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Thermal characteristics of Ni–Ti SMA (shape memory alloy) actuators

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Abstract For two typical actuators of intelligent systems (Ni–Ti SMA cantilever and SMA helical spring), the evaluation of their thermal characteristics is presented. In order to determine the transformation temperatures and other thermal parameters of the two studied elements, the attention was concentrated on thermal analysis experiments. For each actuator configuration, comprehensive graphical interfaces have been developed, to run in Visual Basic, with respect to the results of performed thermal analyses.

Keywords Martensite phase · SMA · Austenite phase · SMA cantilever · SMA helical spring

Introduction

Shape Memory Alloys (SMAs) are smart materials which may undergo mechanical shape changes at relatively low temperatures and retain them until heated, then coming back to the initial shape [1–3].

Specimens of these materials exhibit two unique properties [3, 4], 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 *Pseudo Elasticity* (*PE*)—hysteresis behavior with total strain recovery during a mechanical loading-unloading cycle. The cause is a martensitic phase transformation [3, 5] between a high temperature parent phase, austenite (*A*), and a low temperature phase, martensite (*M*).

In order to distinguish between the two, it is important to know that the martensite phase has a twinned structure with relatively high deformability; austenite is the SMA's stronger phase, with an ordered structure, usually a cubic 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).

Exceptional properties of SMAs', such as: significant internal damping, very high yield stress and large nonlinear elastic ranges are due to the above mentioned characteristics [2, 3, 6, 7].

Due to their unique properties and behavior, SMAs play an increasingly important role in the intelligent systems performance. The recent developments and increasing applications in structural actuation and sensing, demand further increasing capabilities of the functionalized materials, as for example the SMAs' great potential to be used in this field [7–17].

The paper presents the characteristics of two typical actuators of intelligent systems, using as active elements a SMA cantilever and a SMA helical spring (of Ni–Ti composition) working against a conventional steel spring (referred here as the 'biasing' spring).

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Ni–Ti, known commercially as Nitinol, is the material used for the studied SMA elements, 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 [3, 6, 7, 17].

In order to determine the transformation temperatures and other thermal parameters of the two studied elements, the attention was concentrated on thermal analysis experiments. For each actuator configuration, comprehensive graphical interfaces have been developed to run in Visual Basic, with respect to the results of performed thermal analyses, the transferred heat being set in the software. Each one 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.

Experimental

The force that a spring or 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 [16, 18, 19].

To characterize the transformations of the SMA cantilever and the SMA spring, during heating–cooling regimes, it is necessary to establish the start and finish transformation temperatures, under zero stress, and heat transfer of each process [3, 19]. The SMA cantilever and the SMA helical spring were purchased from the Jameco Electronics Company.

Differential Thermal Analysis (DTA) and Differential Scanning Calorimetry (DSC) methods were used to determine the required transformation temperatures of SMA elements, and Thermogravimetric Analysis (TG) was used to prove the stability of the alloys. These methods are the most comprehensive and a popular instrumental technique used for the complete characterization of materials, and especially in the case of fictionalizing SMA alloys [20–27].

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 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 $\alpha\text{-A}_2\text{O}_3$ powder.

Initial, the phase transitions of the test samples were identified by analyzing their behavior at programmed heating up to 180 °C and cooling to ambient temperature, using a linear non-isothermal regime of 10 °C/min. According to the characteristics observed in each type of sample, specific temperature programs were used in order to enhance the quality of the observations. It was noticed that the samples' mass does not undergo any changes at heating and cooling. In consequence, the TG curves are ignored in further measurements and in the present paper.

Results and discussion

Thermal analysis of Ni–Ti SMA cantilever material

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 SMA cantilever measurements contains the following sequences: heating from 30 to 160 °C at 5 °C/min, isothermally holding for 10 min at 160 °C and cooling from 160 to 20 °C by 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 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.

