TESTING OF NITINOL SENSOR ON BENDING DEFORMED POLYPROPYLENE TUBE: COMPARISON OF WINDING METHODS

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Abstract: *A thin nitinol wire with a diameter of 0.05 mm was used as a surface sensor indicating deformation changes of the polypropylene tube during bending. Two types of nitinol wire windings were compared: parallel placement with the longitudinal axis of the tube and transverse windings around this axis. Changes in the electrical resistance of the wire were measured during the bending deformation. The sensitivity of the nitinol sensor, its comparison with conventional wire metal resistance strain gauge made of constantan alloy, its application possibilities, as well as the advantages resulting from the different winding geometry were discussed.*

KEYWORDS: NITINOL, NITINOL SENSOR, BENDING DEFORMATION, WIRE WINDING

1. Introduction

At present, so-called electric strain gauges are used to measure the mechanical stress of loaded machine parts. These are electrical elements placed on the surface of the monitored component or other structural elements that respond to deformation by changing electrical properties. Resistance strain gauges (metal or semiconductor) placed on the surface of structural elements are most often used. There, they convert the deformation caused by the mechanical load into a change in electrical resistance. The cause of changes in the specific electrical resistance of semiconductor resistance strain gauges (silicon) is the deformation of their crystal lattice induced by the action of an external force (so-called piezo resistivity) [1]. Metal strain gauges are most often constructed of constantan [2], an alloy of copper and nickel, in the form of a wire a few hundredths of millimeters in diameter, placed on an insulating pad, which is attached to the surface of mechanically loaded monitored components. Changes in electrical resistivity of constantan resistance strain gauges are caused by changes in wire dimensions (elongation and change in wire cross-section).

Our research task was the experimental development of a deformation sensor made of nitinol wire, which could be used similarly to other wire strain gauges attached to the surface of the monitored objects. This simple sensor could also be built into any part of the composite structure and thus serve to monitor and evaluate the mechanical load or damage to the object. However, the method of placing the nitinol wire on / in the monitored component as well as the winding geometry must be adapted to the expected direction of the deformation forces, the expected range of values, or the required sensor sensitivity (for example to eliminate noise).

This application of nitinol is highly innovative. While a lot of studies deal with the use of nitinol shape memory for medical purposes [3,4,5,6,7], we find only exceptionally work focused on the use of nitinol as a deformation sensor. [8,9]

In this work, we describe and discuss the partial results obtained by a single bending load of PP tubes with two different winding methods of nitinol wire, which led to the development of a sensory composite push rod.

2. Preconditions for resolving the problem

2.1. Nitinol

Nitinol is a metal alloy of nickel and titanium in a different ratio. Its typical properties are shape memory and superelasticity, which are related to the transformation temperature of a particular nitinol alloy and its transitions between the austenitic and martensitic phases [10,11]. The shape memory effect means that it will bend but will return to its original shape when heated. The austenite transformation finish temperature (A_f) has been specified as a key characteristic and the sole parameter for predicting the nitinol material properties. A_f ranges from about 140 °C to +130 °C [12]. However, the shape memory effect is not desirable for the sensory use of nitinol wire, so it is necessary to select a nitinol alloy for this purpose whose transformation temperature is lower than that at which deformation detection will take place [13]. At temperatures above the transformation temperature of the alloy, a superelastic effect is applied to the nitinol strain gauge sensor, which is an advantage over conventional wire resistance strain gauges made of constantan. The elasticity of nitinol reaches up to 10 % [10,14]. The material relaxes along the hysteresis curve [11] and the value of the hysteresis decreases with increasing temperature [15]. The load can act repeatedly, with very little permanent deformation. It is thus possible to monitor the long-term load of cyclically stressed structural elements with an assessment of the state of fatigue of the material, hidden micro cracks, and other damages.

2.2. Comparison of constantan and nitinol wire strain gauges

A comparison of some properties of nitinol and constantan is shown in **Table 1**. The high modulus of elasticity of the constantan in comparison with the values of the modulus of nitinol confirms the relative rigidity and strength of the constantan, with which it resists loading, while nitinol responds to deformation stress with significant flexibility and elongation, up to the ultimate strength. The maximum tensile strength of nitinol is more than double that of constantan. The specific electrical resistance of nitinol is also higher at room temperature, so smaller deformation changes can be well detected electrically (e.g., using a 0.05 mm diameter wire, depending on the selected geometry, the deformation change of the one micrometer/ meter will result in an electrical change of several milliohms).

