Experimentální Analýza Napětí 2011
Experimental Stress Analysis

Modelling of materials with shape memory effect with using finite element method

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Abstract: Materials with shape memory effect exceed conventional materials especially in high reversible deformations (pseudoelasticity) and a possibility of permanent deformation disappearance after applying a heat on them (shape memory effect). The purpose of this article is to define a procedure to acquire characteristic mechanical constants of these materials in order to use Auricchio's material model in FEM software MSC.Marc. A sample in the form of a wire made of the binary NiTi alloy was subjected to tensile test. From the gained stress-strain function the needed values were evaluated. Because of the mechanical properties are strongly temperature-dependent, the tensile tests were performed under various temperatures: 19 °C, 37 °C, 60 °C and 80 °C. Dislocation of a hyperelastic plateau up to higher stresses with increasing temperature is clearly visible. Variation of Young's modulus of both phases (austenite, martensite) which the material is passing through during loading and unloading of the sample is also obvious. The conditions of tensile test were simulated in MSC.Marc and gained graph was compared with experimental data. These results will be used for creating a finite element model of endovascular stent. Another advantage of NiTiNOL is, among the other ones, its excellent biocompatibily.

Keywords: Nitinol, Shape memory, Finite element method, Stent, Biomechanics

1. Introduction

The shape memory alloys made a great progress since the concept of thermoelastic martensitic transformation was introduced in 1949. Nowadays, we can find their application in almost each field of mechanical engineering. Their remarkable properties such as pseudoelasticity and shape memory effect which distinguish them from other conventional materials were considered as a useless side effect first. Aerospace engineering, Biomedical engineering, Transportation, these are only a few examples of areas where shape memory alloys are frequently used. There are many combinations of metals which exhibit shape memory effect, for example Ag-Cd, Au-Cd, Cu-Sn, Mn-Cu.

The aim of this article is characterisation of NiTiNOL. This material was originally discovered in 1962 by Buehler and co-workers when investigating materials useful for heat shielding [1]. It's a binary alloy, composed of Nickel (~55% vol.) and Titan. The term "NOL" comes from the place of its discovery at the Naval Ordnance Laboratory. Among the other SMAs, this material is special for its biocompatibility and therefore its possibility for use in biomedical applications [2]. The need of understanding the mechanisms which occur during loading/unloading and heating/cooling of the material came from project that deals with stent-grafts.

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1.1. Behaviour of SMAs

Before the experimental analysis of the material was proceeded to, there had been a need to understand its behaviour under various conditions. SMAs have two phases, each with a different crystal structure and therefore different properties. The high temperature phase is called austenite and other is low temperature phase called martensite (Fig. 1). The reversible phase transformation from austenite (parent phase) to martensite (product phase) and vice versa forms the basis for the unique behaviour of SMAs [1].

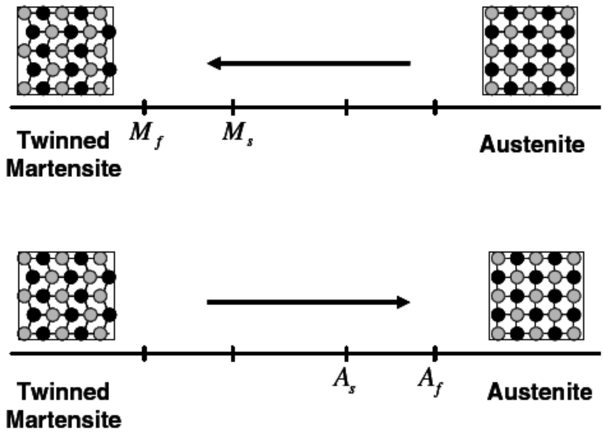

Fig. 1. Temperature-induced phase transformation of an SMA without mechanical loading [1]

1.2. Pseudoelasticity

The pseudoelastic behaviour of SMAs is associated with stress-induced transformation, which leads to strain generation during loading and subsequent strain recovery upon loading at temperature above A_f. A pseudoelastic thermomechanical loading path generally starts at a sufficiently high temperature where stable austenite exists, then develops under an applied load to a state at which martensite is stable, and finally returns to the austenitic phase when returned to zero stress state [1].