It is assumed that the shoulder appearing in the left side of the DSC curve at heating (phase transition detailed in Fig. 2) is due to the austenite to martensite transition

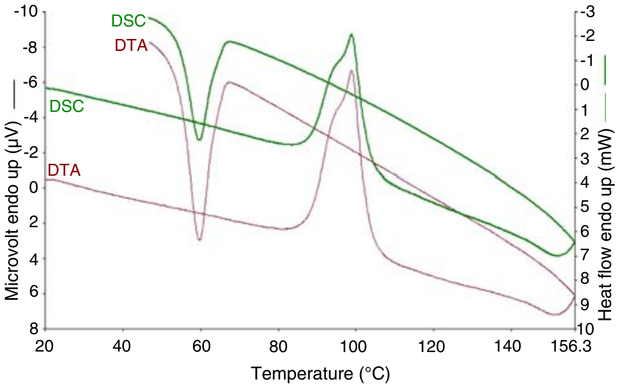


Fig. 1 DTA and DSC curves for Ni–Ti SMA cantilever material, during heating–cooling regime

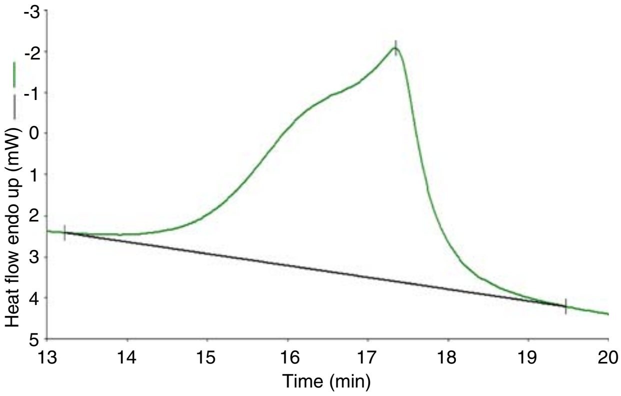


Fig. 2 Detail of DSC curve for phase transition (martensite to austenite) at heating of Ni–Ti SMA cantilever material

kinetics, when inertia takes place at the beginning of the austenite phase until the 98.38 °C temperature is reached.

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

Thermal analysis of Ni–Ti SMA spring material

The heating/cooling sequences to determine Ni–Ti SMA spring material transformation temperatures are: heating from 30 to 100 °C by 1 °C/min, isothermally holding for 10 min at 100 °C, cooling from 100 to 15 °C by 1 °C/min.

Figure 3 shows the Thermal Analysis (DTA and DSC) results, during heating–cooling regime, of 6.82 mg Ni–Ti SMA spring material, in dynamic air atmosphere.

The DTA and DSC curves, presented in the Fig. 3, exhibit two phase transitions, the first one occurs during the heating process while the second one appears during cooling.

DSC parameters for the thermal analysis of Ni–Ti SMA spring material, in dynamic air atmosphere, are presented in Table 2.

For the two studied samples the choice of the heating–cooling rates was made so that all transition thermal effects to be emphasized.

The difference between the absolute values of the transformation temperatures for the two types of samples is due to the difference between the thermal-mechanical processing used to impart the SME to a SMA element. The transformation temperatures increase with increasing heat treatment temperatures and applied stress [3, 6, 28, 29].

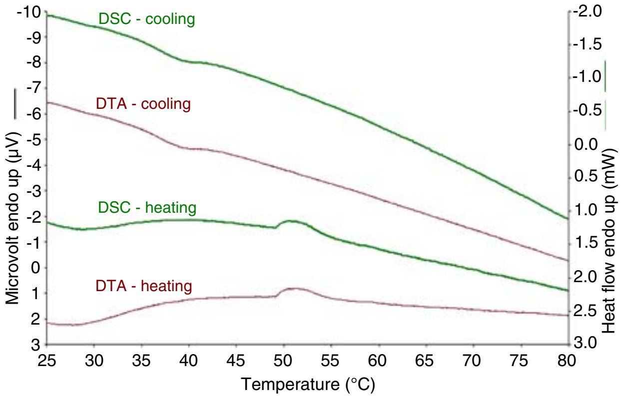


Fig. 3 DTA and DSC curves for Ni–Ti SMA spring material, during heating–cooling regime

The A_f and M_f transformation temperatures, obtained in this section, will be further used for the determination of the real shear modulus values for a high-quality design of SMA cantilever and SMA helical spring with biasing spring configurations.

