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NUMERICAL AND EXPERIMENTAL STUDY OF SHAPE EFFECT BEHAVIOR OF NITINOL WIRE

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Abstract: The aim of this research, returned NiTinol wire to original length by activation. The experimental test and ANSYS v15 software were conducted to study the shape memory effect behavior for NiTinol wire has high temperature about 80°C±10°C. Full annealing of NiTinol wire was employed with a straight shape, this alloy it consists of (Ni-55%, H-0.001%, O-0.05%, N-0.001%, C-0.05% and Ti-Balance). In this research, a NiTinol wire was implemented (2 mm diameter) and (100 mm length). The experimental results and ANSYS software were almost near. Shape memory effect data constants used in ANSYS software were extracted from the experimental test by applying linear interpolation. These data were hardening parameter (C1) about 900 MPa and elastic limit (C3) about 30 MPa. These data were temperature scaling parameter C4=0.89, maximum transformation strain C5=0.074%, martensite modulus C6=20000 MPa and dependency parameter C7=0. The amount of strain (7 %) applied in this test returned to zero after activation NiTinol wire, and that gives an indication that the permanent deformation is decline. The start austenite temperature (A_s) was about 58°C±2℃ and finish austenite temperature (A_f) was about 70°C±2℃. ANSYS software provided good results when compared with the experimental work.

Keywords: *Shape memory effect, NiTinol wire, Tensile test, Finite element modeling, Austenite finish temperature, Martensite start temperature.*

دراسة عددية وعملية لسلوك تاثير الشكل لسلك نيتينول

الخلاصة: هدف هذا البحث، هو اعادة الطول الاصلي لسلك النيتينول بواسطة التنشيط. تم اجراء اختبار تجريبي وبرنامج انسيز الاصدار 15 لدراسة سلوك تاثير ذاكرة الشكل لسلك نيتينول يمتلك درجة الحرارة عالية حوالي 80°C±10°C . سلك نيتينول كامل االتصليب قد استخدم بشكل مستقيم، هذه السبيكة تتالف من (Ni-55%, H-0.001%, O-0.05%, N-0.001%, C-0.05% and Ti-Balance). في هذا البحث، تم استخدام سلك نيتينول (قطر 2 مليميتر) و (طول 100 مليميتر) . وكانت النتائج التي تم الحصول عليها من الفحص التجريبي والانسيز غالبا قريبة. ثوابت بيانات تاثير ذاكرة الشكل المستخدمة في الانسيز مستخلصة من الفحص التجريبي بواسطة تطبيق الاستيفاء الخطي. هذه البيانات هي عامل الصلابة (C1) حوالي 900 ميكاباسكال و حد المرونة (C3) حوالي 30 ميكاباسكال. تلك البيانات هي عامل تدريج درجة الحرارة C4=0.89، اقصى استطالة تحول C5=0.074%، معامل المارتنسايت C6=20000 ميكاباسكال ومعامل الاعتماد C7=0 . قيمة الاستطالة (7 %) المطبقة في هذا الفحص عادت الى الصفر بعد التنشيط، وهذا يعطي مؤشر ان التشوة الدائمي قد زال.

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درجة حرارة بداية الاوستنايت (A_s) كانت حوالي 58°C±2°C و درجة حرارة نهاية الاوستنايت (A_f) كانت حوالي 70°C±2°C. برنامج الانسيز زود نتائج جيدة عندما يقارن مع العمل التجريبي.

1. Introduction

NiTinol wire has two important behaviors, super-elasticity and shape memory effect. This research investigated the shape memory effect of NiTinol wire. These phenomena occur in low temperature in martensitic state, when the shape memory alloy (SMA) is soft and can change its shape in any shape easily. The NiTinol wire stretched to about 8% in martensitic phase at low temperature [2], one can illustrate that the NiTinol wire cannot return to original shape unless heated above the austenite finish temperature. The martensitic transformation is independent on the time spent at the transformation temperature, but it depends on the transformation temperature. These phenomena are shown in figures (1) and (2), respectively.

