Evaluation of the Characteristics of a Shape Memory Alloy Cantilever Actuator Using Thermal Analysis

SONIA DEGERATU, PETRE ROTARU, NICU G. BIZDOACA, GHEORGHE MANOLEA, GABRIELA S. PETROPOL, DAN TONT
Faculty of Electromechanical Engineering
University of Craiova
Bd. Decebal, Nr.107, 200440, Craiova
ROMANIA

Abstract: - Shape memory alloys (SMAs), active materials, play an increasingly important role in the intelligent systems performance due to their unique properties and behavior. The paper presents an evaluation of the characteristics for a typical actuator of intelligent systems, using as active element the SMA cantilever strip. 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 cantilever strip configuration.

Key-Words: - Shape memory alloy, cantilever, austenite phase, martensite phase, transformation temperatures

1 Introduction
Shape Memory Alloys (SMAs) are smart materials which possess the ability to undergo shape change at low temperature and retain this deformation until they are heated, at which point they return to their original shape [1], [2].

Specimens of these materials exhibit two unique properties [2], [3], the Shape Memory Effect (SME) - the ability of SMAs to be severely deformed and then returned to their original shape simply by heating them, and the PseudoElasticity (PE) - hysteresis behavior with total strain recovery during a mechanical loading-unloading cycle. The cause is a martensitic phase transformation [2], [4] between a high temperature parent phase, austenite (A), and a low temperature phase, martensite (M).

Martensite is the relatively soft and easily deformed phase of SMAs, with a twinned molecular structure, while austenite is the stronger phase, with an ordered structure, generally a cubical one.

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).

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], [5], and [6].

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 [6]-[16].

The paper presents an evaluation of the characteristics for a typical actuator of intelligent systems, using as active element the SMA cantilever strip.

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], [6], and [16].

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 cantilever 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 cantilever 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]. 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 [17], [18].

To characterize the transformations of the SMA cantilever material, during heating-cooling regimes, it is necessary to establish the start and finish transformation temperatures, under zero stress, and heat transfer of each process [1], [17].

This section presents the transformation temperatures obtained for the studied SMA cantilever material using Thermal Analysis Methods.

Thermal Analysis Methods comprises a group of techniques in which a physical property of a sample is measured as a function of temperature, while the sample is subjected to a controlled temperature program [19], [20].

Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC) methods were used to determine the required parameters, and Thermogravimetric Analysis (TGA) was used to prove the stability of the alloy [19-23]. These methods are the most comprehensive and popular instrumental techniques used in thermal characterization of materials [21].

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

The measurements were carried out on a Perkin Elmer Thermo-balance in dynamic air atmosphere, in the aluminum crucible.

Initial, the test sample’s phase transitions were identified by analyzing their behavior at programmed heating up to 180°C and cooling at ambient temperature. After this analysis, we can notice that the sample’s mass does not undergo any changes at heating and cooling. In consequence, the TGA curves are ignored in further measurements.

3 Results and discussion
Thermal Analysis measurements (DTA and DSC) of Ni-Ti SMA cantilever material were carried out in dynamic air atmosphere.

The controlled temperature program used for Ni-Ti SMA cantilever measurements contains the following sequences: heating from 30°C to 160°C at 5°C/min, holding for 10 min at 160°C and cooling from 160°C to 20°C at 5°C/min.

The thermoanalytical curves (DTA and DSC), during heating-cooling regime, in dynamic air atmosphere, for 18.275 mg Ni-Ti SMA cantilever material, are presented in Figure 1.

By analyzing Figure 1 we can observe two phase transitions. The first occurs during the heating process while the second one appears during the cooling process. The details of these thermal effects are presented in Figures 2 and 3 (reported from the DSC curve). Figure 2 shows the determined parameters at heating process (martensite to austenite) and Figure 3 presents the parameters at cooling process (austenite to martensite). DSC parameters (related to the Fig. 2 and 3) for the thermal analysis of SMA cantilever material, in dynamic air atmosphere, are presented in Table 1.

