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IDENTIFICATION OF NICKEL-TITANIUM ALLOY MATERIAL MODEL PARAMETERS BASED ON EXPERIMENTAL RESEARCH[1]

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The paper presents an identification process of model parameters of a thin nickel-titanium alloy wire based on experimental research. The wire made of NiTi alloy was subjected to a tensile test to obtain the stress-strain characteristic. Parameters of the non-linear material model were identified based on the obtained experimental results. The material model used in the conducted research may be used for simulation of the shape memory effect and pseudoelasticity of the shape memory alloy. The generated results of numerical simulations have a good approximation with the conducted experimental tests.

Keywords: NiTi, shape memory alloy, numerical research, NiTi stress-strain curves

1. Introduction

The sector of smart materials has been for many years characterized by a dynamic development. Smart materials can be used both in sensor and actuator applications because of their unique properties. Another advantage of smart materials is the possibility to use them in self sensing applications. Smart materials are defined as substances which have one or more properties that can be significantly modified in a controlled manner by external stimuli; such as stress, temperature, electric or magnetic field, radiation, pH, moisture, or chemical compounds (Chopra, 1996).

An important group among smart materials are Shape-Memory Alloys (SMA). SMA, in response to a change in environmental conditions, change their internal structure (phase), which leads to a change in the properties of the alloy (Pieczyska *et al.*, 2006). The factor inducing the phase transformation in SMA depends on the type of the alloy.

Among the SMAs, the nickel-titanium alloys have raised a great scientific interest, and have the largest number of industrial applications. The shape memory effect (SME) in NiTi alloys is due to the phase transformation (from martensite to austenite and reverse) related to a temperature change of the alloy (Abel *et al.*, 2004). There are three main crystal structures in NiTi alloys: twinned martensite, detwinned martensite and austenite. In some commercially produced alloys, a rhombohedral R phase may also be observed (Kciuk *et al.*, 2019; Tobushi *et al.*, 2009). The crystal structures existing in NiTi alloys are different for their mechanical and physical properties, including their electrical resistance (Sławski *et al.*, 2021). This makes it possible to identify phase transformations occurring in NiTi alloys due to the fact that electrical resistance is easily measurable (Antonucci *et al.*, 2007). In addition, the correlation between resistance and internal transformations of NiTi alloys makes it possible to rationalize self-sensing control using resistance as a feedback signal (Sławski *et al.*, 2022).

The main purpose of this paper is identification of the NiTi material model parameters. This paper presents a process of identification of thin NiTi wires material model parameters, which is

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provided with the use of a dedicated test stand. The identified properties are used in a numerical research based on the finite element method (FEM). Results obtained from complex numerical models depend on parameters declared for each component of the model. So, it is important to perform a test concerning material parameters identification to obtain a more accurate numerical model. Validated NiTi material model parameters established as results of the presented paper will be used in further numerical research concerning analysis of polymer based composites containing NiTi wires. Section 2 discusses the material properties and, in addition, the method of performing the experimental research. In Section 3, the experimental results are presented, the identification process is discussed, and the obtained simulation response is demonstrated. The final Section summarizes the key aspects of the performed research.

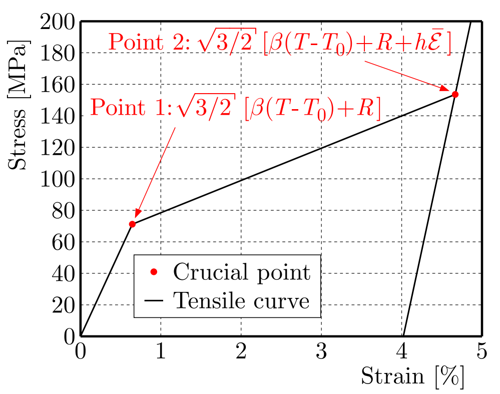
2. Materials and method

This paper discusses the identification process of NiTi alloy material properties based on conducted experimental research. The tests were carried out using a material supplied by Dynalloy (Dynalloy, Irvine, CA, USA), whose trade name is Flexinol. To perform the research, a low-temperature alloy (designation LT) characterized by full transformation at temperatures above 70°C was used (Dynalloy Inc., 2023). The crucial parameter of the investigated material is Young's modulus which depends on the crystal structure of the alloy. According to the manufacturer's information, it is 28 GPa for martensite and 75 GPa for austenite (Dynalloy Inc., 2023).

