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EXECUTIVE SUMMARY OF THE THESIS

Innovative SMA actuator for space applications: study of torsional antagonistic configuration

TESI MAGISTRALE IN SPACE ENGINEERING – INGEGNERIA SPAZIALE

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1. Introduction

The continuous effort in reducing weight and volume of satellites' on board components has thrown the attention on exploring innovative solutions to save mass and space. In the field of materials, Shape Memory Alloys represent and interesting viable option to realize smaller, lighter and reliable actuators. The trend of SMAs' space applications is on the rise as they offer a safer actuation with respect, for example, to mechanical gears which can break or grip, as these alloys' actuation process depends on a change in the crystalline structure of the material. Through heat absorption, indeed, the transition from martensite to austenite takes place, generating a macroscopical shape change that produces the movement [1,2]. A torsional actuator realized through SMA would allow to merge a compact design with a vibrationless actuation. Moreover, by using tubes or rods twisted about their long axis, higher torque output would be possible than those obtainable with linear-to-rotational SMA actuators realized using wires. This type of actuator could find numerous applications: an example will be provided where the actuator is part of a CubeSat panel's hinge. When considering SMA for space applications the design of a rearm mechanism cannot be underestimated or disregarded, as it is essential for multiple actuations. Antagonism has proven to be the most interesting strategy to investigate, offering the possibility for a compact design and the exploitation of different activation strategies. The aim of this work is to take a step forward in characterizing the antagonistic behavior of two SMA tubes working in torsion, providing new insights into previously unexplored possibilities.

2. Space application

A possible space application of such torsional actuator made of two antagonistic tubes could be the hinge of a radiative panel: one tube is already armed and it is activated to promote the shape recovery which generate a torsion, opening the panel. At the same time this would cause the arming the other tube. When the panel needs to be closed, the activation of this last tube happens. Again a shape recovery is obtained, this time causing a torsion in the opposite direction, which brings both the panel in the closed configuration and the first tube in the armed configuration, recreating the initial conditions. The sequence can restart once the panel needs to be opened again. Defining a possible operating framework for such an actuator allows to discuss a parameter of great importance for SMA application: the actuation frequency. The time needed by one tube to cool down until a complete martensitic configuration is obtained must be lower than the time between two subsequent activations. To study this aspect an environmental characterization of the operating conditions is required: since the need for small and compact actuators is essential especially for small satellites, the LEO orbit of the CubeSat IceCube is taken into consideration as representative of a typical application. The hot case scenario has been considered Equation 1 as this is the case in which a radiative panel's opening would be required, and exploiting the parameters of IceCube [3], the temperature associated to the hot case has been computed Equation 2. The time needed by the panel to dissipate the satellite's heat, so that the components' operativity temperature is guaranteed, and by the actuator to dissipate its activation heat, have been computed [4] as respectively 20 minutes and 30 seconds Equation 1, demonstrating the feasibility of this type of application.

3. Material's characterization

The material's characterization was conducted on a tube with a 6mm diameter and an operative length of 90mm, in order to assess its properties and its torsional behavior. Since the maximum recoverable strain for a SMA tube in torsion is 7% [5], a length of 90mm has been chosen considering the aim of performing a 90° rotation during actuation. An Abaqus simulation has been carried out to check that such rotation corresponds to a 5% strain, which has been considered a safe value to avoid plasticization of the material. A preliminary DSC analysis of the tube suggested the necessity of a thermal treatment to shift the transformation temperatures towards higher values. It was realized leaving the tube for 1 hour at 570° and then water quenching it. An additional DSC was then performed (Figure 1), to confirm the occurred change in transformation temperatures (Table 1). The thermomechanical characterization started with the Torque-Rotation test performed using the Instron E3000 mechanical torsional equipment. The chosen temperatures for performing the tests went from -40°C to 60°C in order to characterize the material in martensite, in austenite, and in some intermediate conditions (Figure 2). The load imposed to the tube through a rotation was initially set to 180° and then reduced to 120° to avoid the risk of entering the plastic domain. The same tests were also performed on a 3mm-diameter-tube and a 3mm-diameter-rod revealing that they were not strong enough to arm the 6mm-tube: a bar with a diameter of 3.5mm could probably be suitable for this aim.

