Thermo-Mechanical Characterization of a Shape Memory Alloy Actuator for Passive Thermally Driven Deployable Panel

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Abstract. The design of thermally driven deployable devices is a challenging thermomechanical topic that can be solved by exploiting the characteristics of Shape Memory Alloys (SMA). The SMA mechanical behaviour depends on stress, strain and temperature and the constitutive models available in the literature attempt to provide the relation between these three parameters. Usually, the constitutive equations are based on the thermodynamic equilibrium approach where the temperature and the stress are constant along the material (Brinson model). This work experimentally validates the Brinson model applied to a SMA wire.

1. Introduction

Designing thermally driven deployable structures is one of the most compelling prospects in the field of heat transfer. The already existing thermal energy source, e.g. on-board electronics for the space field or pivotable solar panels in the civil field, can be exploited to passively induce the deployment of movable components. Shape Memory Alloys (SMAs) are already widely used in actuation in a variety of industrial sectors as they can effectively reduce the complexity of a system that uses standard technologies, such as electromechanical, hydraulic or pneumatic activation. The field of application does not only concern the opening/closing of radiant panels, but also the deflection biomedical cannulas, as founded by Konh et al. [1]. In their work, two Nitinol® (50 % Nickel, 50 % Titanium) wires, with diameters of 0.24 and 0.29 mm, are uniformly warm up from room temperature (22 ℃) to 80 ℃ by Joule effect. The thermo-mechanical response was simulated by numerical elastic isothermal stress–strain curves that were based on the Brinson model and by Finite Element model predictions. The results show that the model represents the final experimental strain with an error of less than 10%. Singh et al. [2] also use the Brinson model to predict the behavior of the SMA actuator, which aims to minimize vibrations due to the helicopter rotor. The shape memory wire is $Ni_{51}Ti_{49}$ (51 % Nickel, 49 % Titanium, diameter 0,38 mm) was strained up to 2.5% and heated by Joule effect. The comparison of predicted results with test data show that the model closely predicted the actuator behavior. The literature shows that the best performing shape of SMA is the wire, and this allows a one-dimensional approach to the problem. In the present work the actuator is a Nitinol® wire ($Ni_{50}Ti_{50}$ - 50 % Nickel, 50 % Titanium), which is commercially and readily available and has already been extensively studied. Moreover, the most common and reliable way used to supply heat to an SMA specimen is the Joule effect. The project aims to design a self-deployable panel with a Shape Memory Alloy (SMA) actuator. The device is folded by means of a spring, while the shape memory effect is used to unfolding. The novelty of the present work is experimentally validating the implemented Brinson model proposed by Bacciotti et al. [3]. This thermomechanical model considers a temperature gradient along the wire and defines the stress as a function of the panel deploying angle.

2. The Shape memory effect and the Brinson model

The shape memory effect (SME) is the ability of the material, after a residual mechanical deformation up to 5% [4], to recover its shape when the temperature is increased, thanks to the transition of the martensite/austenite crystal structure. The transition temperatures are the Austenite start/finish (A_s/A_f) and the Martensite start/finish (M_s/M_f) (Fig. 1). The thermomechanical behaviour of shape memory alloy can be predicted by the Brinson model [4]. The constitutive equation is based on the thermomechanical equilibrium in the material where the temperature (T) and the stress (σ) are constant along the material as follows:

$$\Delta\sigma = E \cdot \Delta\epsilon + \Delta\Omega + \Theta\Delta T \qquad (1)$$

where ϵ is the strain while E is Young's modulus and varying with the martensite fraction. In addition, Ω is the deformation due to phase-transformation and Θ is the thermal coefficient of expansion.

