COMPARATIVE STUDY OF ELECTRICALLY AND INDUCTIVELY ACTUATED SHAPE MEMORY ALLOY NITI WIRE USING TENSILE TESTING

Article history
Received
21st February 2024
Received in revised form
2nd April 2024
Accepted
2nd April 2024
Published
1st June 2024

Sivasanghari Karunakaran*, Dayang Laila Abang Abdul Majid and Husam Yahya Imran

Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

*Corresponding author
sivasanghari24@gmail.com

Abstract

Shape memory alloy (SMA) actuators have the capability to actuate high forces while being compact, making them a potential replacement for complex electromechanical systems especially in aerospace applications. Common heating technique of SMA actuator is electrical heating. However, the actuation capability of SMA is dependent on the heat transfer mechanism of SMA as it is very sensitive to temperature and stress, thus lead to the difficulty in controlling mechanism. Owing to the complex controllability of heating techniques, the induction heating technique for SMA wire was undertaken in this investigation and proposed to be promising technique for SMA. A comparison between electrical heating and induction heating were performed using tensile testing. The tensile loading was performed using Instron 3366 Universal Testing Machine (UTS) with a 5 kN load cell and strain rate of 0.04 mm/min. A series of experiment at three different activation temperatures of 60°C,70°C and 80°C were performed for both the electrical and induction heating technique. The electrical actuation was done through power supply, whereas the inductive actuation was done through a specially developed heat control chamber comprises electromagnetic coil. The stress-strain curve for loading path was developed for both techniques and were compared. The results showed that the loading profile for inductively actuated wire was similar to the loading pattern of SMA superelasticity performance compared to electrical actuated wire which was nonlinear and serrated. In conclusion, induction heating technique is seemed to be a promising method to actuate SMA precisely.

Keywords

Shape memory alloy; Induction heating; Electrical heating; Actuation; Tensile test

Introduction

The most common form of SMA actuator is wire and the actuation rate of wire is affected by the changes in temperature or stress. The rate of heat transfer and amount of heat energy into and out of wire influences actuation response, response time and energy efficiency. In addition to that, the interaction of the coupled-behaved SMA wire with the ambient environment directly affect the phase transformation process of SMA wire. This phenomenon further influences the hysteresis behaviour of SMA wire and compromising the functional behaviour of SMA wire. Therefore, the characterization of heat transfer is utmost important in determination the frequency response of SMA actuators [1] and must be trained using reliable heating techniques.

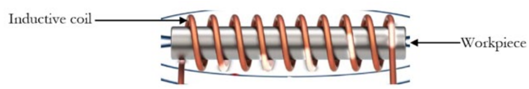


Figure 1: Induction Heating System

To date, available heating methods such as electrical heating, capacitance-assisted resistive, conductive, convective, radiative including laser, and inductive were used to manipulate SMA coupling behaviour in order to achieve desired actuation [2]. Electrical heating is most common method but the current capacity is limited to small, fine and slender components such as wire [3]. Therefore, induction heating technique became a promising method to heat SMA component in shorter time with better thermal control regardless the shape. Induction heating system comprises a workpiece and inductor coil which induces coupling effect through a contactless heating. Figure 1 illustrated the induction heating system in which the workpiece is placed inside the coil. Many research work has implemented induction heating for SMA thermomechanical characterization. Previously, R. Mohr et.al [4] trained shape memory polymers for faster actuation by using induction heating in short response time. Manufacturing industry utilized induction heating for the homogenous heat distribution [5] during production phase and achieved desired mechanical properties. While M. Tanaka et.al [6] utilized contactless induction heating to train urethra valve in medical field.

Here, the aim of this paper is to demonstrate and to compare the efficiency of electrical and induction heating on Flexinol NiTi wire. The change of the stress-strain curve for loading path of the wire is analysed at three different activation temperature.

Methodology

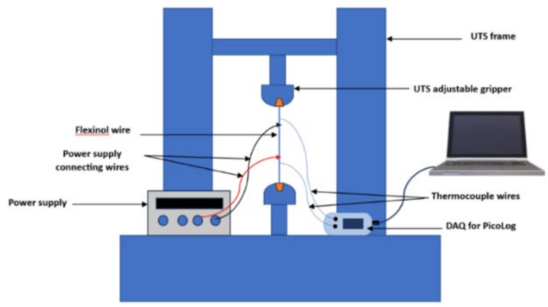
As-received nickel titanium (NiTi) shape memory wires with commercial trade name of Flexinol made by Dynalloy company were used in this investigation. The diameter of the wires was 0.31mm with nearly equatomic composition. The maximum safe stress for the wire was 170MPa as recommended by the manufacturer [7].

