Phase Transformation Temperatures for Shape Memory Alloy Wire

Tan Wee Choon, Abdul Saad Salleh, Saifulnizan Jamian, and Mohd. Imran Ghazali

***Abstract*—**Phase transformation temperature is one of the most important parameters for the shape memory alloys (SMAs). The most popular method to determine these phase transformation temperatures is the Differential Scanning Calorimeter (DSC), but due to the limitation of the DSC testing itself, it made it difficult for the finished product which is not in the powder form. A novel method which uses the Universal Testing Machine has been conducted to determine the phase transformation temperatures. The Flexinol wire was applied with force and maintained throughout the experiment and at the same time it was heated up slowly until a temperature of approximately 100^0C with direct current. The direct current was then slowly decreased to cool down the temperature of the Flexinol wire. All the phase transformation temperatures for Flexinol wire were obtained. The austenite start at 52.54^0C and austenite finish at 60.90^0C, while martensite start at 44.78^0C and martensite finish at 32.84^0C.

***Keywords*—**Phase transformation temperature, Robotic, Shape memory alloy, Universal Testing Machine.

I. Introduction

SHAPE memory alloys are widely used in the engineering applications especially in the robotic, aerospace and vibration control area. To design and optimise the applications of the shape memory alloys, a clear understanding of its behavior and characteristics is required. The phase temperature for the shape memory alloys such as the austenite start (A_s), austenite finish (A_f), martensite start (M_s) and martensite finish (M_f) are the basic temperature that should be determined before designing the system. Unfortunately the properties provided by the manufacture normally were not complete. So further investigation or testing need to be done.

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Differential Scanning Calorimetry (DSC) is one of the famous testing that was done to determine the phase transformation temperatures of the shape memory alloys. The past researchers [1,2,3,4,5], had suggested the DSC as the standard method to determine the phase transformation temperatures for their research purposes but from the analysis that was done, the DSC method is only suitable for the powder form product and not suitable for finished form product such as wire. Some other researchers proposed other methods to determine the properties of the shape memory alloys. Mohammad H Elahinia and Mehdi Ahmadian, [6] suggested to use a linear variable differential transformer (LVDT) with consists of a stack of masses that was actuated vertically by an SMA wire. The stress applied to the SMA wire can be adjusted by adding mass to or removing mass from the stack. A personal computer records these measurements and generates the voltage signals, which were then amplified before applied to the SMA wire. A J Żak *et. al*, [7] had design an experimental rig which contained force sensors displacement measurement and thermocouple to determine the phase transformation temperatures. The Shape memory alloy wire was heated up with the direct current and the testing were done with different value of dead-weight load to the wire. The experiment which designed by A. J Żak *et. al*. not only used to determine the phase transformation temperature but also the thermo-mechanical properties of the shape memory alloy wire.

This phase transformation temperatures are important in designing the system that to be built such as in the robotic area. Z.W. Zhong and C.K. Yeong [8] suggested using the shape memory alloy to design the micro-applications gripper that could give the gripping force within the range of 70–500 mN based on the phase transformation temperatures. The micro-applications gripper that has been designed was cheap compared to other. Mohammad H Elahinia and Mehdi Ahmadian [9] had design the one-degree-freedom robotic arm, actuated by SMA NiTi wire, with a bias spring. The phase kinetics model needs temperature and stress to calculate the fraction of the system. Elwaleed Awad Khidir *et. al.* [10] developed a new concept of the linear smart actuator using the shape memory alloy wire. The actuator functions with the temperature during heating and cooling.

In this paperwork, the austenite start (A_s), austenite finish (A_f), martensite start (M_s) and martensite finish (M_f) will be determined from the experiment which was done by Universal Testing Machine and the wire will be heated up by the direct current. Further discussion on the specimen will be done in section 2 while detail experiment setup in section 3. Section 4 introduces our enhanced data and analysis, and finally the paper is concluded in section 6.

II. Specimen

The shape memory alloy used was the Flexinol wire from Dynalloy, Inc and the detail properties are as shown in Table I. The diameter of the Flexinol wire was 0.02 inch which has the maximum pull force of 34.94 N. The clearance length of the Flexinol wire was 500mm and both end of the wire have been clamped with the barrel crimp as shown in Fig. 1.