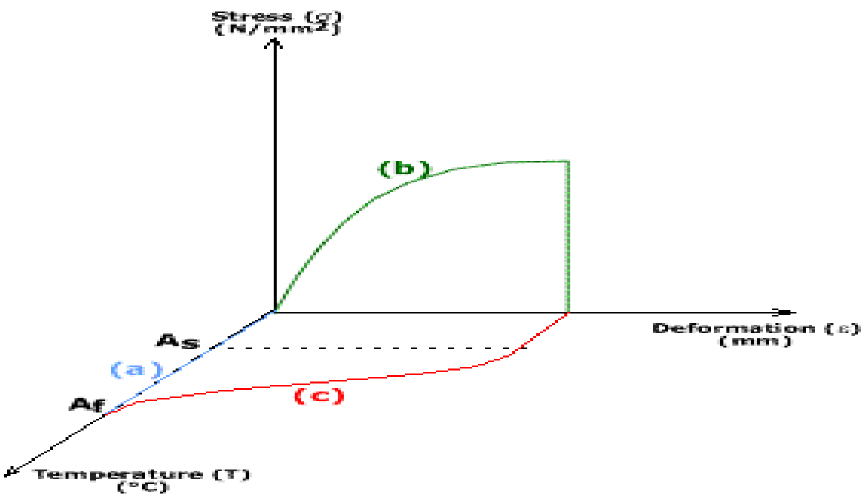

Figure 1: Shape memory effect diagram [3]

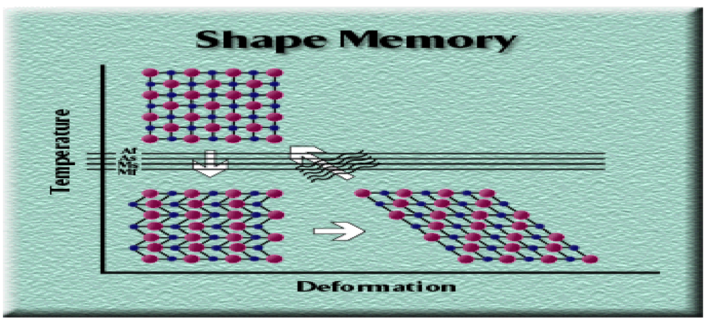

Figure 2: Shape memory effect behavior [4]

Shape effect behavior has more application in aerospace, shape control structure, active surfaces and medical purposes. In this work, high temperature NiTinol wire was employed as shown in figure (3). Wire diameter is 2 mm, black color, annealed, and straight.

Figure 3: NiTinol wire coil used in the present work.

"Shape Memory" describes the effect of restoring the original shape of a plastically deformed sample by heating it. This phenomenon results from a crystalline phase change known as "thermo-elasticity martensitic transformation". At temperatures below the transformation temperature. Shape memory alloys are martensitic, in this condition. Their microstructure is characterized by "self-accommodating twins", the manensite is soft and can be deformed quite easily by de-twinning. Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic [5].

Savi and Braga [6] discussed some characteristics related to the original Fremond’s model. Afterwards, a new one-dimensional model was built upon the original Fremond’s model.

Paiva and Amorim Savi [7] investigated the thermo-mechanical behavior of shape memory alloys, described by pseudo-elasticity, shape memory effect, discussing the main constitutive models for their mathematical description. Differential scanning calorimeter (DSC) is used to find phase transformation temperatures. Several models in this paper were checked. Proved the polynomial model is simple and allow a qualitative description of pseudo-elastic and shape memory behavior, and the model with internal constraints is capable of capturing the general thermo-mechanical behavior of SMA.

Fafa Ben, et al. [8] studied the thermo-mechanical behavior simulation of a NiTinol Staple used for the Correction of Idiopathic Scoliosis. They implemented finite element method to obtain behavior of NiTinol by modeling a 3D beam subjected to a uniaxial load.

It was concluded that the three dimensional constitutive model is able to reproduce the basic macroscopic features of shape memory material, such as the super-elasticity, the shape memory behavior, and different response under tension and compression. The biocompatibility of these alloys is one of the most important points related to their biomedical applications as orthopedic implants [15].

