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Mechanical properties of the NiTitex composite

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Abstract: Our report deals with silicon-textile (SilTex) composites which are reinforced by Nitinol wires (NiTiTex). The Nitinol wires (Nickel-Titanium alloy) are used for its superelastic properties, while silicon-textile matrix endows composite with unpermeable continuous structure. In order to study the effect of NiTinol filaments on mechanical properties, uniaxial tensile tests with different samples were realized. Specimens of SilTex, NiTiTex and NiTinol wire underwent uniaxial loading and unloading and their mechanical response was analysed. It was found out that the implantation of the NiTinol wire into silicon-textile matrix significantly influences mechanical properties of the composite. The testing of the specimens proved that the NiTiTex (assumed as homogenized sample) replicates mechanical response of the NiTinol wire, while SilTex composite demonstrates rather polymer-like response. Two substantial phases were observed during loading of both NiTinol wire and NiTiTex: elastic phase followed by superelastic one, which is typical by increase of the deformation without rise in load. In order to find out, whether it is possible to model the NiTiTex composite as homogenized material, simple elastoplastic model was applied.

Keywords: NiTinol wire; Silicon-textile composite; Stress analysis

1. Introduction

The Nickel-Titanium alloys were first developed between 1962-1963 by the Naval Ordnance Laboratory and commercialized under the trade name NiTinol (an acronym for NIckel TItanium Naval Ordnance Laboratory). Since there NiTinol has found a wide range of engineering applications (medical devices, robotic fields…). The Nickel-Titanium alloy exhibits both superelasticity and shape memory properties [1]. For a more complete review on the properties and behaviour of the NiTi wires, the reader is referred to Heller et al. [2].

A considerable attention has been paid to SMA (shape memory alloy) materials as composite constituents. Barret [3] mimicked low stiffness and large deformation characteristics of biological tissues using a composite consisting of SMA ribbons and low-hardness silicon matrix. They showed that when the SMA is electrically actuated, small strains within the SMA could achieve an order of

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magnitude larger strain within the composite. The performance of these composites applications depends on the quality of the SMA-matrix interface which must have sufficient strength to transfer the stresses and strains [4,5].

Nevertheless, according to the authors' knowledge, no significant attention was paid to the quantification of the change in mechanical response of the separate components and complex composite. This work deals with simple uniaxial testing of the NiTiTex composite and its individual elements which are silicon-textile matrix and reinforcing NiTinol wires. The main goal of the paper is to analyse the hypothesis, whether it is possible to model the NiTiTex composite as homogenized material, reflecting characteristics of its individual components. Simple rheological model, represented by parallel connection of the fibrous (ideal plastic) and matrix (elastic) element, was applied.

2. Materials and methods

2.1. Constituent properties

The matrix of the composite is made of the textile fabric embedded into the silicon which is reinforced by NiTinol wires of the diameter 0.075 mm. The material was fabricated by overlapping two thin layers, each with unidirectional reinforcement, resulting in a presence of two mutually orthogonal directions of NiTi wires within the plane of the final structure.

Superelastic NiTinol usually consist of 55.5wt% Nickel with the balance Titanium [1]. This material, at strain of above ~0.01, will undergo stress induced phase transform from austenite into a martensite crystal structure, and superelastic plateau will be formed, as shown in (Fig. 3b). This response is highly temperature dependent [1]. The silicon-textile matrix of the very low modulus provides for geometrical fibre stability and continuous structure.

2.2. Experimental set-up

In order to compare mechanical response of the constituents and the composite, uniaxial tensile tests were performed on the Messphysic testing machine (Fig. 1). Two samples of each component (silicon-textile matrix, NiTinol wire and NiTiTex composite) underwent simple tension loading and unloading. Deformation of the tested samples was evaluated by video-extensometer, which is built-in testing machine.

Reference dimensions (width and thickness) of the tested samples were measured at several locations by a caliper. The diameter of the NiTinol wire is declared by producer.