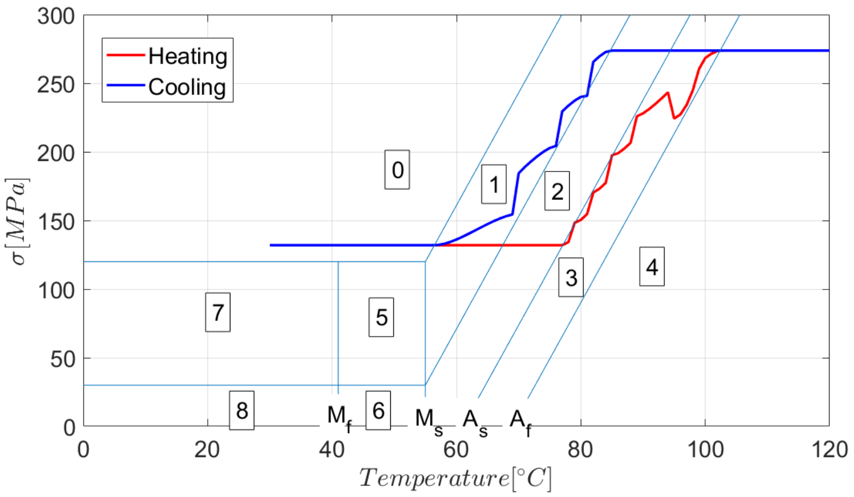

Figure 1: Uniform temperature model, heating and cooling processes: stress over temperature [3].

Figure 1 shows the material phase transition, from Martensite (zone 0) to Austenite (zone 4) or vice versa, as a function of stress and temperature during heating/cooling of the SMA. Martensite (zone 0 - Fig. 1) is obtained after mechanical deformation, in the present project the shrinking of the wire by the tensile machine. Starting from zone 0 the SMA is subsequently heated (red line - Fig. 1) above A_f to reach zone 4 (Fig. 1). Above this temperature, the SMA regains its original shape (shortening of the wire) transforming itself back into the parent austenitic phase (Zona 4 - Fig. 1). The zones between 5 and 8, concern the mechanical deformation at room temperature, while from zone 1 to 3, different crystal structure [4]. In a previous work the authors implemented Brinson model considering a temperature gradient along the wire and defining the stress as a function of the panel deploying angle [3]. In the present paper the authors validate the model by means of the experimental apparatus described below.

3. Experimental apparatus and results

The prototype of the deployable panel equipped with a shape memory actuator (SMA wire, diameter 0.5 mm, length 160 mm) is shown in Figure 2. The wire passes through two pulleys and its force is counter-acted by a torsion spring, which keeps the device closed.

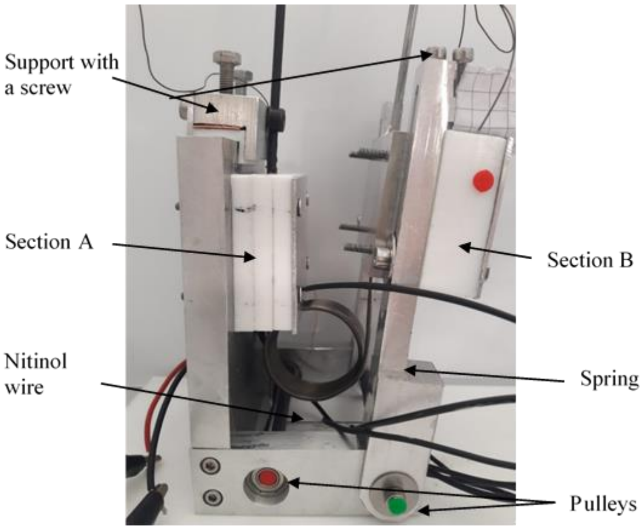

Figure 2: Experimental apparatus in folded configuration.

The wire is clamped between two blocks in the section A and in the section B and tied at the ends with two screws. Once the wire is heated, it shortens due to Shape Memory Effect (SME) and applies a force on the moving plate to deploy it. The wire is instrumented with seven T-type micro thermocouples (0.127 mm wire diameter, max error = ±0.3 °C). The wire is heated by means of joule effect. A power supply unit (GW-Instek®, PSH-6006A, max error = ±3 W), controlled by a 0-10 V signal, sets the electrical potential at the ends of the SMA wire. The controlling signal is calculated via Proportional Integral Derivative (PID) algorithm having the ramp temperature (T_r) as a moving setpoint and the thermocouple temperature (T_{TC}) as measured value. A camera records the deploying of the section B and the rotation angle is measured by video recognition based on the red and green marks in Figure 2 (max error = ± 0.4 degrees). The austenite start transformation temperature $A_s = 65°C$ is measured experimentally by means of a Differential Scanning Calorimeter (DSC) and exploited as reference point in the analysis. The comparison between the experimental results (black) and a thermomechanical model (red) is shown in Figure 3.