Visual Basic applications

Two Visual Basic applications were implemented for SMA cantilever and SMA helical spring with biasing spring design.

The applications presented in this section use a work production operating mode [3, 6, 19, 30–32]. In this kind of operating mode, a shape memory element (SME)—such as a strip or a helical spring works against a constant or varying force to perform work. The SMA element therefore generates force and motion upon heating.

In both configurations the friction effect is neglected and a linear stress–strain behavior is assumed [3, 19, 30–32], in order to simplify the analysis.

The computation algorithms, which allowed developing these applications, are entirely presented in [30–32]. The two numerical examples presented below use the real shear modulus values determined at the operational temperatures presented in the Tables 1 and 2.

Table 1 DSC parameters for Ni–Ti SMA cantilever material

Phase transition	Thermal effect (Endo/Exo)	Transformation temperatures/°C	Transferred heat (ΔH/kJ kg^{-1})	Temp. of the max. transformation rate/°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 2 DSC parameters for Ni–Ti SMA spring material

Phase transition	Thermal effect (Endo/Exo)	Transformation temperatures/°C	Transferred heat (ΔH/kJ kg^{-1})	Temp. of the max. transformation rate/°C	Peak height/mW
Martensite to austenite (at heating)	Endothermic	$A_s = 48.99$ $A_f = 56.19$	5.94	51.26	−0.16
Austenite to martensite (at cooling)	Exothermic	$M_s = 45.15$ $M_f = 33.08$	−4.38	39.07	0.01

Visual Basic application for SMA cantilever material

A Visual Basic project for SMA cantilever design was implemented.

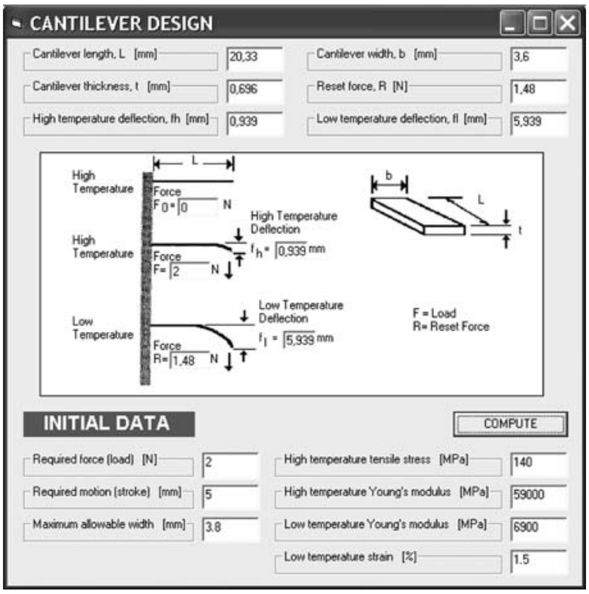
Cantilevers made from SMA strip can be used to provide a lifting force and a nominal amount of motion by heating, as shown in the middle part of the Fig. 4. Below, a numerical design example is given illustrating the abilities of this Visual Basic application.

For the present design example, assume that a cantilever is required to lift a force $F = 2$ N (at electrically energized) for a distance of 5 mm (required motion) and that the maximum allowable width is 3.80 mm. The high temperature stress is $\sigma = 140$ MPa.

The operational temperatures, at heating and cooling, are those presented in the Table 1, $A_f = 111.00$ °C and $M_f = 48.25$ °C respectively. For these temperatures the experimental determined values of Young's modulus are $E_h = 59{,}000$ MPa and $E_l = 6{,}900$ MPa respectively.