Table 1. *Selected properties of constantan and nitinol [13,16,17]*

Property	Constantan	Nitinol
Melting point	1210 °C	1310 °C
Tensile strength	340–535 MPa	≥ 1070 MPa
Specific electrical resistance	12-49 μΩ·cm	82 μΩ·cm
Young's modulus	115–162 GPa	41–75 GPa
Modulus of elasticity in shear	44 GPa	10.8 GPa

2.3. Strain gauge sensitivity

The sensitivity of the strain gauge is expressed by the constant k **(1)** [18], which in the case of constantan strain gauges is around 2. These strain gauges are used to measure deformations with relative elongation up to approximately 2 mm/m. Nitinol wire can be used to measure deformations with relative elongation up to several cm/m. Compared to the conventional metal constantan strain gauge, nitinol shows a high sensitivity to deformation. For example, the sensitivity of a 0.05 mm diameter nitinol wire, expressed by the constant k, is approximately 100 times higher than that of constant strain gauges (k> 200), which is typical for semiconductor strain gauges.

$$k = \frac{\Delta R}{R_0 \cdot \varepsilon} = \frac{\Delta R \cdot l}{R_0 \cdot \Delta l} \qquad \textbf{(1)}$$

ΔR … the increase in the resistance of the strain gauge at the relative elongation of the object surface ε
R_0 … strain gauge resistance at initial mechanical load
l … the original length of the object
Δl … elongation of the deformed object

3. Experimental

3.1. Material

The model deformed object was a 20 cm long hollow polypropylene tube resistant to the temperature with the crystalline structure at random (PP-RCT). It was manufactured by a β-nucleation process, which significantly improves the crystal structure of the random PP copolymer. The tube was reinforced with glass fiber in the middle layer, outer diameter 20 mm, wall thickness 2.5 mm. This material is characterized by resistance to wall stress at elevated temperatures, low thermal expansion, high dimensional stability, and resistance up to 90 °C.

Nitinol wire with a diameter of 0.05 mm (Fort Wayne Metals, Indiana, USA/Ireland), superelasticity (not shape memory) is declared by the manufacturer as the main property. This nitinol is intended primarily for medical and other low-temperature applications, i.e., for use at room or body temperatures. It should withstand an elongation of up to 8 % at room temperature without significant permanent deformation, or the permanent deformation after 8 % elongation should be less than 0.5 %. The ultimate tensile strength of a material is 1241 MPa at room temperature, elongation > 10 %, austenite activation temperature 10 - 18 °C. At rest, this wire has electric resistance of approximately 2.1 Ω/cm.

The described nitinol wire about 20 cm long was attached to the first PP tube using epoxy resin as a single fiber in the direction of the longitudinal axis of the tube. An 80 cm long wire was attached to the second PP tube with epoxy resin in several transverse windings symmetrically distributed in the left and right halves of the tube (2 x 6 windings + one wide central winding). To eliminate the possibility of cutting the nitinol wire during tube bending, the central part of the tube was designed so that this part was wireless and the deformation movable crosshead from above hit only the tube body. The free ends of the nitinol sensor wire were held to the screw terminal for measuring the electrical resistance on the oscilloscope.

3.2. Method

The three-point bend test of PP tubes with nitinol sensors was performed on the universal testing machine (dynamometer) Instron using the control SW Tinius Olsen Horizon. For this purpose, a special tube holder was made (**Fig.1**). The tubes were inserted into grooved holders at both ends so that the middle part of the tubes was in the air, and therefore the samples could bend with a maximum radius in the middle part, which was acted upon by the deformation force of the descending crosshead from above. The deformation crosshead moved from above in a direction perpendicular to the horizontally placed tube. The constant feed rate was chosen to be 0.01 mm/s up to a final load of 250 N. The starting point was approximately 1 mm above the tubes. The total movable crosshead displacement was approximately 9.7 mm (including 1 mm above the tube), followed by the crosshead return at 1 mm/s. The final deformation, bending of the tubes with nitinol wire fixed in the direction of the longitudinal axis, was simulated in the program Blender 2.9.2.0. The tubes were modeled using Bézier curves and fitted according to reference photographs taken during the three-point bending. The dimensions of the resulting models of the bent tubes were corrected according to the parameters of the real tubes before deformation.

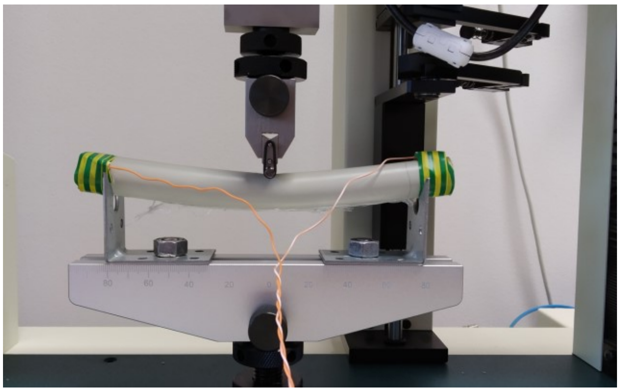

Fig.1. *Three-point bend test arrangement*

3.3. Results and discussion

3.3.1. Tube with axially placed nitinol wire

The online measurement of the electric resistance during the deformation test of the tube with nitinol wire placed longitudinally with a long axis is recorded in **Fig.2**. A graphical 3D simulation of the final tube deformation is shown in **Fig.3**.