This Flexinol wire was chosen because of the ready-to-use characteristic compared to the ordinary nitinol wire which required special training before it can be used and furthermore the Flexinol can be easily heated by the direct current.

TABLE I
PROPERTIES OF FLEXINOL® WIRE

Parameters	Value
Density	6.45 g/cm^3
Specific heat	6-8 cal (mol.^{0}C)
Melting Point	1250 ^{0}C
Heat of transformation	10.4 BTU/lb
Thermal conductivity	0.05 cal (cm-^{0}C-sec)
Thermal expansion coefficient	
Martensite	6.6 x 10^{-6} /^{0}C
Austenite	11.0 x 10^{-6} /^{0}C
Electrical resistivity	
Martensite	421 Ohm/Cir Mil Ft
Austenite	511 Ohm/Cir Mil Ft
Linear resistance	0.12 Ohm/inch
Density	6.45 g/cm^3
Specific heat	6-8 cal (mol.^{0}C)
Melting Point	1250 ^{0}C

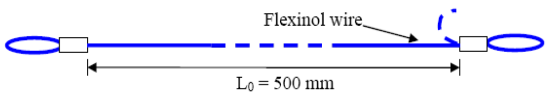

Fig. 1 Clearance length of Flexinol wire

III. Experiment Setup

The Experimental layout that will be conducted by the Universal Testing Machine is shown in the Fig. 2. The Flexinol wire was heated up by the direct current which supplied by the DC power supply and measured by the digital multimeter to ensure the increment and decrement of the voltage was small. The temperature of the Flexinol wire was measured by the thermocouple type K. The force and displacement reading of the Flexinol wire will then measured by the Universal Testing Machine.

The Flexinol wire was held by the clamper of the Universal Testing Machine and the clamper wires were then connected to all equipments as shown in the Fig. 2. The value of the force reading was initially set to zero and the Flexinol wire was applied with pretension of approximately 1 N. This was done manually with a constant low speed of increment to avoid any extreme pretension to the wire. After the pretension of the Flexinol has been done, the displacement was then set to zero. The Flexinol wire was then ready to be tested.

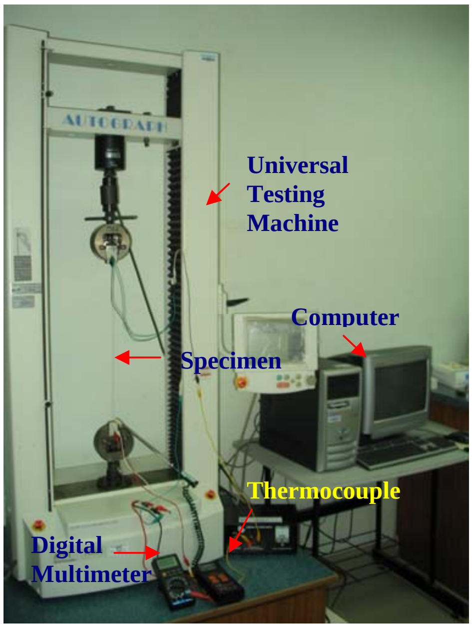

Fig. 2 Layout of experiment setup

The experiment is divided into two major part; the heating process and the cooling process. For the heating process, the voltage throughout the Flexinol wire was increased to around 0.05 V. When the force was set to zero, the reading of the displacement and temperature were taken. These steps were repeated until the temperature of the Flexinol wire reach to approximately 100^{0}C.

The experiment followed with the cooling process. The voltage throughout the Flexinol wire was then decreased to 0.05V. When the force was set to zero, again the reading of the displacement and temperature were taken.

The heating and the cooling process were repeated for other sets where the value of the initial force applied to the Flexinol wire was set to be 5.0 N, 10.0 N, 15.0 N and 20.0 N. The displacement and temperature reading will be taken when the force equal to the initial applied value.

The reading of the parameters needed should be carefully taken especially during the phase transformation occur, whereas the changes of the specimen length against temperature increase due to the change of the electrical resistivity of the Flexinol wire itself.

IV. Data and Analysis

The data from the experiment was then export to the FlexPro program to be analysed. Each set of the data of forces 0.0 N, 5.0 N, 10.0 N, 15.0 N and 20.0 N were plotted as graph length of the Flexinol wire versus the temperature for the heating and cooling process as shown in Fig. 3, 4, 5, 6 and 7.