During such process there are four significant points where the phase transformations begin or end (Fig. 2). In this article they will be named as:

- σ_{Ms} [MPa] – stress level at which phase transformation from austenite to martensite begins.
- σ_{Mf} [MPa] – stress level at which phase transformation from austenite to martensite ends.
- σ_{Aa} [MPa] – stress level at which phase transformation from martensite to austenite begins.
- σ_{Af} [MPa] – stress level at which phase transformation from martensite to austenite ends.

2. Material and Methods

2.1. Tensile test

The tensile test was performed in laboratory of Technical University of Liberec. First problem that had to be solved was clamping of the samples in the form of wires with a diameter smaller than 1 mm. We had to find proper clamps which wouldn't cause a stress concentration in its tightening part and following fracture of a sample before real strength limit is reached.

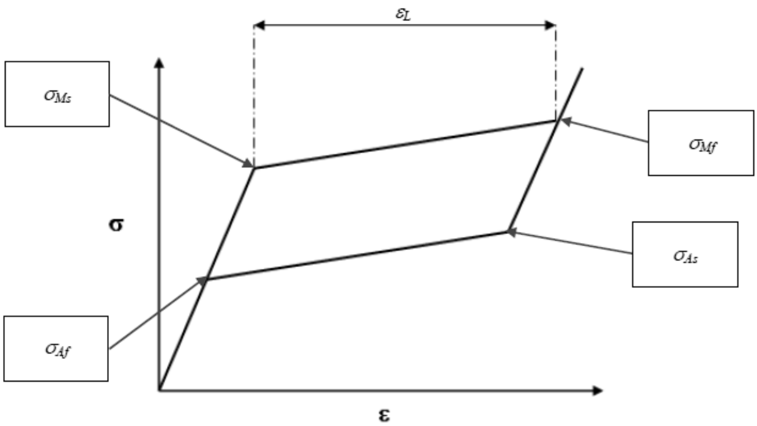

Fig. 2. Simplified stress-strain response of SMA with marked transformation stresses

By the reason that we weren't able to find suitable clamping system that would fulfil our requirements we had to design our own (Fig. 3). Its design was also meant to serve for fatigue tests which we plan to realize as a next step. As the main advantage we consider that there's only a short side lengths of a sample. These are lead over a circular part of the clamp and at the end of this part the wire is tightened between two planar plates.

Fig. 3. Clamping system for wires with a small diameter

To examine pseudoelastic effect of our material, the tensile test was done. A wire with a diameter of 0.18 mm with active length 100 mm was clamped to a universal testing machine TIRA test (Tempos s.r.o.). Velocity of the test was set to 5 mm/min. First test was performed until fracture of the wire. Thanks to this we found out at which stress limits the phase transformations occur.

Next tests were done in order to see the whole pseudoelastic effect. Upper load of the specimen was chosen high enough for a transformation from austenitic to martensitic phase to be completed. Then the machine was set to unload the specimen with the same velocity back to zero load. This step reveals what's happening during the backward transformation. The whole cycle was repeated twice to compare the differences. As mentioned above, the transformation stresses are highly temperature dependent so the tensile tests were also done in four different temperature conditions: 19 °C (ambient temperature), 37 °C (body temperature), 60 °C and 80 °C.

2.2. Shape memory alloys in MSC.Marc

For the finite element method analysis the MSC.Marc (MSC.Software s.r.o.) software was chosen. The reason to simulate a shape memory alloy is that we plan to make the whole model of the stent-graft and thanks to FEM try to make optimization of its design.

MSC.Marc has an Auricchio SMA material model implemented in its basic installation. The easiest way for us to verify the model was to simulate experimental tensile test which were done before. In fact, there are two Auricchio models that can be used. First of them is purely mechanical and is suitable to simulate pseudoelasticity, the second one is thermal and consider also change of the temperature during an analysis.

Due to the constant temperature under which tensile tests were performed, Auricchio mechanical model was suitable for our purpose. Model of the wire (Fig. 4) was characterized by 8-noded hexahedral elements. On one end of the wire the boundary condition of zero displacement was applied. On the opposite side we applied time-dependable node displacement. From the experiments we found out that sufficient strain of the specimen is ε = 10% to determine all the transformations. After this strain was reached, model was, again, unloaded to a zero stress.

