Electrical and thermal characteristics of nitinol wires for linear heat detectors

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Abstract. In this work were investigated the modifications of electrical and thermal properties that occur with the phase changes (M→A) during heating a Nitinol shape memory alloy wire for using it as a linear heat detector. The investigations were made using three Nitinol wires with different diameters (1; 0.1 and 0.075 mm). For the thermal characterization we used differential scanning calorimetry (DSC Netzsch 200 Maia) using two different heating rates and for resistivity a milliohmmeter (Extech 380560) and a thermocouple. The results were analyzed from the point of sensitivity of the smart element in order to be used as heat variation detector.

1. Introduction
Linear heat detectors (LHDs) are designed to provide early fire detection or overheating where other detection methods would not be effective either because of environmental conditions or because of prohibitive costs due to the high need for punctual detectors.

Thus, LHD senses a fire in its incipient stage along a line. LHDs available in the fire safety systems market are analog (that function on the principle of the decrease of dielectric resistance) [1, 2], digital (two twisted conductors isolated with a polymer melting at a certain temperature) [3], optical fiber (Bragg grating, Raman scattering) [4, 5], silicon based (which respond to infrared radiation) [5] and pneumatic (gas expansion) [6].

Using shape memory alloys (SMAs) in fire detection systems is justified by state changes that occur with the rise in temperature. State transition from martensite (M) phase to austenite (A) phase and the one-way and two-way shape memory effect [7, 8] that occurs with it was the basis for the development of some fire detectors [9] and sprinklers [10]. For these actuators were used both copper and iron based SMAs but also Ni-Ti alloys [11].

Regarding the change in electrical resistivity that occurs with state change, in the literature has been reported the development of Cu-based SMAs fire detectors [12]. These showed a slow increase in resistivity with increasing temperature, but if the temperature exceeds a certain value there was a sudden drop in resistivity. The reported variation of resistivity for the Cu-based SMAs is about 10-20%. Regarding the Ni-Ti SMAs, researches revealed a complex behavior of the resistivity dependence on temperature, some authors concluding that electric resistance still cannot be safely used as a feedback signal in actuator applications [13]. Most studies on the thermo-electrical properties of Nitinol wires were made by subjecting them to stress and the heating was made by the Joule-Lenz
effect (distributed heat source over the entire length of the wire due to electrical heating) [13–16]. A change in resistivity of about 15-20% with the state change (M-A) was reported in these.

In this work will be investigated the thermal and electrical properties of Nitinol wires of different diameters. The purpose is to analyze changes in wire’s thermal and electrical properties while they are subject to external heat sources (and not by Joule-Lenz effect), i.e. through convection and radiation, and while the wires are stress free, in order to investigate the possibility of using them as LHDs operating on the principle of resistivity variation with temperature.

2. Materials and methods
In order to investigate the possibility of using Nitinol MSA wires in fire detection systems as LHDs were used three Nitinol wires with different diameters (1; 0.1 and 0.075 mm) purchased from the trade.

2.1 DSC analysis
Up to 50-mm long sample fragments were cut from the three sample wires, weighing less than 50 (20) mg, for DSC experiments. For this purpose, a NETZSCH differential scanning calorimeter type DSC 200 F3 Maia was used, with sensitivity: < 1 W, temperature accuracy of 0.1 K and enthalpy accuracy—generally <1%. The device was calibrated with Bi, In, Sn, and Zn standards. Temperature scans were performed between 20 and 150°C, with two heating rates: 5 K/min and 50 K/min, that represent the rise of temperature under normal conditions, when there is no fire (e.g. heating caused by the solar radiation) and the sudden rise of temperature that occurs in case of a fire. The DSC thermograms recorded during heating were evaluated with Proteus software, provided by NETZSCH.

2.2 Electrical properties analysis
It was investigated the variation of electrical resistivity with temperature for the 3 samples of Nitinol wires. It was used a radiative heat source (heater) that was gradually approached to the sample in order to simulate the rise in temperature. During the tests, the wires were stress free. The electrical resistance was measured for a 14 cm length for different diameter wires. The electrical resistance was measured using an Extech 380560 milliohmmeter. For measuring the temperature, a DT 838 thermocouple was used. The thermocouple was not attached to the wire, in order to measure the ambient temperature near the wire and so observe the changes that occur in the electrical properties of the wire at different environmental temperatures.