Heating Methods

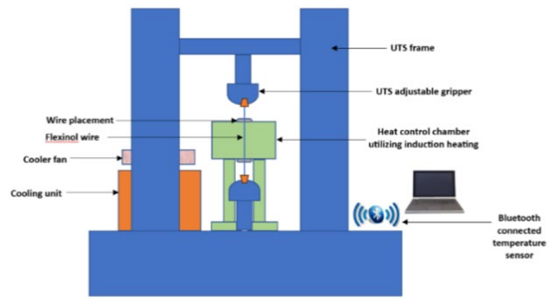
Instron 3366 Universal Testing Machine (UTS) with a 5 kN load cell was used to perform tensile test on NiTi wire which comprises loading path only. The tensile test for both electrically and inductively actuated heating were conducted at three different activation temperatures which are 60°C, 70°C and 80°C respectively. The strain rate used for Flexinol wire is 0.04 mm/min as recommended in ASTM F2516[8].

Figure 2 (a) shows the schematic diagram of the electrical heating technique used to activate NiTi wire. A J-type thermocouple attached between two junction points of the wire to the Data Acquisition PicoLog connector. This PicoLog device was connected to the laptop to receive and display the temperature data of the wire during the testing. The wire was heated by electrically through power supply connected directly to the specimen wire.

The induction heating technique applied to Flexinol wire actuation was shown in the schematic diagram in Figure 2 (b). The heat control chamber mounted with tensile test and connected with cooling unit to provide uniform heating and cooling environment throughout the test. The specimen wire was inserted through the chamber comprises inductive coil and a pretension of approximately 0.1N was to tighten the Flexinol wire. Following it, the displacement and load cell were calibrated. The temperature data is controlled and monitored through the temperature sensor connected with Bluetooth device in the chamber to the laptop.



(a)

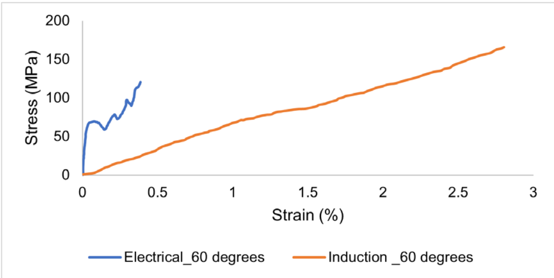


(b)

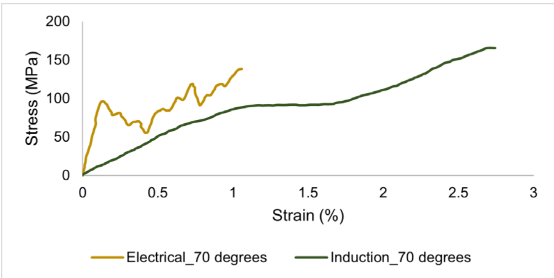
Figure 2: Schematic Diagram Heating Techniques: (a) Electrically Actuated NiTi Wire and (b) Inductively Actuated NiTi Wire

Results and Discussions

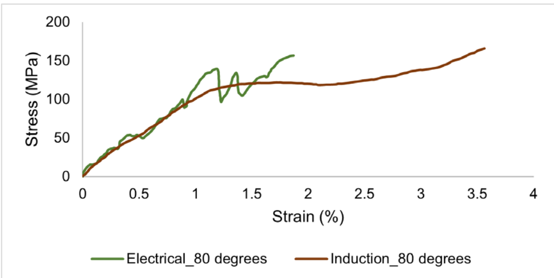
During thermomechanical training of Flexinol wire, the stress induced transformation is the most prominent mechanism for development of maximum strain generation. During the loading process of the wire, the phase transformation from austenite to martensite phases occurs due to the crystallographic changes in structure, thus resulting in the formation of the dislocation of phase interfaces [1]. In addition, the actuation strain for induction heating was greater than electrical heating. This phenomenon is very prominent with the effect of the different activation temperature during thermomechanical training [3]. Increasing activation temperature increases the rate of change of the lattice structure, thus trigger the phase transformation of wire more distinctly.