When the Visual Basic project for SMA cantilever design runs, a user-friendly interface is displayed (Fig. 4).

After providing the initial parameters in the dialogue boxes of the user interface, in the lower part of the interface (Fig. 4), by pressing the compute button the designed parameters are 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.



Cantilever length, L [mm] 20,33
Cantilever width, b [mm] 3,6
Cantilever thickness, t [mm] 0,696
Reset force, R [N] 1,48
High temperature deflection, fh [mm] 0,939
Low temperature deflection, fl [mm] 5,939

Force F_0= 0 N
Force F= 2 N
f_h= 0,939 mm
Force R= 1,48 N
f_l = 5,939 mm

Required force (load) [N] 2
High temperature tensile stress [MPa] 140
Required motion (stroke) [mm] 5
High temperature Young's modulus [MPa] 59000
Maximum allowable width [mm] 3.8
Low temperature Young's modulus [MPa] 6900
Low temperature strain [%] 1.5

Fig. 4 Dialog interface for SMA cantilever design

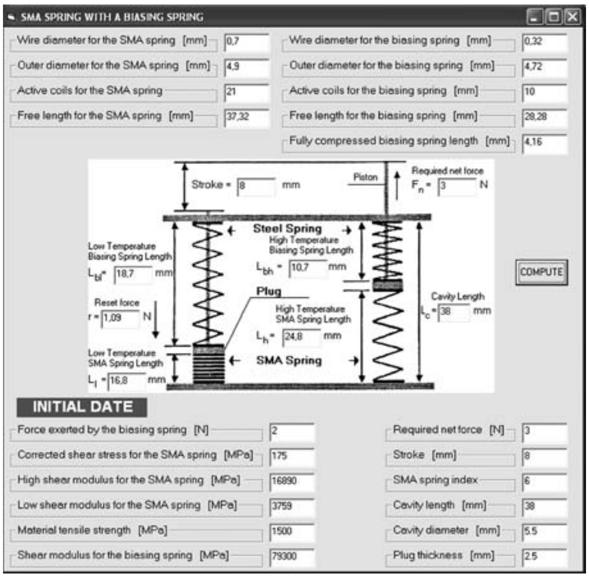
SMA cantilever can be used to provide thermal control of a microswitch or automatic control of a cooling fan [3, 33].

Visual Basic application for SMA spring material with biasing steel spring

For the design of SMA helical spring material with biasing steel spring configuration we have implemented a Visual Basic project.

The use of SMA spring as actuator provides the following advantages: reasonable force/motion characteristics, a compact size, a high work output, silent operation, design simplicity, and near step function operation [3, 6, 14, 15, 18, 19].

In the analyzed system, the varying force is produced by a steel spring (middle part of the Fig. 5). The force that the SMA spring must now work against varies with deflection.



Wire diameter for the SMA spring [mm] 0,7
Wire diameter for the biasing spring [mm] 0,32
Outer diameter for the SMA spring [mm] 4,9
Outer diameter for the biasing spring [mm] 4,72
Active coils for the SMA spring 21
Active coils for the biasing spring [mm] 10
Free length for the SMA spring [mm] 37,32
Free length for the biasing spring [mm] 28,28
Fully compressed biasing spring length [mm] 4,16

Stroke = 8 mm
F_n = 3 N
L_{bl}= 18,7 mm
L_{bh} = 10,7 mm
r = 1,09 N
L_c = 38 mm
L_h= 24,8 mm
L_l = 16,8 mm

Force exerted by the biasing spring [N] 2
Required net force [N] 3
Corrected shear stress for the SMA spring [MPa] 175
Stroke [mm] 8
High shear modulus for the SMA spring [MPa] 16890
SMA spring index 6
Low shear modulus for the SMA spring [MPa] 3759
Cavity length [mm] 38
Material tensile strength [MPa] 1500
Cavity diameter [mm] 5,5
Shear modulus for the biasing spring [MPa] 79300
Plug thickness [mm] 2,5

Fig. 5 Dialog interface for SMA spring with biasing steel spring design

At low temperatures, the steel spring is able to completely deflect the SMA spring to its compressed length. When increasing the temperature of the SMA spring, it expands, compressing the steel spring and moving for example, a push rod.

