Analyze of shape memory wires behavior under external solicitation using finite elements analysis (FEA)

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Abstract. Nitinol shape memory alloys present many applications in the industrial areas based on exceptional memory effect properties. The behavior of a shape memory alloy (superelastic effect) underwire form (four diameters: 1, 1.5, 2 and 2.5 mm and three lengths: 75, 150 and 375 mm) at drawing was analyzed using finite element analysis (FEA). The wire shape was C letter. The experimental temperature test, in a first step, was 23 °C (room temperature) and we analyze the appliance of four solicitation forces in order to determine the specific deformations and tensions. In second simulation step we apply a higher temperature, respectively 80 °C, in order to analyze the behavior of the element through transformation phase from martensite to austenite. The simulation provides information on the total deformation, equivalent stress, and equivalent elastic deformation of the intelligent elements under external solicitations pointing the appearance of maximum and minimum solicitation areas.

1. Introduction

The role of shape memory alloys in the field of fire protection is clear: a shape memory element can detect an increase in temperature and, at the same time, react to the increase, performing a work [1-3]. The various applications of shape memory alloys in fire protection can be divided into three groups according to the action to be performed by the intelligent element: fire detection (detection of rising temperature), detection and operation by realizing a work and simply actuation of the element. In the last group, the shape memory element is used only to directly convert electrical energy into mechanical energy. In the case of simple actuation, all the advantages that electronics currently brings, can be used [4, 5].

Detection of a change in temperature can be achieved by sensing the modifications in resistivity associated with the martensite-austenite transformation or by the shape memory process itself. Both aspects can be exploited for practical applications. Like conventional materials, shape memory alloys show a slow increase of resistivity as temperature increases, but when heating is continued in the transformation temperature range, there will be a sudden and marked reduction of the resistivity of about 10 to 20%.

Another possibility for making a linear detector is the use of the shape memory effect itself. Figure 3 shows the contraction of a Cu-Zn-Al wire according to the temperature. This reduction (dimensional change) is sufficient to activate an alarm system using a micro-switch or an equivalent device. This change is quite complex in Ni-Ti alloys but very distinct in Copper-based alloys [6].
When a measuring circuit records a certain rate of decrease in the strength of the material, it indicates the temperature has risen and the temperature of transformation in the solid state has been reached. On the other hand, a sudden increase in the strength of the memory shape material indicates a decrease in temperature during the transformation process. Thus, a system can be secured against overheating, e.g. a fire alarm or electrical installation that can be secured against overload and undercover cooling. These types of detectors become the most interesting when large or long-length installations need to be protected, e.g. electrical cables. This can be easily achieved by using an alloy wire with shape memory [7].

If two elements with shape memory and different transformation temperatures are used and placed in series, a two-stage indicator can be made. Such detectors can activate an alarm before activating a fire extinguishing system.

Major accidents resulting in fires occur due to negligence, gas leaks, short circuits and overheating of electrical appliances, etc. During a fire-like accident, the fire should be stopped as soon as possible to avoid loss of life, properties and material goods. Currently, Halon fire extinguishing systems are being replaced by water spray systems with very fine droplets to suppress the fire even in areas where electrical appliances are involved [1, 2].

The literature investigated the effects of several important factors, such as the water spray modality, the size of the water drop and the water spray flow rate on the fire extinguishing mechanism, and proved that water spraying with solid cones and smaller size water drops become very effective in fires extinguishing [1-3].

This article analyzes, in two stages, the behavior of NiTi alloy wires with different dimensions (diameter and length) on an external stress in the first stage and in the second stage when it is heated over the transformation temperature range. The alloy and the shapes of the smart element can be used for fire detection and prevention applications.

2. Preparing the experiment with Ansys program

Using the Ansys program, four solid elements were designed, figure 1 a), made of nitinol shape memory effect alloy with different diameters (1, 1.5, 2 and 2.5 mm - figure 1 b)) three different lengths, figure 1 c) in the form of the letter C [8].