(a)



(b)



(c)

Figure 3: Comparison of Loading Profile for Electrically and Inductively Actuated NiTi Wire. (a) Actuation at 60°C, (b) Actuation at 70°C, and (c) Actuation at 80°C.

Figure 3 illustrated the evolution of loading profile for both electrically actuated wire and inductively actuated wire for three different activation temperatures which are 60°C, 70°C and 80°C respectively. The performance of wire by electrical heating was non-linear with many serrated patterns. The trend of actuation response was up and down throughout the loading path. On contrary, the inductively actuated wire showed a consistent linear pattern with smooth line. The trend of actuation response is similar to the loading profile of superelasticity of SMA. This indicates that the inductively actuated wire able to perform according to the typical superelasticity behaviour. The physical properties of wire during loading process elastic modulus at austenite can be extracted from the output of induction heating with more accurate data compared to the electrical heating. Table 1 shows the elastic modulus for both the heating techniques. The elastic modulus of inductively actuated wire showed increasing values with activation temperature, whereas for the electrically actuated wire, the values was inconsistent. This is due to the inconsistency in heat transfer mechanism between the electrical heating source and the wire, allowing non-uniform heat distribution along the wire .

Table 1: Elastic Modulus for Electrically and Inductively Actuated NiTi Wire

Temperature (°C)	Electrical Heating (GPa)	Induction Heating (GPa)
60	24	67
70	47	94
80	23	125

Therefore, in comparison to electrical heating, the induction heating technique is foreseen as a promising heating technique for SMA material. Based on the result obtained, the trend of electrically actuated wire prove that the heat transfer is non-homogeneous and the heat distribution is non-uniform [2]. Moreover, the serrated trend of electrically actuated wire clearly indicates that the production of by product due to direct heating might be present and eventually influences the mechanical properties of the wire [2,3]. Furthermore, compared to electrical heating technique, the induction heating contactless, preventing overheating and any physical damages to the wire [2].

Conclusion

In present study, induction heating technique is proposed to be effective method for SMA material compared to electrical heating technique. It has been found that the actuation gained by induction heating is good enough to use in practical applications. Induction heating is capable to actuate Flexinol wire once the optimum activation temperature is achieved, depending on the desired application. This study could provide the designer to accurately predict the coupling behaviour of SMA using induction heating.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the Ministry of Higher Education under the Fundamental Research Grant Scheme with grant no. FRGS/1/2019/STG07/ UPM/02/1.

REFERENCES

[1] Talebi, H., Golestanian, H., Zakerzadeh, M.R. and Homaei, H., 2014, April. Thermoelectric heat transfer modeling of shape memory alloy actuators. In The 22st Annual International Conference on Mechanical Engineering-ISME2014, Ahvaz, Iran.

[2] Karunakaran, S., Majid, D.L.A.A., Jaafar, C.N.A., Ismail, M.H. and Imran, H.Y., 2022. Heating Techniques of Shape Memory Alloy (SMA)-A Review. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 99(2), pp.207-220.

[3] Pfeifer, R., Hustedt, M., Wesling, V., Hurschler, C., Olender, G., Mach, M., Gösling, T. and Müller, C.W., 2013. Noninvasive induction implant heating: an approach for contactless altering of mechanical properties of shape memory implants. Medical engineering & physics, 35(1), pp.54-62.

[4] Mohr, R., Kratz, K., Weigel, T., Lucka-Gabor, M., Moneke, M. and Lendlein, A., 2006. Initiation of shape-memory effect by inductive heating of magnetic nanoparticles in thermoplastic polymers. Proceedings of the National Academy of Sciences, 103(10), pp.3540-3545.

[5] Kabiri, Y., Kermanpur, A. and Foroozmehr, A., 2012. Comparative study on microstructure and homogeneity of NiTi shape memory alloy produced by copper boat induction melting and conventional vacuum arc melting. Vacuum, 86(8), pp.1073-1077.

[6] Tanaka, M., Wang, F., Abe, K., Arai, Y., Nakagawa, H. and Chonan, S., 2006. A closed-loop transcutaneous power transmission system with thermal control for artificial urethral valve driven by SMA actuator. Journal of intelligent material systems and structures, 17(8-9), pp.779-786.

[7] Dynalloy Inc, 2017. Technical Characteristics of Flexinol Actuator Wires.

[8] ASTM F2516-07, 2022. Standard test method for tension testing of nickel-titanium superelastic materials