To fully define the material, following constants must be known: σ_{Ms}, σ_{Mf}, σ_{As}, σ_{Af}, which were mentioned in paragraph 1.2. In addition to this, the length of heyperelastic plateau ε_L (Fig. 2) and Young's modulus of austenite E_A and martensite E_M are also required. All these constants can be evaluated from experimental tensile curves. The stresses at which phase transformation occur lays at the beginning and end of hyperelastic plateau and Young's modulus is evaluated, of course as a tangent of an angle that stress-strain curve related to the phase contains with horizontal axis.

For example, in the case of a tensile test which was done for a temperature of 19 °C, the constants were following: σ_{Ms} = 510 MPa; σ_{Mf} = 560 MPa; σ_{As} = 150 MPa; σ_{Af} = 130 MPa; ε_L = 0.07; E_A = 26 300 MPa; E_M = 14 700 MPa.

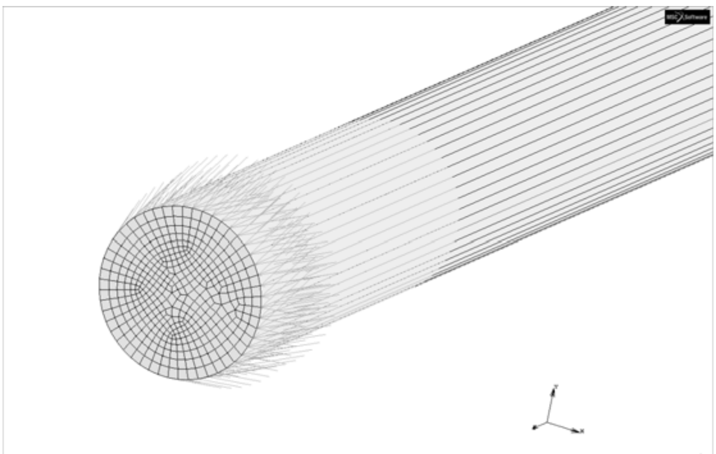

Fig. 4. FEM model of a wire; end loaded with a displacement

3. Results

3.1. Tensile test

Due to the page restrictions of the article only two graphs of performed tests are shown. Evaluated transformation stresses from all tests are summarized in Table 1.