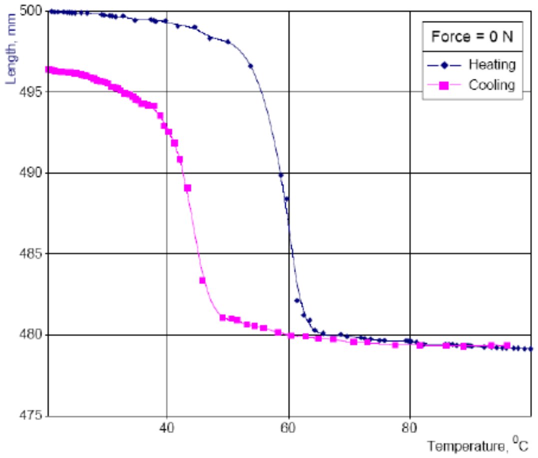

Fig. 3 Set data for the set experiment with 0.0 N force applied to the Flexinol wire

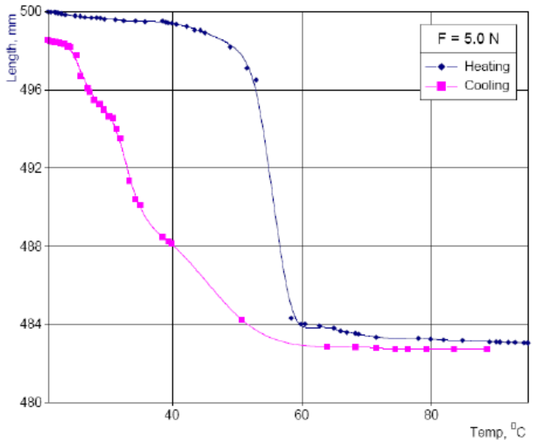

Fig. 4 Set data for the set experiment with 5.0 N force applied to the Flexinol wire

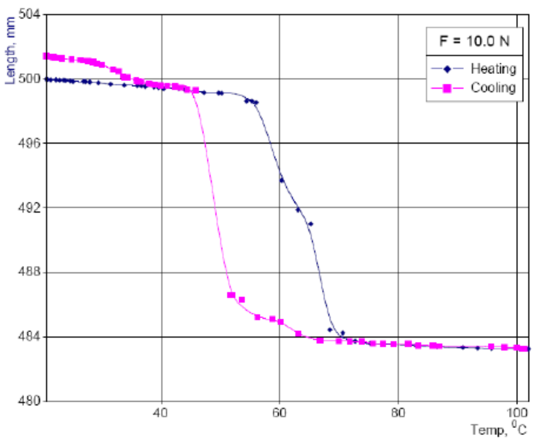

Fig. 5 Set data for the set experiment with 10.0 N force applied to the Flexinol wire

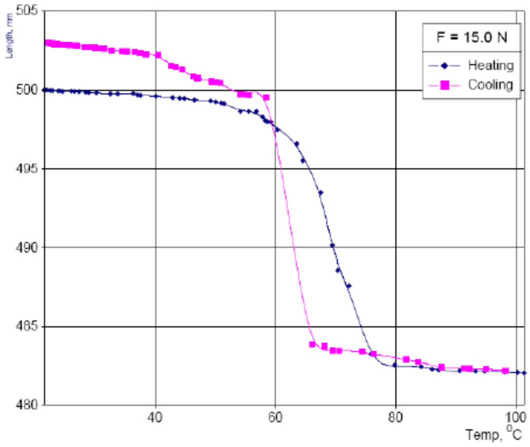

Fig. 6 Set data for the set experiment with 15.0 N force applied to the Flexinol wire

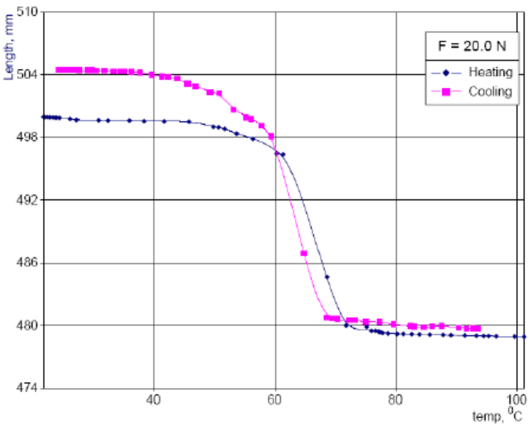

Fig. 7 Set data for the set experiment with 20.0 N force applied to the Flexinol wire