2. Experimental Work

In this research, high temperature about 80°C±10°C NiTinol wire full annealing was employed with a straight shape, it consists of (Ni-55%, H-0.001%, O-0.05%, N-0.001%, C-0.05%, Ti-Balance), imported from Nexmetal Inc 8780 19th Alta Loma, California 91701. The wire has a circular cross-section with (2 mm diameter) and (100 mm length). This wire model was tested with low and high temperature above the austenite finish temperature (A_f) about (A_f+10°C), to reduce the secondary side effects and be sure the wire reached the full activation.

2.1 Phase Transformation Temperatures

It is very important to calculate the phase transformation temperatures, these included austenite start temperature (A_s) and austenite finish temperature (A_f). The idea is to find these temperatures, in order to know the range of activation temperatures. At the beginning, activated NiTinol wire by applied electric current, NiTinol wire was deformed shape before turning the switch on of circuit, and all devices connected with the NiTinol wire, as shown in figure (4).

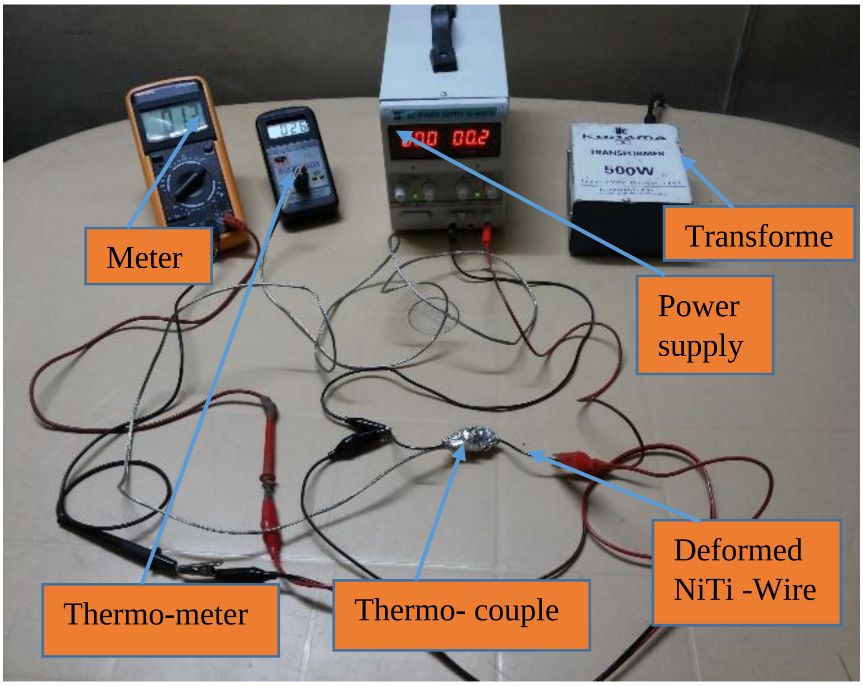

Figure 4: Devices connection with deformed NiTinol wire used in present work before supplying the power [13]

When the switch of circuit was on the current of power supply increases slowly, until the NiTinol wire begins to initiate the change, this moment presents start of austenite temperature (A_s) and indicates its value about 58°C±1°C in thermocouple screen type (K-type) and induced in power supply values of current and voltage (4 A, 1.6 V), respectively.

After obtaining start of austenite temperature (A_f), current of power supply continues to increase, temperature of NiTinol wire continues to elevate, deformable NiTinol wire begins to change its shape gradually, until it becomes straight.

At this moment, thermo couple records the temperature of the NiTinol wire and its value about 70°C±1°C, power supply indicated amount of current and voltage 6.2 A, 1.7 V, respectively, as shown in figure (5).