In order to identify the material model properties, the tensile curve of the NiTi alloy was determined. In most cases, investigations of the mechanical properties of NiTi alloys were carried out on normalized samples using universal testing systems (Hartl and Lagoudas, 2008; Pieczyska *et al.*, 2005). In the present paper, tensile tests were performed on thin NiTi wires using a dedicated automated test stand developed for this research. The used test stand was composed of: STAV 500/280 stand (AXIS Sp. z o.o., Gdańsk, Poland) for mounting the sample (using the designed handle) and measure the displacement, FB50 force gauge (AXIS Sp. z o.o., Gdańsk, Poland). The process of recording measurement data was performed by the cDAQ-9174 data acquisition system (NI, Austin, TX, USA) (Hartwich *et al.*, 2023). The test samples were thin nickel-titanium alloy wires with a diameter of 150 μm and an equal length of 150 mm.

The applied material model allows for simulation of the shape memory effect and generation of stress-strain characteristics of NiTi alloy. The selected material model was developed as a part of the work of Auricchio (2001) and was implemented in the Ansys environment (Ansys, 2023). A schematic curve which represents behavior of the considered material mode, along with parameters that allow defining its shape, are presented in Fig. 1.

(a)



(b)

Property	Symbol	Unit
Hardening parameter	h	GPa
Elastic limit	R	MPa
Maximum transformation strain	$\bar{\mathcal{E}}$	$\frac{1}{\text{mm}}$
Temperature scaling parameter	β	$\frac{\text{MPa}}{°\text{C}}$
Reference temperature	T_0	°C
Element temperature	T	°C

Fig. 1. Schematic tensile curve with crucial points marked

Identification of the material model properties is possible by mapping the experimentally determined stress-strain characteristics. Five tensile tests were carried out as a part of the research, and then the extreme results were dismissed. The experimental research consisted of stretching the mounted sample at a constant speed (50 mm/min) until a set strain of 4.9% was achieved, then the stand was returned to the initial position at the same speed. Experimental research was carried out at room temperature, in addition, measurements were made under stagnant air conditions in an unventilated room.

The numerical research has been conducted with the use of the FEM. The discretized numerical model was assembled from 21 beam elements with length of about 4.76 mm and diameter of 150 μm in the cross-section. All degrees of freedom were blocked for the node which was located at one end of the model. Stresses were induced by displacing the node located at the second end of the model in the longitudinal axis. For the model used to determine temperature versus strain characteristics similarly, all degrees of freedom were blocked for the end node. The node located at the second end was loaded with a constant force inducing stress equal to 172 MPa. At the same time the model was subjected to a variable temperature rising and falling within the range from 22°C to 100°C.

3. Results and discussion

The tensile curves of a thin NiTi alloy wire were determined for five samples of the wire with diameter of 150 μm. The obtained waveform is consistent with predictions based on theoretical knowledge (Mohd Jani *et al.*, 2014). It is possible to distinguish successive areas of stress-strain characteristics correlated with changes in the crystal structure of the NiTi alloy. The research results divided into different areas, together with the linear regression determined for them, is presented in Fig. 2.