2.3. Rheological model

Mechanical response of the NiTiTex composite is described using a simple rheological model which consists of parallel connection of the elastic (representing silicon-textile matrix) and ideal plastic (representing NiTinol wires) material (Fig.2). The model of ideal plastic material was adopted to capture constant stress at phase transformation. To avoid misunderstanding, the term yield stress (usual in the theory of ideal plastic materials) is substituted by transformation stress. The stress in such a material is described as follows:

$$\sigma = \frac{F}{A} = \frac{(F_M + F_W)}{A} = \frac{1}{A}(\sigma_M \cdot A_M + \sigma_W \cdot A_W) =$$
$$= \frac{1}{A}\left(\varepsilon \cdot E_M \cdot A_M + A_W \left[\frac{\sigma_{TW}}{2} + \frac{E_W}{2}\left(\varepsilon - \left|\varepsilon - \frac{\sigma_{TW}}{E_W}\right|\right)\right]\right), \quad (1)$$

where F denotes applied force, E is Young´s modulus and A denotes total area. Lower indexes M (SilTex *matrix*) and W (NiTinol *wire*) relate the quantity to the corresponding composite components. The lower index T represents transformation point.

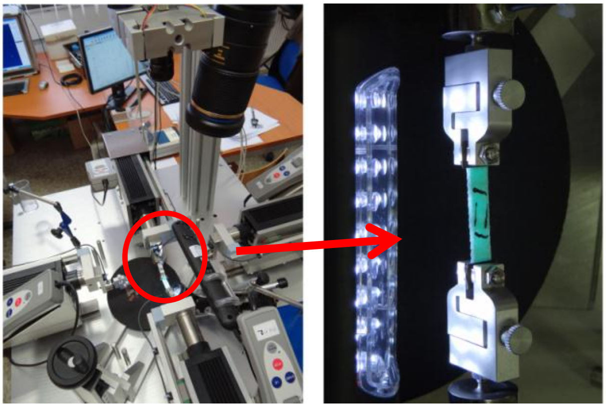

Fig. 1. On the left-Messphysic biaxial testing machine (Zwick/Roell). On the right- detail of the clamped sample.

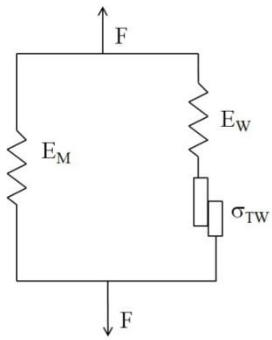

Fig. 2. Parallel elastoplastic rheological model of the homogenized composite. Left arm represents the elastic silicon-textile matrix while right arm refers to the ideal plastic NiTinol wire.

3. Results

Material parameter describing rheological properties of the homogenized material (E_M, E_W *and* σ_{TW}) were determined from the uniaxial tensile tests of individual components (Fig. 3) as the average value from two measurements (Table 1).

During uniaxial loading of the NiTinol wire, the typical behavior referred to the superelastic materials was observed. The material, at strain above ε~0.01, undergoes stress induced phase change from austenite into martensite crystal structure, and superelastic plateau will be formed (Fig. 3b). The end of the plateau refers to the completion of the phase transformation.

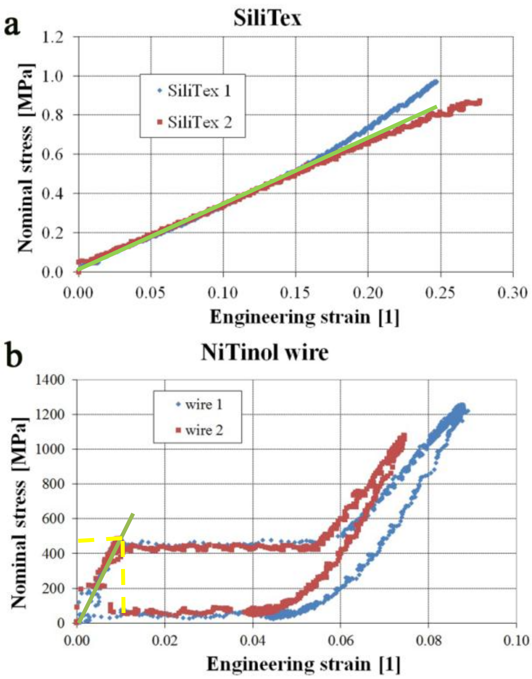

Fig. 3. (a) - Uniaxial loading of the silicon-textile matrix. E_M was determined as the initial slope of the tangent of the loading curve (green line). (b) - Uniaxial loading of NiTinol wire. E_W was determined as the initial slope of the tangent of the loading curve (green line). The transformation state (σ_{TW}) is defined at the start of the plateau (yellow dashed line).