The Strain-Recovery test was then performed, stabilizing the tube in austenite and reducing the temperature beyond M_f under a constant loading condition. From Figure 3 it can be seen the angle at which the equilibrium between the applied torque and the resistance of the material (martensite phase) is reached. By heating again, the recovery of the rotation through Shape Memory Effect is allowed, even though a residual deformation is visible as a gap between starting and ending point of each curve. Thanks to this test an experimental determination of the Clausius-Clapeyron coefficients has been possible (Table 2).

The material characterization is not completed until the antagonistic behavior is investigated: to do this, a dedicated experimental setup has been realized. Moreover, studying the torsional antagonism between two equal tubes has been considered the most worthwhile first step to take.

4. Experimental setup

Demonstrating that two tubes can work in torsion, mutually arming themselves, required an experimental setup to be designed and realized. The vertical configuration was chosen to avoid the presence of moments generated by the weight of the components themselves, which would affect the tubes. Aluminum components have been designed to allow the clamping of one edge of each tube to the structure, while the central component serves as a rigid connection between the two tubes, thanks to which they can exchange the torque. The mandrels and the collet chuck springs allow for the proper tubes' tightening and interface with the rest of the chain. The structure is composed by Bosch strut profiles and completed by two aluminum plates. The setup is completed by some supporting structure to allow the mounting of a pulley, whose aim was to transfer the rotational motion of the central components transmitted through a rubber band to an angular sensor (Figure 4). These last components were not included in the final experiment since the low temperatures reached do not allow the use of the angular sensor. Their usage is planned for another setup configuration, which allows to have two separated cameras for the tubes, leaving all the other components to room temperature (Figure 5).

The final experimental setup can be seen in Figure 6: the tubes have been separately wrapped with a constantan wire to allow alternative heating through Joule effect, and a thermocouple has been placed on each tube to measure the temperatures. The rotation was monitored thanks to a graduated scale attached on a wheel, firmly connected to the central component.

5. Test and results

The temperature range chosen for the cycling was initially set from -20°C to 60°C (chosen as a conservative range with respect to the 0°C-45°C range identified from Figure 3), and was then increased starting from -35°C to 60°C in order to better monitor the rotation recovery. To reach such low temperatures in a controlled way the whole experiment has been carried out in the MTS environmental chamber. Before starting the first cycle, a precise sequence for imposing the pretorsion has been followed:

I. The temperature is brought to -50°C to guarantee martensitic conditions;
II. The chamber is opened to tighten the collet chuck springs, and then it is closed;
III. The temperature is brought to -50°C;
IV. The chamber is opened to give a 120° pretorsion to the lower tube, and then it is closed;
V. The temperature is stabilized to -35°C allowing the first cycle to start.

The sequence of any cycle consists in:

1. Activating the power supply of the armed tube (Tube1) until 60°C is reached, allowing the rotation recover and the arming of the upper tube (Figure 7);
2. Turning the power supply off allowing for the whole system to go back to -35°C;
3. Activating the power supply of Tube2 allowing the rotation recover and the arming of the Tube1 (Figure 8);
4. Turning the power supply off allowing for the whole system to go back to -30°C;
5. Repeating this 5 steps for another cycle.

These steps are clearly reported in the following figure, where the antagonistic action exerted by Tube2 with respect to Tube1 (and viceversa) is evident: the cycling steps' evolution can be followed both for Tube1 (red) and Tube2 (green) to understand how one tube influences the other. To allow for multiple actuations, indeed, Tube1 must be brought back to its initial configuration, correspondent to point 1, after every activation (1-2). To do so, a rearm made of two steps is performed: Tube1 is cooled down to transform towards martensite (2-3), then it is deformed through the activation of Tube2 (3-4). The cycle is completed by Tube2 cooling (4-5), with point 5 coincident with point 1.