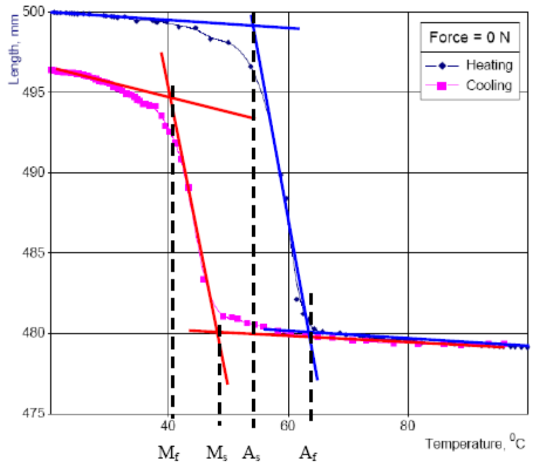

Fig. 8 Steps to determine the phase transformation temperature of Flexinol wire

From each set of the experiments, Austenite start, austenite finish, martensite start and martensite finish were determined as shown in the Fig. 8. Austenite start and austenite finish will be obtained from the heating process curve while martensite start and martensite finish from the cooling process curve which represented as diamond line and square lines.

Table II shows the phase transformation temperatures for all set of experiments for the Flexinol wire. Graphs of temperature versus force will be plotted from the result shown in Table II as shown in Fig. 9. The graphs were linear and the point for each curve which crosses the temperature axis will be the real phase transformation temperatures where most analysis will use these values.

TABLE II
PHASE TRANSFORMATION TEMPERATURES FOR FLEXINOL® WIRE WITH DIFFERENT FORCE CONDITION

Force (N)	A_s (°C)	A_f (°C)	M_s (°C)	M_f (°C)
0.0	54.75	62.83	48.08	40.20
5.0	51.89	58.58	46.79	24.91
10.0	56.12	69.90	52.65	46.33
15.0	62.64	76.24	66.09	58.17
20.0	60.76	71.05	68.00	57.14

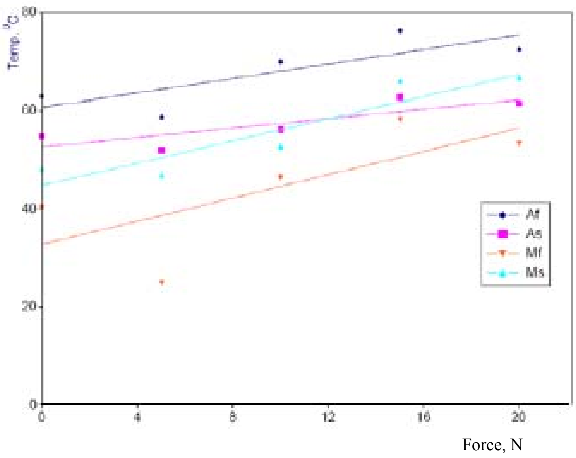

Fig. 9 Phase transformation temperatures when without force applied

From Fig. 5, the phase transformation temperatures for the Flexinol wire are as shown in the Table III.

TABLE III
PHASE TRANSFORMATION TEMPERATURES FOR FLEXINOL® WIRE

A_s (°C)	A_f (°C)	M_s (°C)	M_f (°C)
52.54	60.90	44.78	32.84

V. CONCLUSION

This method can be used to determine the phase transformation temperatures for the shape memory alloy which is not in the form of powder.

The test conducted with the Universal Testing Machine is more convenient and only required additional equipments such as the thermocouple and the DC power supply to heat up the shape memory alloy.

Although this method can be used but there is still some difficulty faced such as the difficulty in controlling the parameters during conducting the experiment especially in the process of natural cooling of the wire and in the measurement of temperature of the wire changed during the process of loading and unloading. This will affect the changes in electrical resistivity of the martensite and austenite phases during the transformations [12].

The phase transformation temperatures of the Flexinol wire that has been done were austenite start at 52.54^0C and austenite finish at 60.90^0C, while martensite start at 44.78^0C and martensite finish at 32.84^0C.

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