In the loading, the NiTiTex composite replicates mechanical response of the NiTinol wire (Fig. 4a). First elastic phase is followed by superelastic plateau, as well as the transformation appears at "transformation" strain (~0.01). Nevertheless the initial stiffness of the composite reflects mechanical properties of the matrix ($E \sim E_M$). The experimental data are evaluated in the form of average of two different measurements (Fig. 4a).

The simple elastoplastic rheological model was applied in order to model mechanical response of the composite, which is assumed as the homogenized structure reflecting characteristics of individual components. While reference cross-section area of each sample is measured with standard deviation, the model nominal stress (1) is computed for the medium, maximum and minimum area (Fig. 4b).

Authors calculated model diameter of the wire which could produce mechanical response of the same quantitative level as the real experimental response. Assuming identical material characteristic of the composite (E_M, E_W *and* σ_{TW}), diameter of the NiTinol wire would have to be 0.05 mm.

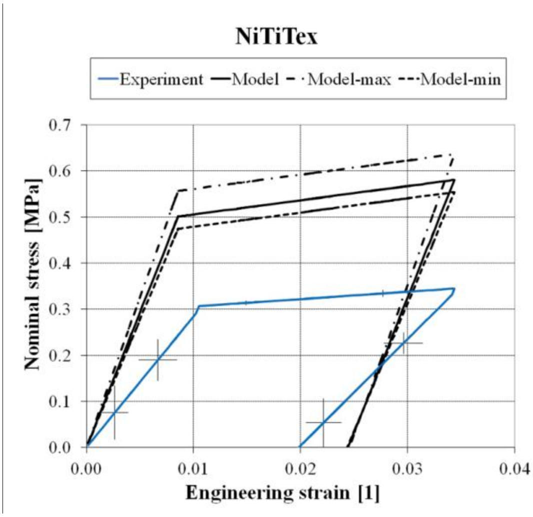

Fig. 4. – Uniaxial loading of the NiTiTex composite. The experimental curve (blue curve) is evaluated as the average of two measurements. Error bars include both measurements error and inter-sample variance. Model curve is evaluated for the medium, maximum and minimum cross-section.

4. Discussion and conclusions

Individual components as well as the whole silicon-textile composite reinforced by NiTinol wires were subjected uniaxial testing. It was observed that:

- NiTinol mechanical response demonstrates superelastic behaviour, characteristic by first elastic phase, followed by superelastic plateau.
- Mechanical response of the silicon-textile matrix has an elastic character.
- NiTiTex composite subjected to uniaxial loading reflects the behaviour of the NiTinol wires (elastic phase followed by superelastic plateau), nevertheless mechanical characteristic of the composite (initial Young´s modulus) has the same order as Young´s modulus of the silicon-textile matrix.

Final NiTiTex experimental curve was obtained as the average of two measurements. Discrepancy between the real data and physically awaited loading curve is evaluated in the sense of standard deviation. Vertical standard deviation could be caused by using of load cell with high measurement range (-250 N to +250 N) which has not adequate resolution (force during loading reached approximately 2 N). Horizontal standard deviation could be explained by vibration of the mechanical system as well as by vibrations in material itself. Nevertheless the most probable reason of horizontal errors is failure of extensometer which was working with insufficient luminance contrast.

Simple elastoplastic rheological model was adopted in order to find out, whether is possible to assume the NiTiTex composite as homogenized material, reflecting characteristics of its individual components. The model suggested as the parallel connection of the elastic (matrix) and ideal plastic (wire) element was able only to simulate individual phases typical for loading of superelastic material.

Authors tried to clarify whether the discrepancy between the model and experiment could be caused by applying of the inaccurate NiTinol wire diameter d. They have varied the value of d, while material characteristics of the composite (E_M, E_W *and* σ_{TW}) were fixed, in order to find the model matching the experiment not only qualitatively but also quantitatively. The final value of the diameter is 0.05 mm while the producer declares the diameter of 0.075 mm. Diameter of the NiTinol wire measured by a micrometre coincides rather with the value proclaimed by producer. This leads the authors to the conclusion that the incompatibility is probably caused by application of inadequate model. One explanation could be in fact, that model does not take into account the adhesion between NiTinol wires and silicon-textile matrix, which has essential impact on the mechanical behaviour [3,4].

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