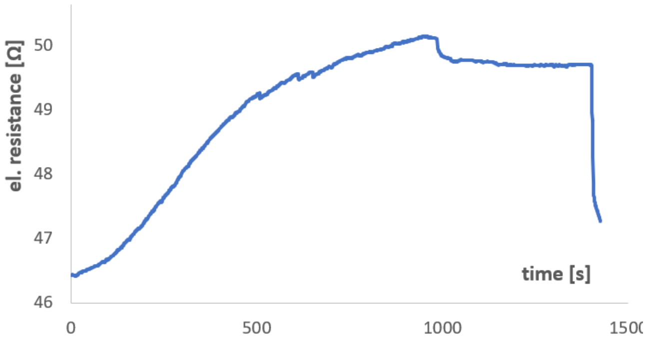

Fig.2. *Recording the electric resistance of the nitinol wire placed on the tube longitudinally with its long axis during deformation*

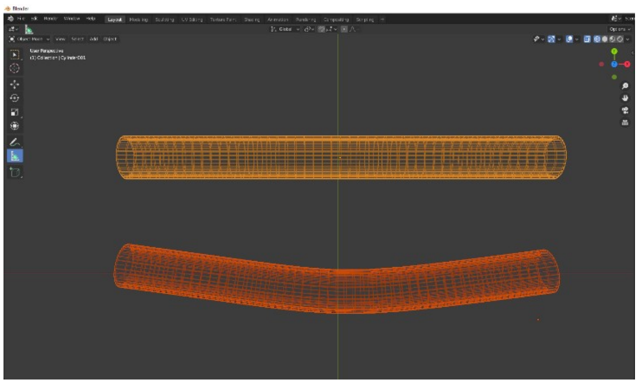

Fig.3. *3D graphic illustration of a tube before and after deformation*

The calculation of the maximum bending length of the area furthest from the deformation crosshead can be simply converted to the calculation of the parabola arc length. This shape is closest to the final bend shape, because with a very slight bend (here an angle of approximately 4-7°) the outer parts of the deformed tube essentially copy the shape straight lines, while the central part is approaching the circle. Therefore, this formula **(2)** can be used to calculate the length of the lower arc of the bent tube:

$$L = \frac{1}{2}\sqrt{b^2 + 16 \cdot a^2} + \frac{b^2}{8 \cdot a} ln\left(\frac{4 \cdot a + \sqrt{b^2 + 16 \cdot a^2}}{b}\right) \quad \textbf{(2)}$$

a … distance between the top of the parabola and the center of the chord (here: effective length of the deformation path of the crosshead, 8.7 mm)
b … chord length (here: original length of the undeformed tube, 200 mm)
L … the length of the lower arc of the bent tube, L=201 mm

Suppose, therefore, that due to bending, the total elongation of the wire on the lower arc of the deformed tube occurred by approximately 1 mm. This change was recorded as an overall increase in electrical resistance of approximately 3.6 Ω. This means that a change in the length of the tested nitinol wire by 1 μm meant an increase in the value of el. resistance by several milliohms.

3.3.2. Tube with transverse winding

The record of the el. resistance measurement from the bending of the PP tube with the transverse nitinol wire winding is shown in **Fig.4**.

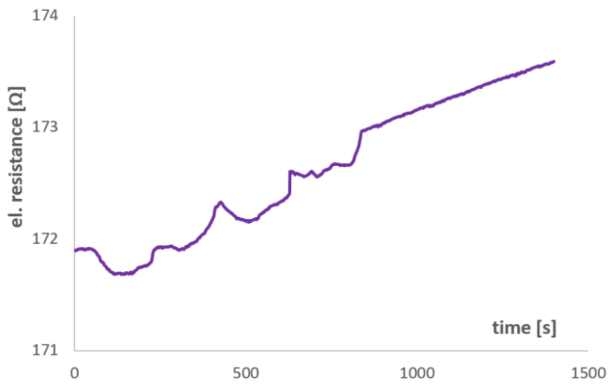

Fig.4. *Recording the electrical resistance of the nitinol wire placed on the tube transversely in the wraps during deformation*