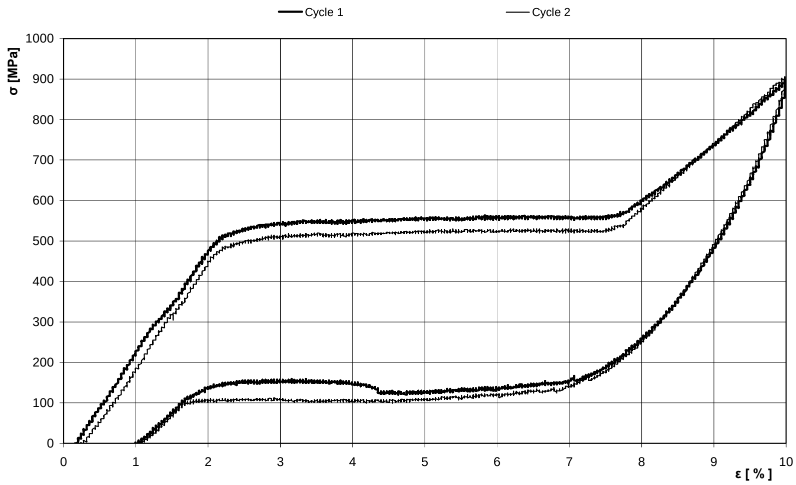

Fig. 5. Stress-strain curve from tensile test at 19°C

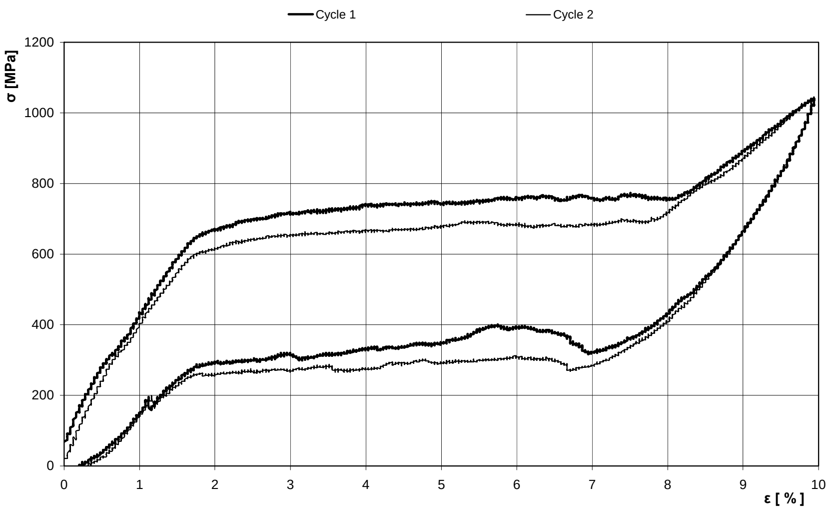

Fig. 6. Stress-strain curve from tensile test at 37°C

Table 1. Transformation stresses of NiTi alloy

Temperature [°C]	σ_{Ms} [MPA]	σ_{Mf} [MPA]	σ_{As} [MPA]	σ_{Af} [MPA]
19	510	560	150	130
37	650	750	330	280
60	730	860	440	380
80	830	1070	620	500

3.2. FEM analysis

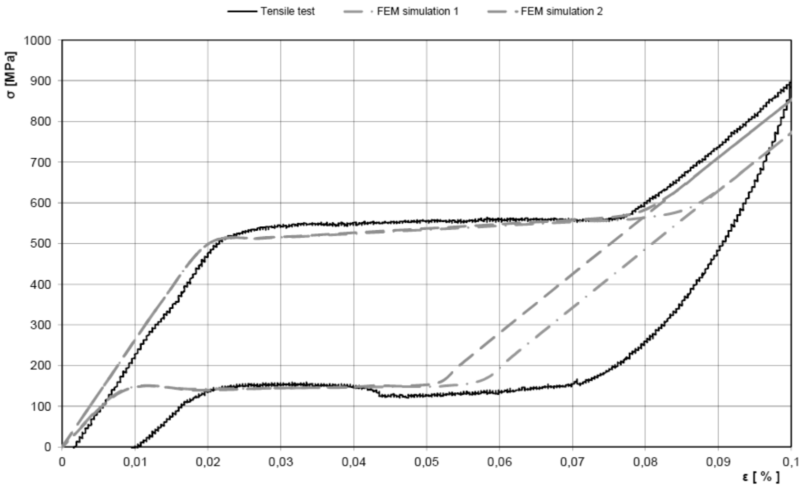

Fig. 6. Results of tensile test FEM simulation

4. Conclusions

By comparing the data gained from experimental tests and FEM simulations (Fig. 6) it can be seen that in loading part there's a good agreement between the two methods. However the unloading part is other case. In the case of FEM analysis, Value of the Young's modulus of martensite causes that point σ_{As} occurs at the different strain level. This inaccuracy can be solved by adjustment of Young's modulus of martensite phase.

Another thing that could be noticed about the graphs is that after a sample is completely unloaded it doesn't return to a zero strain in the case of experimental data. Similar behaviour can be found also in the works of other authors [3, 4, 5, 6]. It could be caused by residual strains that will disappear itself after a while. If the unloading speed was lower, this phenomenon maybe wouldn't have occurred.

Acknowledgement

This project was supported by the Ministry of Industry and Trade of the Czech Republic, grant n° FR – TI1/584.

References

[1] Lagoudas D.C., *Shape memory alloys: Modeling and Engineering Applications* (Springer Science, New York, 2008). ISBN 978-0-387-47684-1.

[2] Yahia L'H., *Shape memory implants* (Springer-Verlag, Berlin Heidelberg, 2000). ISBN 3-540-67229-X.

[3] Duerig T., Pelton A., Stöckel D., "An overview of nitinol medical applications," *Materials Science & Engineering*, **A273-275**, pp. 149-160 (1999).

[4] Kleinstreuer C., Li Z., Basciano C.A., "Computatioal mechanics of Nitinol stent grafts," *Journal of Biomechanics*, **41**, pp. 2370-2378 (2008).

[5] Nayan N., Buravalla N., Ramamurty U., "Effect of mechanical cycling on the stress-strain response of a martensitic Nitonol shape memory alloy," *Materials Science and Engineering A*, **525**, pp. 60-67 (2009).

[6] Migliavacca F., Petrini L., Colombo, M., "Mechanical behaviour of coronary stents investigated through the finite element method," *Journal of Biomechanics*, **35**, pp. 803-811 (2002).