![Figure 1](image.png)

**Figure 1.** Schematic representation of the analyzed elements and their geometric shape (letter C shape) a) geometric dimensions of the analyzed NiTi elements b) solid element diameters c) connection length and radius for obtaining the C-shaped element.
For practical applications, the dimensions of the active elements are very important, and their behavioral changes are relatively large and can decisively require the use of one material or another. In this regard, replacing an element with a diameter of 2 mm and 10 wires, with one with a diameter of 0.2 mm can solve several operating problems, such as the speed of response and cooling of thermally sensitive elements, if they can successfully replace the single-stranded material. The elements of different lengths were connected to achieve the C shape, obtaining three sets of elements with four samples of distinct diameters. The behavior of the same alloy in the form of the letter C with twelve different dimensional parameters at external stress is sought, considering the opposite end, embedded. Volumetric elements of SOLID185 type were used meshing the model [8, 9]. Having to deal with bodies with regular geometry, these elements were created using the sweep method. For the validation of the chosen meshing, was used the condition that by doubling the density of the network (mesh), the modification of the results does not exceed a percentage of 5%. The SOLID185 element is used for 3-D modeling of solid structures, figure 2. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal directions x, y and z.

![Figure 2. Solid elements after meshing a) sets of four elements depending on diameters b) detail of the network mesh.](image)

The element can be characterized by the following specific properties: Plasticity, hyper-elasticity, stiffness on load, creep, high deviation and high compression capacities. It also has a mixed formulation capability to simulate deformations of almost incompressible elasto-plastic and fully incompressible hyper-elastic materials.

In this experiment, two steps were applied to determine the temperature at which it is stressed, figure 3 a), for the first stage it was considered the room temperature of 22 °C, stage in which the material is in martensitic state below $M_f$, for the mechanical stress that leads to the change, for example, of 5N and a second stage of heating the NiTi element with shape memory form, to 80 °C, figure 3 b), for passing over the transformation temperature range, the second step with the cessation of the mechanical stress and the application of the temperature over $A_f$, to recover the initial shape[10].

After meshing, each NiTi wire from the shape memory alloy was divided into 39,984 elements using 214867 nodes. The wires, each separately, were stressed with the following forces: 0.03, 1.5, 3.5 and 5N, figure 2 a). The influence of the diameter and length of the wires on their behavior at various external demands was followed. This force produces either a phase transformation of austenite into martensite "detwinned" – the "stress-induced martensite scenario" or, in this case, leads to a self-induced reorientation resulting in "detwinned" martensite through the "reorientation scenario", depending on the relative position of the loading temperature and of the transformation temperature of the required NiTi alloys [11-15].
Increasing the hardness of the NiTi shape memory alloy and the corresponding introduction of defects in the microstructure also causes changes in the transformation temperatures and can lead to an augment in the generated stresses compared to the NiTi alloy hardened with larger grains and a lower density of dislocations. [6-8].

Properties used to make the AMF (NiTi) material model: Modulus of elasticity of austenite $E^A$: 70 GPa, Modulus of elasticity of martensite $E^M$: 30 Gpa, Poisson's ratio $\nu$: 0.33, Thermal expansion coefficient of austenite $\alpha^A$: 22x10$^{-6}$ K$^{-1}$, Thermal expansion coefficient of martensite $\alpha^M$: 22x10$^{-6}$ K$^{-1}$, martensitic start transformation temperature $M^\&$: 23 ºC, martensitic end transformation temperature $M^{0\&}$: -2 ºC, austenitic start transformation temperature $A^\&$: 21 ºC, austenitic end transformation temperature $A^{0\&}$: 50 ºC.

3. Analysis of experimental results
In the case of the initial shape recovery mechanism, the arching of a shape memory element produces a variable force, while the weight produces a force at a constant level [16], this type of actuation is desirable to keep the stress at a constant level and to prevent functional problems during the interval, such as changing transformation temperatures. Therefore, a constant level of demand is further analyzed. Under the direct action of tension, a high force, relatively small dislocations can be reached, even if under the torsion or bending load larger dislocations are achieved [17].

Therefore, the design of the “C-shape” geometry is analyzed, in which the bending loads dominate in order to reach the capacities to achieve high demands. This geometric shape can also be used for cyclic applications where it is necessary to make net displacements, for example as in the case of valves, figure 4 a).