![Fig.1 DTA and DSC curves for Ni-Ti SMA cantilever material, during heating-cooling regime](image-url)
The Af and Mr transformation temperatures, which were obtained in this section, will be used for the determination of the real shear modulus values for a high-quality design of SMA cantilever actuator.

4 Visual Basic application
SMAs possess a great potential for use in actuator applications. They can be used in several different configurations including cantilever strips, helical springs, straight wire, torsion tubes, and torsion springs [2]. The advantages include a high work output, silent operation, simplicity of design, control and near step function operation [2], [16].

A Visual Basic application was implemented for SMA cantilever actuator design.
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, transformation temperatures, force and/or motion requirements, and cyclic requirements [4], [5], [17].

### 4.1 SMA’s operating modes

The most used operating modes of SMAs are: free recovery, constrained recovery and work production [4], [5], [18].

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], [18], [24], [25] and [26]. The element therefore generates force and motion upon heating.

In our configuration the SMA cantilever strip works against a constant force.

### 4.2 Mechanical considerations and design assumptions

The mechanical considerations for SMAs components design are presented in [2], [5], [24], and [26].

In the design of SMA cantilever actuator configuration the friction effect is neglected and a linear stress-strain behavior is assumed, in order to simplify the analysis [2], [18], [24], [25], and [26].

### 4.3 Computation algorithm

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

- **high temperature strain**
  \[ \epsilon_h = \frac{\sigma}{E_h} \]  

- **cantilever thickness** [2]
  \[ t = L^2 0.6666 \times \frac{(\epsilon_l - \epsilon_h)}{(f_l - f_h)} \]  

with:
- \( L \) = cantilever length;
- \( \epsilon_l \) = low temperature strain. In order to ensure a good cyclic life (50000 cycles) \( \epsilon_l \) is constrained to a low value of 1.5%;
- \( f_l \) = low temperature deflection;
- \( f_h \) = high temperature deflection;
- \( f_r-f_h \) = required motion (see the middle part of the Figure 4).

- **outer fiber bending stress** [2]
  \[ \sigma = \frac{6FL}{bt^2} \]  

where \( b \) is the cantilever width.

- **cantilever length**
  \[ L = \sqrt{\frac{6F}{\sigma \cdot b \left(0.6666 \cdot \frac{(\epsilon_l - \epsilon_h)}{(f_l - f_h)}\right)^2}} \]  

- **high temperature deflection** [2], [5]
  \[ f_h = 0.6666 \cdot \frac{\epsilon_h L^2}{t} \]  

- **low temperature deflection**
  \[ f_l = f_h + \text{motion} \]  

- **low temperature reset force** [2], [5]
  \[ R = \frac{E_j \cdot \epsilon_j \cdot b \cdot t^2}{6} \]  

### 4.4 Numerical example

A Visual Basic application for SMA cantilever design was implemented.

The list of the most important relations involved in the background application computation was already presented at subsection 4.3.

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

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

Cantilevers made from SMA strip can be used to provide a lifting force and a nominal amount of motion by heating, as shown in the middle part of the Figure 4.

For the design example, assume that a cantilever is required to lift a force \( F = 2N \) (at electrically energized) for a distance of 5 mm (required motion) and that the maximum allowable width is 3.8 mm.

A cyclic life of 50000 cycles is required.

A maximum design high temperature outer fiber stress, \( \sigma \), of 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 $A_t = 111^\circ C$ and $M_t = 48.25^\circ C$. 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 cantilever design is run, a user interface is displayed, Figure 4. 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: cantilever length, thickness and width, reset force, high and low temperature deflections. The middle of the window displays the typical SMA cantilever configuration as well as all design parameters.

The analyzed SMA cantilever configuration is frequently used to provide thermal control of a microswitch or automatic control of a cooling fan [2], [27].

4 Conclusion
The paper presents an evaluation of the characteristics for a typical actuator of intelligent systems, using as active element the SMA cantilever.

Thermal analysis of Ni-Ti SMA cantilever 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 for the samples. These experimental transformation temperatures were necessary to precisely establish the real shear modulus values of material, for a high-quality design of the SMA cantilever actuator.

In addition, for the SMA cantilever 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;
- warning popup when the maximum imposed value of a parameter is exceeded;
- 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.

References:


