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CHARACTERIZATION AND DESIGN OF A SHAPE MEMORY ALLOY WIRE ACTUATOR

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Abstract **– Shape Memory Alloys (SMAs), smart materials, play an increasingly important role in the intelligent systems performance due to their unique properties and behavior. The paper presents the design strategy for a typical actuator of intelligent systems, using as active element the SMA wire. The attention was focused on thermal analysis experiments, in order to determine the transformation temperatures for the studied SMA element. For design optimization, a comprehensive graphical interface (based on the thermal analysis results), which runs under Visual Basic environment, has been developed for the SMA wire configuration.**

Keywords: *SMA, austenite phase, martensite phase, SMA wire.*

1. INTRODUCTION

Shape Memory Alloys (SMAs) are smart materials which exhibit some unique properties, i.e. shape memory effect and pseudo-elasticity [1], [2]. The cause is a martensitic phase transformation between a high temperature parent phase, austenite (A), and a low temperature phase, martensite (M). In absence of stress, the start and finish transformation temperatures are typically denoted M_s, M_f (martensite start and finish) and A_s, A_f (austenite start and finish) [2]–[5].

The aforementioned two main properties are responsible for the exceptional characteristics that SMAs possess such as significant internal damping, extremely high yield stresses and large nonlinear elastic ranges [2], [3], and [5].

Due to their unique properties and behavior, SMAs play an increasingly important role in the intelligent systems performance. Recent applications in structural actuation and sensing demand increased material capabilities, and SMAs possess a great potential for use in these applications [5]–[7].

The paper presents the characteristics and the design strategy of a typical actuator of intelligent systems, using as active element a SMA wire (of Ni-Ti composition).

Ni-Ti, known commercially as Nitinol, is the material used for the studied SMA element, due to its several advantages: very large recoverable motion, great ductility, excellent corrosion resistance, stable transformation temperatures, high biocompatibility and the ability to be electrically heated for shape recovery [2], [5] and [8].

The SMA wire was purchased from the Jameco Electronics Company.

The attention of the authors was focused on thermal analysis experiments, in order to determine the transformation temperatures for the studied SMA element.

For design optimization a comprehensive graphical interface (based on the thermal analysis results), which runs under Visual Basic environment, has been developed for the SMA wire actuator configuration. It provides a user friendly environment that allows intelligent system parameters configuration as well as the choice of the most adapted analysis methods and data display.

2. EXPERIMENTAL

The force that a wire of any material produces at a given deflection depends linearly on the shear modulus (rigidity) of the material. SMAs exhibit a large temperature dependence on the material shear modulus, which increases from low to high temperature. Therefore, as the temperature is increased the force exerted by a shape memory element increases dramatically [1], [2]. Consequently, the determination of the transformation temperatures is necessary to establish the real shear modulus values at these functional temperatures for a high-quality design of intelligent systems [2], [5] and [7].

Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC) methods were used to determine the required transformation temperatures of SMA element, and Thermogravimetric Analysis (TG) was used to prove the stability of the alloy. These methods are the most comprehensive and a popular instrumental technique used for the complete characterization of materials, and especially in the case of functionalizing SMA alloys [9]–[12].

During the tests, both isothermal and non-isothermal regimes combined with heating–cooling experiments, were used in order to characterize SMA sample.

The measurements were carried out on a horizontal Diamond Differential/Thermogravimetric Analyzer from Perkin-Elmer Instruments in dynamic air atmosphere (150 mL/min), in aluminum crucible, using as reference similar amounts of inert α-A_2O_3 powder.

Initial, the phase transitions of the test sample were identified by analyzing his behavior at programmed heating up to 180 ^{0}C and cooling to ambient temperature, using a linear non-isothermal regime of 10 ^{0}C/min.

It was noticed that the mass of the sample does not undergo any changes at heating and cooling. In consequence, the TG curve is ignored in further measurements and in the present paper.

3. RESULTS AND DISCUSSION

Thermal Analysis measurements (DTA and DSC) of Ni–Ti SMA wire material were carried out in dynamic air atmosphere. The controlled temperature program used for SMA wire measurements contains the following sequences: heating from 30 to 160 ^{0}C at 5 ^{0}C/min, isothermally holding for 10 min at 160 ^{0}C and cooling from 160 to 20 ^{0}C by 5 ^{0}C/min.

The thermoanalytical curves (DTA and DSC), during heating–cooling regime, in dynamic air atmosphere, for 18.275 mg Ni–Ti SMA wire material, are presented in Fig. 1. By analyzing Fig. 1 we can observe two phase transitions. The first occurs during the heating process while the second one appears during the cooling process. The transitions, as can be seen from DSC curves in Fig. 1 correspond to typical first order phase transitions.

DSC parameters for the thermal analysis of Ni–Ti SMA wire material, in dynamic air atmosphere, are presented in Table 1.

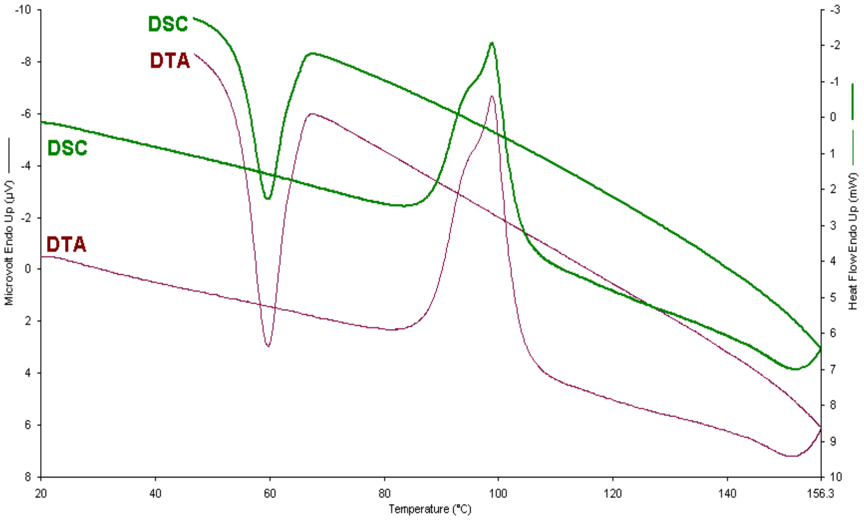


Figure 1: DTA and DSC curves for Ni-Ti SMA wire material, during heating-cooling regime.

Phase transition	Thermal effect *Endo/Exo*	Transformation temperatures *°C*	Transferred heat *ΔH/kJ·kg^{-1}*	Temp. of the max. transformation rate *^{o}C*	Peak height *mW*
Martensite to austenite (at heating)	endothermic	A_s=80.16 A_f=111.04	36.63	98.79	-5.68
Austenite to martensite (at cooling)	exothermic	M_s=67.98 M_f=48.24	-28.75	59.72	4.44

Table 1 - DSC Parameters for Ni-Ti SMA Wire Material.

4. DESIGN STRATEGY FOR SMA WIRE ACTUATOR

SMAs possess a great potential for use in actuator applications. The advantages of these actuators include a high work output, small size, smooth and silent operation, simplicity of design, control and near step function operation, long life [2], [5], and [7].

This article includes the design strategy for an actuator based on shape memory wire.

The first step an engineer should take when undertaking a design involving shape memory material is to clearly define the design requirements. These usually fall into one of the following interrelated areas: operating mode, mechanical considerations, actuation mode, transformation temperatures, force and/or motion requirements, and cyclic requirements [2], [5], [7], [12] and [13].

4.1 SMA's operating modes

The most used operating modes of SMAs are: free recovery, constrained recovery and work production [2], [5] and [7].

The application presented in this paper uses a work production operating mode. In this kind of operating mode a shape memory element, works against a constant or varying force to perform work [2], [5] and [13]. The element therefore generates force and motion upon heating.

In our configuration the SMA wire works against a constant force. As illustrated in Fig. 2, if a dead weight is suspended by a shape memory wire, at low temperature the wire will be deformed to a length L_1 before it is prevented from further deformation by a mechanical stop. At low temperature, the force exerted by the wire, F_1, is much less than the force exerted by the dead weight.

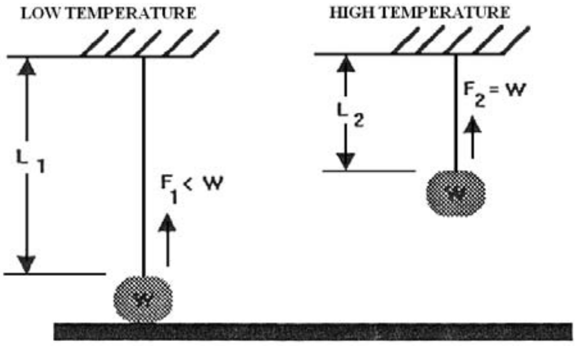


Figure 2: Shape memory wire operation.

When the wire is heated above the A_f temperature it recovers to length L_2, with a force F_2, equal to the gravitational force of the dead weight.

4.2 Mechanical considerations

In the design of SMA wire actuator configuration the friction effect is neglected and a linear stress-strain behavior is assumed, in order to simplify the analysis [2], [5] and [7].

4.3 Actuation mode

The Ni-Ti shape memory wire actuator is actuated via direct current (change in temperature is internally generated by resistance heating), because of the high resistivity of Ni-Ti (80 - 89 μΩ·cm). It is possible to apply direct D.C. or A.C. currents to a Ni-Ti wire actuator, but care must be taken so that the maximum temperature reached is at or below 250 ^{0}C, in order to avoid thermal instability [2].

4.4 Operational temperatures

The operational temperatures of SMA wire actuator, at heating and cooling, are identical with the transformation temperatures, A_f=111°C and respectively M_f=48.24°C, presented in the Table 1.

4.5 Computation algorithm

The most important relations involved for the SMA wire actuator design are:

- wire diameter

$$d = \sqrt{\frac{4G}{\pi\sigma_h}} \quad \text{[mm]} \qquad (1)$$

with:
G = weight, in [N]:
σ_h = maximum design stress at high temperature, in [MPa];

- high temperature strain

$$\varepsilon_h = \frac{\sigma_h}{E_h} \qquad (2)$$

where E_h is the value of the Young's modulus for the material at high temperature, in [MPa];

- required (free) length

$$L_f = \frac{sroke}{\varepsilon_l - \varepsilon_h} \quad \text{[mm]} \qquad (3)$$

where ε_l is the low temperature strain;

- the length increment needed at A_f temperature to produce the force G

$$length\ increment = \varepsilon_h \cdot L_f \quad \text{[mm]} \qquad (4)$$

- high temperature length

$$L_h = L_f + length\ increment \quad [\text{mm}] \qquad (5)$$

- low temperature length

$$L_l = L_h + stroke \quad [\text{mm}] \qquad (6)$$

- low temperature stress

$$\sigma_l = \varepsilon_l \cdot E_l \quad [\text{MPa}] \qquad (7)$$

where E_l is the value of the Young's modulus for the material at low temperature, in [MPa].

- reset force

$$R = \sigma_l \cdot \frac{\pi \cdot d^2}{4} \quad [\text{N}] \qquad (8)$$

4.6 Numerical example

A Visual Basic application for Ni-Ti SMA wire actuator design was implemented.

The list of the most important relations involved in the background application computation was already presented at subsection 4.5.

Below, a numerical example is given illustrating the abilities of this Visual Basic application developed for the SMA wire configuration.

This numerical example uses the real shear modulus values determined at the operational temperatures presented in the Table 1.

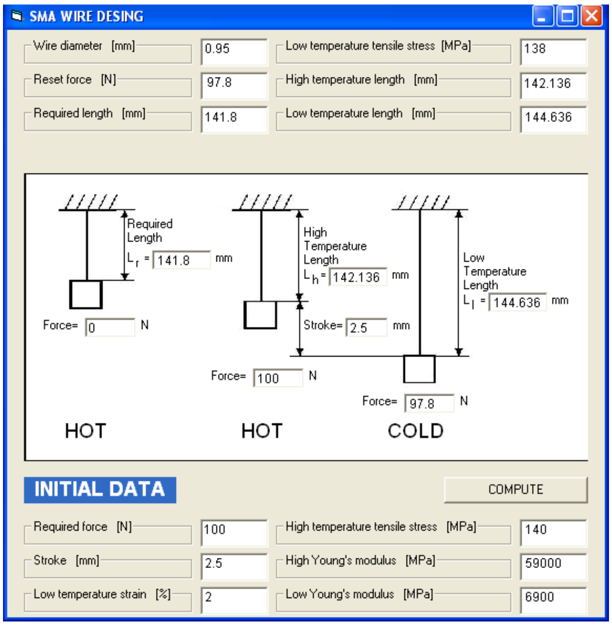
Wire actuators can deliver considerably more force than spring actuators, but the amount of stroke is limited. Again it is assumed that a linear stress-strain behavior exists for design purposes.