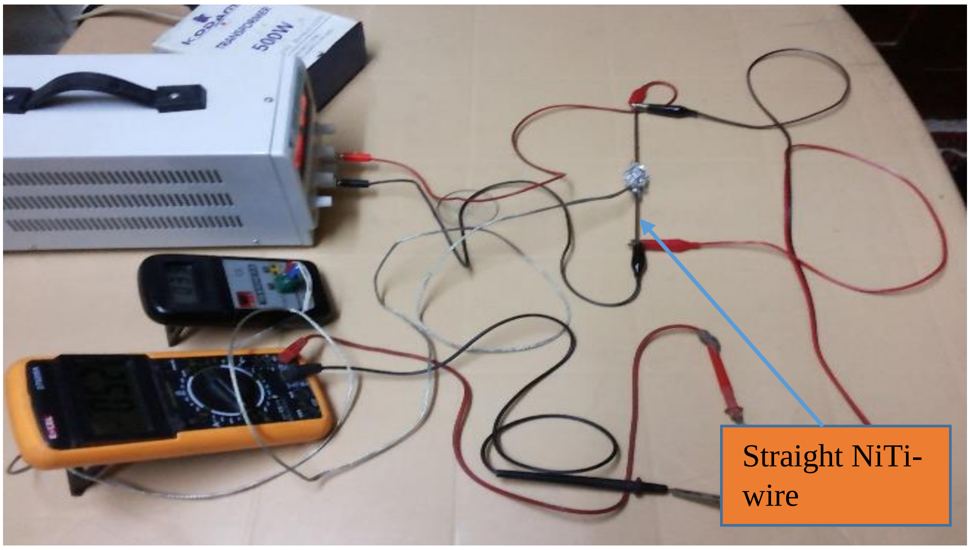

Figure 5: Straight NiTinol wire after supplying the power [13]

2.2 Tensile Test Model of NiTinol Wire

NiTinol wire behaves as a shape memory effect material with recoverable strains of up to 8 % [9, 10, 14]. In this work, the implementated model of NiTinol wire is full annealed, straightened shape (2 mm diameter) and (100 mm length) according to ASTM F2516 [11].

Before beginning the test, NiTinol wire was prepared, and the wire was installed in grips of machine, then tensile machine was started with strain rate 0.5 mm/min, when the displacement of NiTinol wire reaches 7 mm (strain 7 %) machine stops (pause). After stopping the machine, machine be comes in unloading case without activation NiTinol wire. When load becomes zero, machine stops and begins to activate the NiTinol wire by supplying a suitable current from power supply due to evaluated temperature above the finish austenite temperature (A_f) approximately (A_f+10°C), to ensure the activation case and avoid the secondary effects, NiTinol wire connection with other devices are shown in figure (6), and curve of stress-strain is shown in figure (7).

Experimental data was input into the computational model, as shown in table (1). These data were obtained by applying linear interpolation for the stress-strain curve, and for same formulas utilized for this purpose [1].

$$C1 = (3/2)\, h \qquad (1)$$

$$C2 = T_0 \qquad (2)$$

$$C3 = R = \frac{\sigma_f^{AS} - \sigma_s^{SA}}{2} * \sqrt{\frac{3}{2}} \qquad (3)$$