This method of ‘biasing’ provides a convenient way to obtain two-way motion form from a SMA spring, and is the most common method used in actuator applications [3, 17, 18].

Figure 5 shows the parameters involved in the design of a total system made up of a SMA spring and a biasing steel spring.

The basic problem here is to design a SMA actuator spring of the smallest force output possible, which will generate the required net, output force (F_n). In order to minimize the force that the SMA spring should provide to deflect the biasing spring at high temperatures, the spring rate of the biasing spring (K_b) must be as lower as possible. The minimum spring rate of the biasing spring will usually be imposed by spatial constraints (envelope length and diameter), since spring rate is inversely proportional to the mathematical cube of the average spring diameter [3, 6].

Below, a numerical example is given illustrating the abilities of the Visual Basic application. For the present design example, the following requirements: a Ni–Ti spring/biasing spring combination is required providing a net force $F_n = 3$ N with an 8 mm stroke, the maximum cavity length and diameter are 38 and 5.5 mm, respectively must be accomplished.

Assuming that the force exerted by the biasing spring $F_h = 2$ N, the maximum corrected shear stress $T_c = 175$ MPa, the SMA spring index $c = 6$ and the low temperature shear strain $\gamma_l = 0.015$ (in order to ensure a good cyclic life of 50,000 cycles).

The transformation temperatures, at heating and cooling, are those presented in Table 2, that are $A_f = 56.00$ °C and $M_f = 33.00$ °C respectively. For these temperatures the experimental determined values of shear modulus are respectively $G_h = 16890$ MPa and $G_l = 3759$ MPa. Also the two springs are separated by a plug of thickness 2.5 mm.

Using standard steel spring design procedure, we assumed that the maximum shear stress for the wire is $T = 1{,}500$ MPa. The bias spring shear modulus is $G = 79{,}300$ MPa.

When the Visual Basic project for SMA spring with biasing spring design is run, a user interface is displayed (Fig. 5).

First the user has to provide the initial parameters in the dialogue boxes in the lower part of the interface. The actuator system (SMA spring and biasing) is presented in the middle of the interface (Fig. 5). The upper part of the interface contains boxes for design parameters (for both SMA spring and biasing).

The application displays warning pop-ups for two reasons:

- the difference between the cavity length and SMA’s outer diameter becomes smaller than 0.5 mm.
- the full compression biasing spring length has higher values than the length of the high-temperature biasing spring.

The analyzed configuration is frequently used for SMA Latching Mechanisms, for SMA Bell Crank Mechanisms [3, 6], and for SMA Controlled Valves developed in our laboratory and used in the robotic field [3, 33, 34].

Conclusions

The present paper evaluated the thermal characteristics of two typical actuators of intelligent systems, where Ni–Ti SMA cantilever and SMA helical spring with biasing steel spring were used as active elements.

Thermal analysis of Ni–Ti SMA cantilever material and Ni–Ti SMA spring material, exhibiting their transformations during heating–cooling regimes, was performed in dynamic air atmosphere.

By using Thermal Analysis Methods, the experimental start and finish transformation temperatures for the two types of samples were determined. The results confirmed that the absolute values of the transformation temperatures depend to a great extent on thermal-mechanical processing which can be used to impart the SME to a SMA element.

The experimental transformation temperatures were necessary to precisely establish the real shear modulus values for a high-quality design of two actuators.

In addition, for each 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.

These two Visual Basic applications are already used by ICMET-Craiova, Romania for engineering purposes and by several research groups within the University of Craiova.

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