For design calculations, wire diameter and length are found by constraining the maximum tensile stress (at high temperature) and strain (at low temperature) to values which will ensure that the required fatigue life for the wire is obtained.

Assume that a straight wire Ni-Ti actuator must be designed which will raise a G=100 N weight a distance of S=2.5 mm (stroke), when the temperature change occurs from 48 to 111 ^{0}C. A cyclic life of 15000 cycles is required. A maximum design stress of σ_h= 140 MPa will be used, to ensure good cyclic life.

The operational temperatures, at heating and cooling, are those presented in the Table 1, that are respectively A_f = 111°C and M_f = 48.25°C. For these temperatures the experimental determined values of Young's modulus are E_h = 59000 MPa and respectively E_l = 6900 MPa.

When the Visual Basic project for SMA wire actuator design is run, a user interface is displayed, Fig. 3.



Wire diameter [mm] 0.95
Reset force [N] 97.8
Required length [mm] 141.8
Low temperature tensile stress [MPa] 138
High temperature length [mm] 142.136
Low temperature length [mm] 144.636

Required Length L_r = 141.8 mm
Force= 0 N
High Temperature Length L_h= 142.136 mm
Stroke= 2.5 mm
Force= 100 N
Low Temperature Length L_l = 144.636 mm
Force= 97.8 N

Required force [N] 100
Stroke [mm] 2.5
Low temperature strain [%] 2
High temperature tensile stress [MPa] 140
High Young's modulus [MPa] 59000
Low Young's modulus [MPa] 6900

Figure 3: Dialog interface for SMA wire actuator design.

After providing the initial parameters in the dialogue boxes of this user interface, by pressing the compute button the designed parameters are being displayed in the upper part of the window: wire diameter, reset force, required length, low temperature tensile stress, high temperature length, and low temperature length.

The middle of the window displays the typical SMA wire configuration as well as all design parameters.

5. APPLICATIONS

Ni-Ti, known commercially as Nitinol, material used for the studied SMA element, due to its several advantages is used in a variety of applications [2], [5], [6] and [13]-[15].

The variety of forms and the properties of SMA wires make them extremely useful for military, medical, safety, and robotics applications.

For example, in the medical field, the superelastic wires are now used for the corrective measures. Owing to their elastic properties and extendibility, the level of discomfort can be reduced significantly as the SMA applies a continuous, gentle pressure over a longer period. Visits to the orthodontist are reduced to perhaps three or four per year. Another one, a wire that in its "deformed" shape has a small cross-section can be introduced into a body cavity or an artery with reduced chance of causing trauma. Once in place and after it is released from a constraining catheter the device is triggered by heat from the body and will return to its original "memorised" shape [5], [16].

Also, Ni-Ti wires are being used in robotics actuators and micromanipulators to simulate human motion. By changing their configuration, the self-reconfigurable robots have various potential applications in extreme environments inaccessible to humans: in space or deep sea, in nuclear plants, for urban search and rescue in damaged buildings, military maintenance and so on. They respond to client-oriented production and task-oriented robotic system requirements [2], [5] and [6].

6. CONCLUSIONS

The paper presents the experimental and computational approaches related to Ni-Ti SMA wire actuator design.

Thermal analysis of NiTi SMA wire material, exhibiting his transformations during heating-cooling regimes, was performed in dynamic air atmosphere.

By using Thermal Analysis Methods the authors determined the experimental start and finish transformation temperatures, which are the operational temperatures of the SMA wire actuator. These experimental transformation temperatures were necessary to precisely establish the real shear modulus values of material, for a high-quality design of the SMA wire actuator.

In addition, for the SMA wire configuration, a Visual Basic application was developed, providing:

- adequate dialogue boxes for fast and easy initial parameters configuration;
- fast computation and display of all required information for a complete SMA element design;
- remarkable facilities to analyze results and choose an optimal solution.

This Visual Basic application is already used by ICMET-Craiova, Romania for engineering purposes and by the Faculty of Electromechanical Engineering of Craiova, Romania for didactical ones.

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