$$C4 = ß \tag{4}$$

$$C5 = \varepsilon_L = \sqrt{\frac{3}{2}} * \varepsilon_L \tag{5}$$

$$C6 = E_m \tag{6}$$

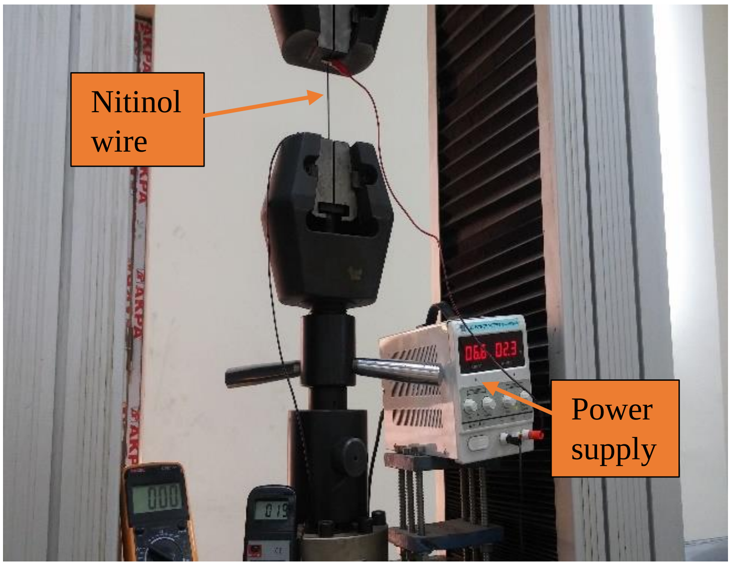

Figure 6: Shape effect test

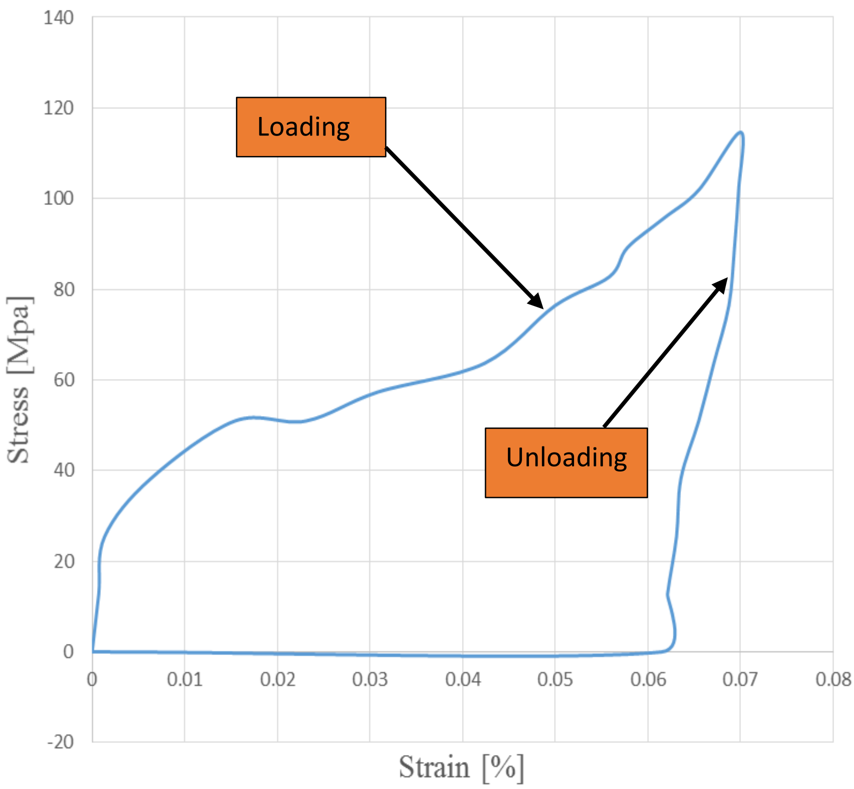

Figure 7: Experimental shape memory effect of NiTinol wire with 7% total strain.

Table 1: Experimental shape memory effect data from stress-strain curve of the present work

Constant	Value	Meaning	Property
C_1	900 MPa	h	Hardening parameter
C_2	296 K	T_o	Reference temperature
C_3	30 MPa	R	Elastic limit
C_4	0.89	β	Temperature scaling parameter
C_5	0.074 %	$\overline{\varepsilon_L}$	Maximum transformation strain
C_6	20000 MPa	E_m	Martensite modulus
C_7	0	m	Dependency parameter

3. FE Modeling of Shape Memory Effect of NiTinol Wire

Finite element modeling is a method can predict the behavior of model and find the results usually being near to the results in experimental work. The model in present work consists of a wire of (2 mm diameter) and (100 mm length), which was then undergone to a linear displacement of 7 mm at one end, while the other end was fully fixed.

The model consisted of 3076 hexahedral elements and 24609 nodes. This model is meshed with 3D structure-thermal solid elements of type 5 coupled field. SOLID5 is a higher order 3D 8-node solid element, as shown in figure (8). Figure (9) depicts the elements distribution of the model.

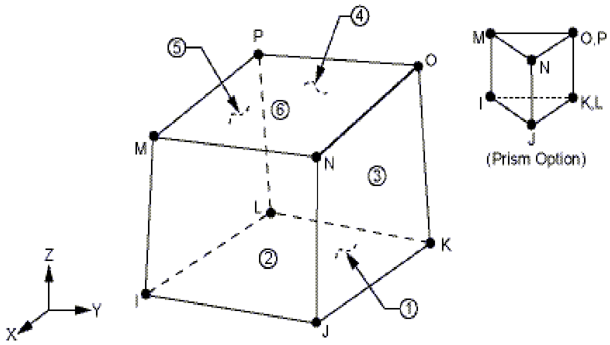

Figure 8: 3D structure solid elements of type solid5 [12]