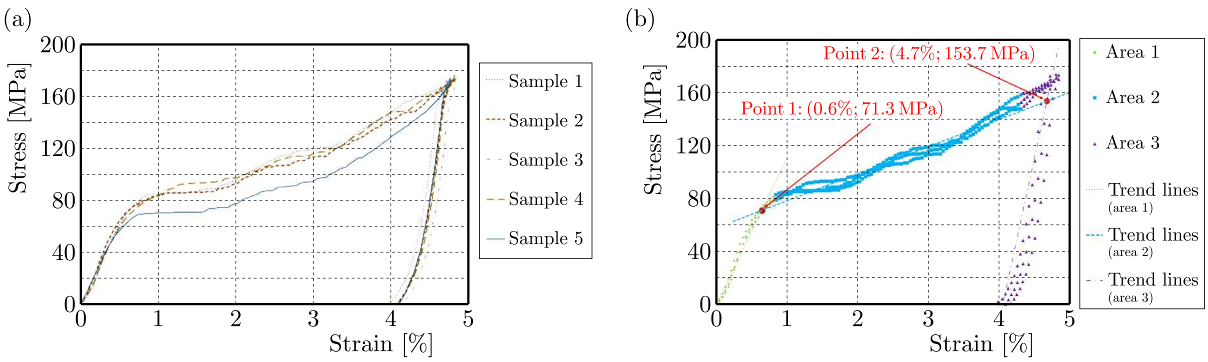


Fig. 2. (a) Experimental results, (b) the tensile result of the NiTi wire along with the trend lines determined for each loading stage

In the first stage of the loading, elastic stretching of martensite takes place, then followed by a phase transformation of the alloy – the crystalline structure changes from martensite to detwinned martensite at the strain range of approximately 0.6% to 4.6%. The last loading stage is associated with further deformation of the already completely detwinned martensite until the target stress is achieved. During the unloading, the stress gradually decreases to the initial position, however significant residual strain of approximately 4% is recorded. The crossing points of the trend lines are equivalent to the points separating the different areas of the characteristic. Point 1 (strain: 0.6%, stresses 71.3 MPa) defines the start of material transformation between martensite to detwinned martensite while point 2 (strain: 4.7%, stresses 153.7 MPa) determines the end of transformation. The stress-strain characteristics generated by the calibrated numerical model compared to the experimental results and temperature-strain characteristics are presented in Figs. 3a and 3b, respectively.

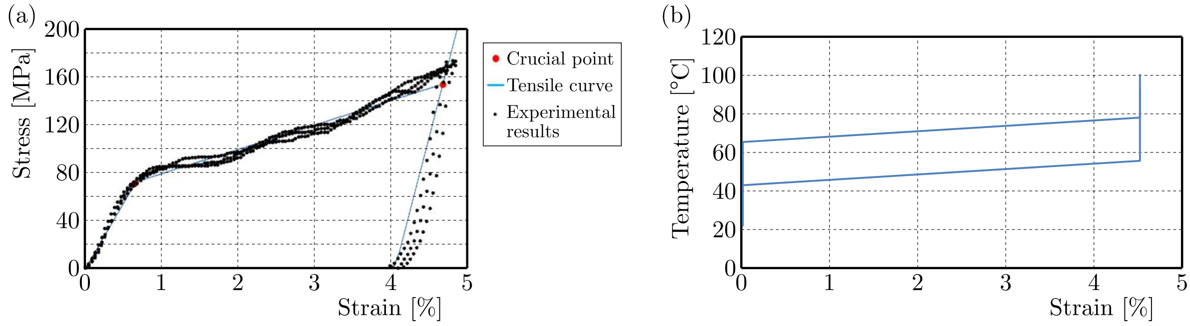


Fig. 3. (a) Stress-strain curves obtained during the tensile loading of five NiTi wire samples and the curve generated by the numerical model, (b) temperature to strain characteristics generated by the numerical model with 172 MPa maximal load

The tensile curve obtained from the model is a close reproduction of the experimental results, which is clearly visible in Fig. 3a. In addition, the model has been calibrated in such a way that the full transformation takes place in the temperature range from 40°C to 78°C along with the maximum strain of 4.5% according to the manufacturer's information (Dynalloy Inc., 2023). This can be seen in the temperature-to-strain characteristics (Fig. 3b).

4. Conclusions

On the basis of the conducted experimental investigation, it can be concluded that:

- the obtained results for successive tensile tests are similar to each other,
- the obtained results are consistent with the predicted ones based on theoretical knowledge of NiTi alloys. Therefore, different stages of stress-strain curves can be easily interpreted.

In addition, it can be claimed that the material model developed on the basis of experimental results:

- reproduces the experimental results with high accuracy,
- is consistent with the catalog data provided by the material manufacturer,
- has the potential to support further, more complex numerical research.

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