The experiments were performed in accordance with the occupational health and safety laws and regulations in order to eliminate all the risks and dangers which can affect the human resource during the experiment procedures [17-20].

3. Results and discussions
It was investigated the thermal properties of the 3 Nitinol wires with different diameters (1, 0.1 and 0.075 mm) using differential scanning calorimetry. For the two heating rates (5 K/min and 50 K/min) were identified critical temperatures of reverse martensitic transformation using tangent method, for each wire sample.

As it can be seen in Error! Reference source not found., for the heating rate of 50 K/min of the 1 mm diameter wire, the starting transformation point from martensite phase to austenite phase (A_s) is at 107 °C and the final point of the transformation is at 135 °C (A_f), with the peak at 120 °C (A_m). For the 5K/min heating rate, the phase transformation begins at 107 °C (A_s), the ending is at 125 °C (A_f) and the peak at 113 °C (A_m). It can be noticed that the absorbed heat (ΔH/m) is higher for the 50K/min heating rate (the reaction is strongly endothermic).

As it can be seen in Error! Reference source not found., for the heating rate of 50K/min of the 0.1 mm diameter wire, the A_s is at 52 °C, A_f at 78 °C, with A_m at 60 °C. For the 5K/min heating rate, the A_s is at 77 °C, A_f at 91 °C and A_m at 80 °C. It can be noticed that the absorbed heat is higher for the 50K/min heating rate (similar to the 1 mm diameter wire). For the heating rate of 5K/min, for the 0.1
mm diameter wire it can be seen a intermediate phase (three-stage martensitic transformation behavior) [21].

Figure 1. DSC thermogram of the Nitinol wire, Ø 1mm.

Figure 2. DSC thermogram of the Nitinol wire, Ø 0.1mm.
For the 0.1 mm diameter wire it can be noticed that the state transition begins at a lower temperature than the 1 mm wire, which means it can be used to detect a sudden increase in temperature and trigger an alarm earlier.

Figure 3. DSC thermogram of the Nitinol wire, Ø 0.075 mm.

The behaviour of the 0.075 mm diameter wire is similar to the 0.1 mm diameter wire (Error! Reference source not found.). Thus, for the heating rate of 50K/min of the 0.075 mm diameter wire, the $A_s$ is at 52 °C, $A_f$ at 70 °C, with $A_{50}$ at 60 °C. For the 5K/min heating rate, the $A_s$ is at 70 °C, $A_f$ at 92 °C and $A_{50}$ at 79 °C. The near transformation phase temperatures can be explained by the small diameter of the wires and that the time in which the temperature rises in the section of the two wires (0.1 and 0.075 mm) are almost equal (the temperature in the wire rises instantly).

Table 1. Synoptic table with DSC results for the Nitinol wires of 1, 0.1 and 0.075 mm diameter.

| d[mm] | Sample mass [mg] | dT/dt [ºC/min] | As [ºC] | Af[ºC] | A50[ºC] | ΔH/m [J/g] |
|-------|-----------------|----------------|---------|--------|---------|------------|
| 1     | 20              | 5              | 107     | 125    | 113     | -4.764     |
|       |                 | 50             | 107     | 135    | 120     | -13.96     |
| 0.1   | 8.2             | 5              | 77      | 91     | 80      | -16.05     |
|       |                 | 50             | 52      | 78     | 60      | -7.91      |
| 0.075 | 4.4             | 5              | 70      | 92     | 79      | -13.08     |
|       |                 | 50             | 52      | 70     | 60      | -6.84      |

In Error! Reference source not found. can be seen that the heating rate influences the temperature at which Nitinol wires changes its crystallization system. This fact should have a direct influence on the wire’s electrical resistivity. Also, for the greater heating rate, the starting
transformation point from martensite phase to austenite phase \((A_s)\) is lower than the smaller heating rate. This suggests that the wires behave by nature as thermovelocimetric aldetectors (respond faster to a bigger heating rate). The diameter of the wire influences the starting transformation temperature, in the sense that it \(A_s\) decreases with decreasing diameter.

Therefore, the sensitivity of the LHD made of Nitinol SMA is given by its diameter and the heating rate. The Nitinol SMA can be used as LHDs in environments where the nominal temperature does not reach the starting transformation temperature (maximum environment temperature is smaller than \(A_s\)).