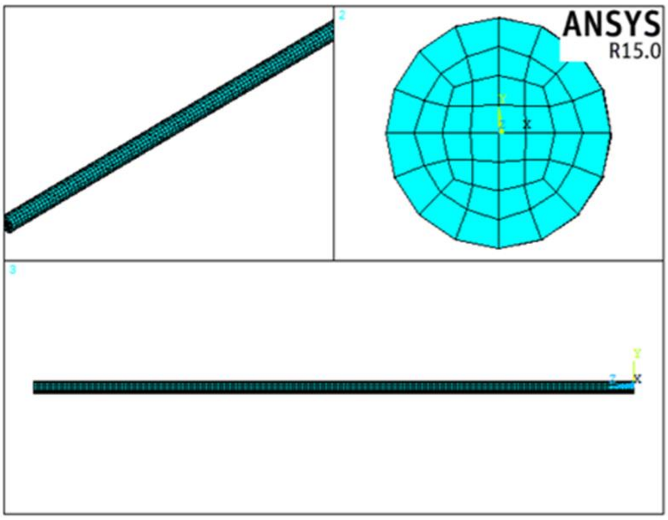

Figure 9: FE Model geometry and element distribution

SOLID5 has a 3-D magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. The element has eight nodes with up to six degrees of freedom at each node. Scalar potential formulations (reduced RSP, difference DSP, or general GSP) are available for modeling magneto static fields in a static analysis. When used in structural and piezoelectric analyses, SOLID5 has a large deflection and stress stiffening capabilities [12]. The shape memory effect behavior of shape memory alloys of the model initializes the data table using the TB, SMA command's (MEFF) option.

Also, the results of the simulation of total displacement can be obtained, as shown in figure (10), and Von Mises stress is shown in figure (11).

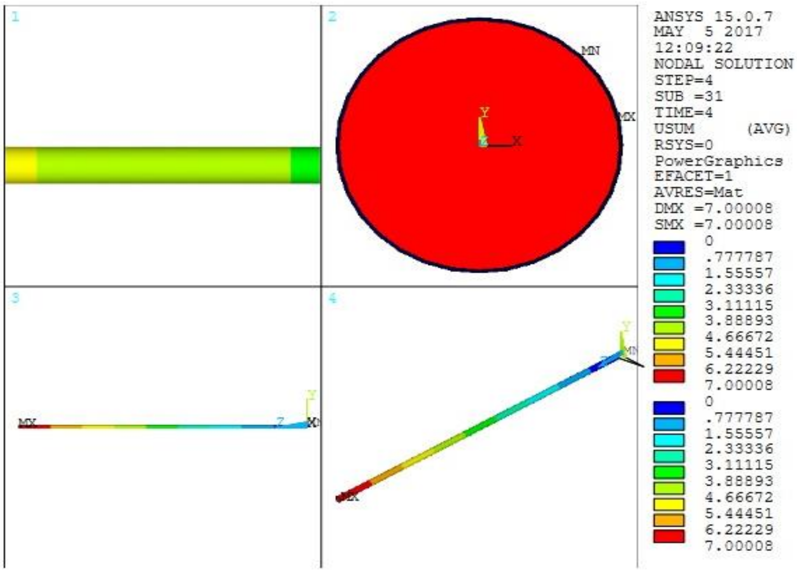

Figure 10: FEM total displacement in ANSYS

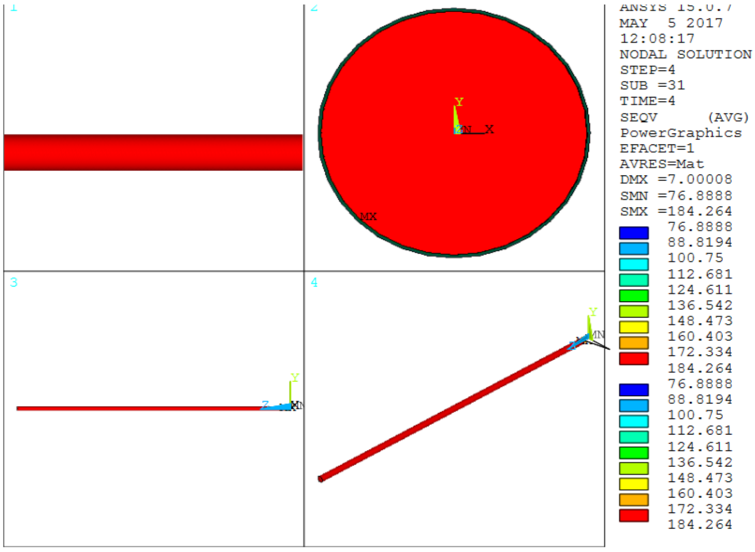

Figure 11: FEM Von Mises equivalent stress in ANSYS.

