Congress, Oct. 4-8, Vancouver, Canada, Paper number: IAC-04-I[1].4.07
[8] Kato, H., N. Inagaki, K. Sasaki. "A One-Dimensional Modelling of Constrained Shape Memory Effect", Acta Materialia. Vol. 52, pp. 3375-3382, 2004.
[9] Brinson, L. C., A. Bekker, S. Hwang. "Deformation of Shape Memory Alloys due to Thermo-Induced Transformation", Journal of Intelligent Material Systems and Structures, Vol. 7, pp. 97-107, 1996.
[10] Savi, M. A., A. Paiva, A. P. Baeta-Neves, P. M. C. L. Pacheco. "Phenomenological Modeling and Numerical Simulation of Shape Memory Alloys: A Thermo-Plastic-Phase Transformation Coupled Model", Journal of Intelligent Materials Systems and Structures: Vol. 13, pp. 261-273, May 2002.
[11] Ikuta, K., M. Tsukamoto, S. Hirose. "Mathematical Model and Experimental Verification of Shape Memory Alloy for Designing Micro Actuator", Proceedings of IEEE Micro Electro Mechanical Systems, New Jersey, pp. 103-108, 1991.
[12] Prahlad, H., I. Chopra. "Comparitive Evaluation of Shape Memory Alloy Constitutive Models with Experimental Data", Journal of Intelligent Material Systems and Structures: Vol. 12, pp. 383-395, June 2001.
[13] Ma, N., G. Song, "Control of Shape Memory Actuator Using Pulse Width Modulation", Smart Materials and Structures. Vol.12, pp. 712-719, 2003.

[14] Song, G., V. Chaudhry, C. Batur, "Precision Tracking Control of Shape Memory Alloy Actuators Using Neural Networks and a Sliding-Mode Based Robust Controller", Smart Materials and Structures. Vol. 12, no. 2, pp. 223-231. April 2003.

[15]. Raparelli T., Zobel P B and Durante F, "SMA wire position control with electrical resistance feedback", Proc. 3rd WorldConf. on Structural Control*, (Como, Italy, 2002)* vol 2, pp391-398.
[16] Ma, N., G. Song, H-J. Lee. Position Control of Shape Memory Alloy Actuators With Internal Electrical Resistance Feedback Using Neural Networks. Smart Materials and Structures: Vol. 13, (2004), pp. 777-783.

[17] Ma, N., G. Song and H-J Lee, "Position control of shape memory alloy actuators with internal electrical resistance feedback using neural networks", Smart Materials and Structures, **13**(2004) pp777-783
[18] Wu, X. D., J. S. Wu and Z Wang, "The variation of electrical resistance of near stoichiometric NiTi during thermomechanical procedures", Smart Materials and Structures, **8**(1999) pp574-578.
[19] Nam T. H., T. Saburi, Y. Kawamura and K. Shimizu, Mater. Trans. JIM, **31** (1990) 262