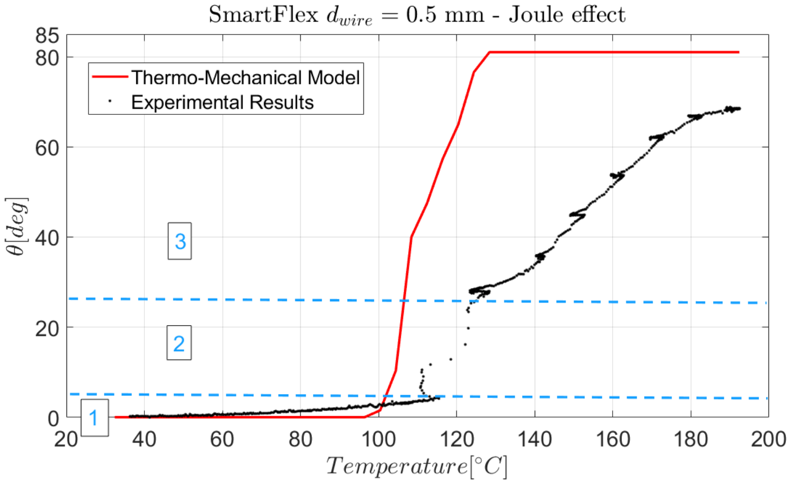

Figure 3: Joule heating; Thermo-mechanical Model [6] and Experimental Results.

Notice that the actual maximum experimental deploying angle is 10 deg smaller than the numerical simulation only because of a technical issue that prevents the device from a full deploy and that will be fixed in the near future. Thus, as in Kohn et al. [1], the Brinson model can predict the final stress with good accuracy, even if under different thermal and mechanical constraints. The plot, shown in Figure 3, can be divided into three zones, labelled from number 1 to 3. The first zone is the initial phase of deploying the panel, with a slope of 0.1 deg/°C, reaching 5 deg at about 115 °C, in 2.5 min. Within zone 2, the anomalous trend of the experimental results is due to the variation of electrical resistance as a function of the martensite/austenite crystal structure transformation. The electrical resistance decreases significantly with increasing temperature [5], hindering the PID temperature control. The temperature drops from 115 °C to 110 °C, and then rises again to 123 °C, unfolding the panel by another 20 deg. Finally, in the third zone, the device fully unfolds ($\theta_{\text{exp}} \approx 70$ deg) for a temperature range of 123-190 °C, in 3.5 min. The slope of the experimental data is 0.6 deg/°C, while the slope due to the implemented Brinson model is 1.9 deg/°C.

4. Conclusion and future development

The present work is the first step towards the design of a passive SMA actuator for a passive thermally driven deployable panel. The design and testing of an actual SMA actuator (Nickel-Titanium wire SmartFlex® Wire) thermally activated by Joule effect is carried out. Experimental results are compared with numerical results obtained with a thermo-mechanical model showing that the device unfolds completely and the disagreement with the numerical results is only due to a geometrical constraint. In the future the wire will be warmed up a heater at the wire end to investigate the effect of a temperature gradient along the wire on the deploying efficiency.

Nomenclature

T	Temperature	[°C]	ϵ	Strain	[-]
θ	Deploying angle	[deg]	Ω	deformation due to phase-transformation	[MPa]
σ	Stress	[MPa]	Θ	thermal coefficient of expansion	[MPa/°C]
E	Young's modulus	[GPa]			

Subscripts

A	Austenite	M	Martensite
exp	experimental	num	numerical
f	finish	s	start
r	ramp	TC	thermocouple

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