In finite element analysis, shape memory effect for NiTinol wire was subjected to the same amount of strain using the elastic limit, tangent modules and same constants mentioned in chapter four. The curve of shape memory effect is shown in figure (12).

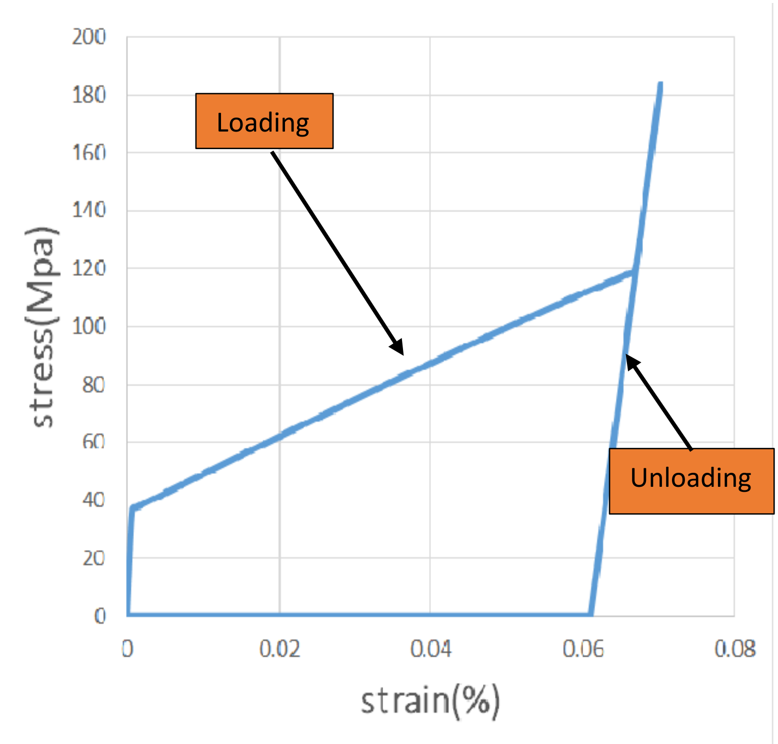

Figure 12: FEM shape memory effect of NiTinol wire with 7% total strain.

4. Results and Discussion

In this study the tensile test of NiTinol wire was experimental and numerical employed by the applied ANSYS software. During the test, the temperature remained above austenite finish temperature (A_f+10), in interval when the stress becomes zero. Shape memory effect data constants used in ANSYS software were taken from the experimental test by applying linear interpolation. These data are hardening parameter (C1) 900 MPa and elastic limit (C3) 30 MPa. The other data constants obtained from the employed formulas in reference [1], C4=0.89, C5=0.074%, C6=20000 MPa and C7=0. The mount of strain 7 % applied in this test returned to zero after applied activation that gives an indication that the permanent deformation is decline 100%. The values of start austenite temperature was (A_s) about 58°C$\pm$2℃, and finish austenite temperature (A_f) was about 70°C$\pm$2℃. These results were almost found near to previous results [5]. In case the NiTinol wire cannot able to return in original shape, this is mean behavior NiTinol wire dose not has validity.

5. Conclusions

1. Area between curves presented the energy dispersion.
2. Wire strain returned to the zero position after activation.
3. Stress-strain curve closed in both study.
4. Activation of NiTinol wire was done by applied a current.
5. NiTinol wire has a good response.
6. NiTinol wire has a high recovery strain more of 7%.
7. Element type solid5 referred to coupled field case.
8. Validity of NiTiol wire is a good.
9. Shape effect behavior is useful for smart composite materials.
10. Shape effect behavior has wide applications.

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