Figure 4 shows the results obtained in the Ansys R19.1 program for b) the reaction force, c) the equivalent stress and d) the equivalent elastic deformation.

The equivalent stress is used when there is a multiaxial stress state with multiple stress components acting at the same time in the same structure. In such a case, we can use a selected criterion to transform the entire tension tensor into a single equivalent component, which can be treated as tensile stress and therefore used compared to the strength of the material [18-20]. Various criteria can be used, but among them, there is one with an incomparably higher popularity than the others - the von Mises efficiency or otherwise called the distortion energy criterion. It is commonly used in engineering, for example, finite element analysis programs use it as a default measure of stress. In the case of NiTi alloy the average stress values are between 0.225 Pa and 193.65 MPa, figure 4 b). Obviously the most requested areas are found on large and medium length wires in their middle area and in the case of long length wires at the fastening ends.

In terms of diameters, there are clear differences between thinner threads (d = 1mm) and thicker threads (d = 2.5mm). In the first case, there is a state of stress evenly distributed over the entire thread with...
lower values than for thinner threads, this result is confirmed for all types of lengths. Figure 4 a) shows the recesses and the direction of the applied forces as well as their values.

![Diagram](image1)

**Figure 4.** Ansys results for a) reaction force, b) equivalent stress and c) equivalent elastic deformation

The equivalent elastic deformation is seen as an external control parameter of the deformation process at ambient temperatures. Von Mises deformation satisfies the theoretical properties of both groups, supporting its use for measuring equivalent deformation [21]. On the other hand, Hencky deformation does not satisfy the simple properties of the shear group, which assumes that it is not suitable for measuring the equivalent deformation in simple shear [22-23]. The equivalent elastic deformation has values between $7.2542 \times 10^{-9}$ and $0.0032337$ mm / mm which represents deformations from the level of picometers to that of micrometers.

All these local deformations applied to the 39984 elements, in which the Nitinol threads meshed, lead to displacements of the order of micrometers and even millimeters on a macroscopic scale. The areas with higher deformations overlap with those of material stress, figure 4 b), in particular for the gripping parts of the elements and the middle area of the element C towards the end on which the stress is applied.
Figure 5 presents the results obtained from the Ansys analysis for Nitinol elements with various lengths and diameters a) total deformation, b) equivalent stress and c) equivalent elastic deformation. All the results below are scaled to 0.5, in reality they are deformed (elongated) 2 times more.

Figure 5 a) shows the evolutions of the total deformations of the experimental elements in Ansys after establishing the stress conditions. All elements regardless of the length or diameter of the wire are deformed from 0 to a maximum of 76.14 mm for the sample with a diameter of 1.5 mm. The most deformed areas and marked in red are in the case of the longest wires at the end where the pulling force was applied. Further, the deformation zones decrease in intensity up to the embedded part, confirming the deformation of the material, especially in the areas with high stress, figure 5 b).

The intervals of variation of the considered elements represent a sum of the values obtained for all three wire lengths taken into account by coloring differently the actuation zones according to the values and with the indication of the maximum zones for the equivalent stress and for the equivalent elastic deformation.
Figure 5. Results from Ansys analysis for Nitinol elements with various lengths and diameters
a) total deformation, b) equivalent stress and c) equivalent elastic deformation

The equivalent elastic deformation (mm / mm) shows different areas of the maxima that appear, figure 5 c), for cases R0.5 and R1.25 respectively the thinnest and thickest, taken in the analysis, the maximum areas are located in the middle of the wires (the wires with the longest lengths are considered) in the other two cases R0.75 and R1 they are located in the sampling areas. These confirm the areas with maximum equivalent demands, figure 5 b). The minimum equivalent deformations have the lowest values, obviously, for the thinner samples (R0.5) but between the other 3 thicknesses there are no big differences even the sample R1 presenting a higher minimum (the largest of them) compared to R1.25. In the case of stressing the material in a totally martensitic state and in which the reorientation stage takes place, which happens only in the first step, there is no phase transformation, this means that no heat is added to the system by plastic deformation.

4. Conclusions
Shape memory alloys, especially nitinol, have many applications in various industrial and medical fields. The properties of shape memory alloys can also be used in the field of fire protection and prevention as temperature sensitive elements.

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