The fluctuations of the electrical resistance in the first part of the graph correspond to the situation when the bending of the tube stretches more wire in the lower part, i.e., in the area furthest from the point of the descending crosshead pressure. The wire in the winding is stretched unevenly: in the lower part it is stretched, but in the upper part of the tube (in the place with a smaller deflection) the wire is pulled centrally. This means that the wraps tend to move away from each other towards the middle part of the tube and move to the position of the winding at an angle of 45°, which is their relatively most stable position during the deformation. Continued deformation and bending lead to increase tension in the nitinol wire, which was compensated by (accidental) slippage of the wraps into this position. Each such "slip" to a more stable position will temporarily reduce the tension in the wire, which was reflected in another slight decrease in the measured electrical resistance. The maximum deformation occurs in the central part of the tube. The state, which occurred from about 850th second, corresponds to a situation where the wraps closest to the center of the tube are already in a maximum stable position of 45° and the increase in total resistance is constant and corresponds to increasing tension and elongation of the whole wire.

If we convert the whole system of a tube with a wire winding by unrolling the tube sheath into 2D, we can compile the formula for calculating the wire length based on the Pythagorean equation **(3)**. We calculate the difference between two hypotenuses: in the first term of the equation, the hypotenuse of the deformed system is expressed by a cathetus based on the bending length simulated by the parabola (L) and in the second cathetus expressed by the tube circumference times the number of wraps (2 π r·13). In the second term of the equation, the first cathetus is equal to the length of the undeformed tube (200 mm) and the second cathetus remains the same, i.e., the circumference of the tube times the number of wraps. It follows from the formula that the more wraps (n), the less the bending of the deformed tube (L) itself influences the change in wire length.

$$\Delta L = \sqrt{(L_2)^2 + (2\pi r \cdot n)} - \sqrt{(L_1)^2 + (2\pi r \cdot n)} \quad \textbf{(3)}$$

Δ L … nitinol wire extension
L_1 … original length of the tube before deformation (200 mm)
L_2 … length of the tube after deformation (simulated by a parabola according to formula **(1)**, i.e., approximately 201 mm)
r … tube / wrap radius (10 mm)
n … number of wraps (13)
L … length of the tube bent into the shape of a parabola (see **(2)**)

The result is a theoretical extension of the wire of only about 0.25 mm! This change was recorded as a total increase in electrical resistance of approximately 2 ohms during the deformation.

3.3.3. Discussion

Since the total load of the tube was the same for both tested geometries (shift of the crosshead along the same path, at the same speed and to the same end load), it is possible to compare the total increase of electrical resistance during deformation, which should correspond to the total elongation of the nitinol wire. In the first case, the total increase was about 3.6 Ω (from the original 46 Ω), in the second case there was an increase of about 2 Ω (from the original 172 Ω), it means about an increase in resistance by 8 % and 1 %. Thus, the sample with the wraps showed relatively smaller deformation changes than the sample with the linearly placed wire. The reason is the fact that the largest deformation changes during bending occurred in the central part of the tube, and therefore were in fact the most tensile-stressed wire wraps that were closest to the center. Thus, the maximum elongation of the wire occurred at only a fraction of the length of the entire winding. Also, the absolute elongation of the wire in wraps is less than if the wire of the same length was stretched linearly.

4. Conclusion

Several findings emerge from this deformation test:
1. When the nitinol wire (cross-section 0.05 mm) was stretched by 1 micrometer, the electrical resistance increased by 3.6 milliohms. When using this superelastic form of nitinol wire it was possible to achieve up to 8 -10 % of elongation with around 0.5 % of permanent deformation.
2. A shorter nitinol wire placed longitudinally with the long axis of the tube records small deformations with higher sensitivity than a longer wire in the transverse wraps.
3. Nitinol sensor wire in the form of a transverse winding must be wound at an angle of 45° to provide maximum stability of the wire during its loading (tensioning) and to prevent accidental fluctuations during deformations in the form of slippages of the upper parts of the wraps.
4. The nitinol sensor wire in the form of a transverse winding can react to random deformation deflections of the support tube in all directions. Thanks to the stable winding, the electrical resistance

returns to almost the original values according to the load level, during relaxation.
5. We do not find out the direction of deformations of a tube with nitinol wire in the form of a transverse winding. We only record that the deformation has occurred.
6. In the case of a tube with a linearly placed wire, we obtain information about the direction of deformation. We will refine this sensory data when more wires will be placed in/on the tube wall linearly around the circumference and each will have its output.
The proposed nitinol sensor can replace the use of strain gauges wherever it is necessary to directly electrically measure or monitor the deformation of a solid object, as an indicator of damage to cyclically or long-term mechanically stressed parts: for example in aerospace, automotive, pressure and force measurement in pneumatic devices, during short-term and long-term loading of building structures, as sensors to assess the strength of welded or glued joints, as a part of monitored beds (sleep laboratories, home and health care of lying patients), etc.

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