The electrical properties study was made for the temperature range 20 - 110ºC, representing the range from room temperature to the maximum alarm trigger temperature (corresponding to A-D class linear heat detectors, according to SR EN 54-22).

The graphs were drawn for heating only, the cooling zone being irrelevant for their use as LHDs. The condition a LHD needs to comply is to have an alarm temperature as low as possible but higher than the nominal temperature of the environment.

For the 1 mm diameter wire (Error! Reference source not found.a) there is a linear increase in resistivity up to 114 ºC, after which a decrease is observed. The temperature from which the decrease begins corresponds to the \(A_s\) temperature (Error! Reference source not found.). This behavior corresponds to the one reported in literature by other authors (resistivity initially increase to a certain point and then decreases).

In the studied temperature range, resistivity increased by 7.81% from 0.75 \(\Omega\)mm\(^2\)/m to 0.81 \(\Omega\)mm\(^2\)/m. Since this study was in the range 20 - 110 ºC, the temperatures corresponding to \(A_s\), \(A_f\) and \(A_{50}\) points are outside the studied temperature range in this case.

It can be assumed that the 1 mm wire can only be used in environments where the mean temperature is higher and a higher alarm temperature is required.

For the 0.1 mm diameter wire (Error! Reference source not found.b) it is noticed a drop in resistivity of 11.06% from 0.98 \(\Omega\)mm\(^2\)/m at room temperature to 0.87 \(\Omega\)mm\(^2\)/m at 110ºC.

Similar results were obtained for the 0.075 mm diameter wire (Error! Reference source not found.c), with a drop in resistivity of 11.6% in the studied temperature range, from 0.96 \(\Omega\)mm\(^2\)/m at room temperature to 0.85 \(\Omega\)mm\(^2\)/m at 110 ºC. At this one it can be seen an increase in resistivity up to the temperature corresponding the \(A_s\) transformation point (around 47ºC), and after the temperature exceeds the \(A_{50}\) point there is a linear drop in resistivity.

From all the Nitinol wire samples, the greatest resistivity variation had the one with the smallest diameter (0.075 mm).

Models of resistivity calculation were made in literature [13], [14]. The expression for the electric resistivity is the sum for each phase of specific resistivity multiplied by their volume fraction [22-24].

The shape of the R-T graphs also depends on technological factors intervening in the stages of elaboration, thermo-mechanical treatments or plastic deformations. Also, the number of thermal cycles
influences the configuration of the R-T graphs. The wires with the lowest plastic deformation had a larger variation in resistivity [22–24].

4. Conclusions
The starting transformation point from martensite phase to austenite phase ($A_s$) is influenced by the heating rate and the diameter of the wire. The Nitinol SMA wires with the smaller diameters had a bigger resistivity variation. They behave by nature as thermovolocimetrical detectors (respond faster to a bigger heating rate).

Therefore, the sensitivity of the LHD made of Nitinol SMA is given by its diameter and the heating rate.

The Nitinol SMAs can be used as LHDs in environments where the nominal temperature does not reach the starting transformation temperature (maximum environment temperature is smaller than $A_s$).

If we want to use a Nitinol SMA wire in an environment with higher usual temperature, then we have to use a wire with a larger diameter.

A LHD made of a Nitinol SMA wire is like a series of resistances. So the length of the wire and the size of the heat source will influence the total resistance.

Using electronic devices for monitoring resistivity variation, an alarm signal can be given the moment the resistivity variation in time exceeds a certain value.

By incorporating the Nitinol SMA wires into the household appliances or electrical and electronic devices and using them as LHDs, can be reduced the detection time in one of the most common cause of fire – electrical malfunction.

So it can be achieved a much faster detection than the punctual detector systems, because on these, the detection time is determined by the time required for the fire effluents (e.g. smoke, gas, heat) to reach the punctual detectors (being influenced by the room height, air movement, the number of detectors and their location), while the Nitinol MSA wires can be used as LHDs and put directly on the circuits that present the highest fire risk, being so able to detect the onset of a fire even before ignition of combustible materials. Most combustible materials have higher flammability temperatures than the starting transformation point from martensite phase to austenite phase of the Nitinol MSA wires studied in this work (e.g. most polymers used in electrical equipment have a flammability temperature higher than 300 °C). By choosing the right diameter for the wire that has $A_s$ higher than 70 °C, it can be used to monitor electric conductors (70 °C being the average operating temperature for most electrical conductors, according to the electrical regulations).

5. References
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