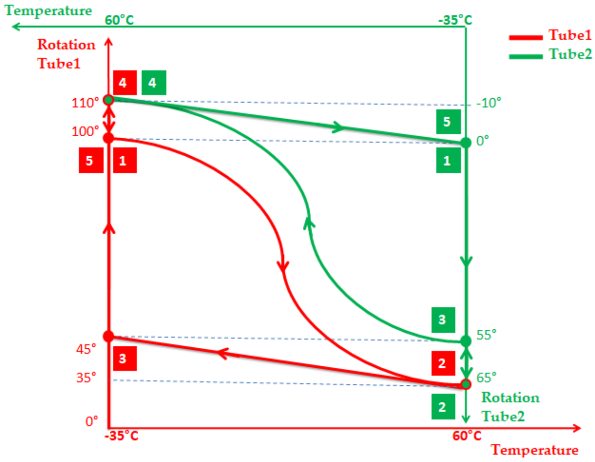

Figure 10 Antagonistic action between the tubes during cycling

Registering every cycle with a videocamera allowed to monitor the angle configuration evolution as a function of temperature, and the result of the cycling can be seen in Figure 9, where a total of 100 cycles are displayed. The predeformation imposed in step IV has been chosen to be about 100°, in order to avoid the plasticization of the material, which probably occurs if the tube is deformed more. Evidence of this has been also provided by applying different predeformations, up to 120°, value at which the worsened performance has indeed been addressed to a probable plasticization. The rotation recovered after a 100° predeformation (value chosen for the cycling) settles down to a mean value of 70°, proving the stabilization of the samples. Possible causes for the stabilization at lower rotation-recovered value have been identified as residual strains, stress reduction, and internal frictions in the chain. The shift of 10° from one activation and the other can be seen as an expression of the two-way effect combined with the elastic return of the armed tube: as the activated tube starts transforming from austenite to martensite, its stiffness decreases, allowing the other tube in martensite to recover a fraction of the rotation.

6. Conclusions

The concept of torsional antagonistic SMA actuator has been chosen among different options as the one with the highest potential for possible future applications and the greatest interest from a research perspective. The actuator's space application as a CubeSat panel's hinge has been proposed and it's feasibility in terms of activation frequency has been demonstrated. A preliminary thermomechanical characterization of the material has been carried out, followed by the conception and realization of the experimental setup. The final test sequences have been defined, and the cycling outputs have been presented. The setup has proven to work efficiently, allowing the demonstration of the torsional behavior of the two SMA tubes working in antagonism. Moreover, the performed 100 cycles prove the tubes stabilization, and demonstrate the influence on the torsional behavior of different factors: the imposed predeformation, the change in material stiffness with temperature, the high number of activations. Further improvements as regards the experimental setup are clearly possible, for example ensuring an accurate measurement of the rotation values. The actuator design must be then developed defining the most suitable configuration between the tubes depending on the application. It should be noted that, for practical applications, SMA samples should be fabricated with the most suitable composition. This can be valuable, albeit costly, as it allows for precise tuning of the transformation temperatures, thereby reducing the need for thermal treatments.

7. Equations, Tables, Figures

Equations

$$Q_{hot} = Q_{sun} + Q_{alb} + Q_{IR} + Q_i = 207.19W$$

Equation 1

$$T_i = \frac{Q_{hot}}{\varepsilon \cdot A_S \cdot \sigma} = 59.2\ ^\circ C$$

Equation 2

$$t = \frac{\Delta T \cdot m_{sat} \cdot c_t}{A_s \cdot \varepsilon \cdot \sigma \cdot T_i^{\,4}}$$

Equation 1

Tables

Transformation Temperature	Before Thermal Treatment	After Thermal Treatment
M_f	< -80°C	-33.4°C
M_s	10.7°C	25.2°C
A_s	-1.9°C	-6.5°C
A_f	14.4°C	39.2°C

Table 1 Tube's transformation temperatures before and after the thermal treatment

Clausius-Clapeyron coefficients	[MPa/°C]
C_{M_f}	13.6
C_{M_s}	25.4
C_{A_s}	3.7
C_{A_f}	10.9

Table 2 Clausius-Clapeyron coefficients

Figures

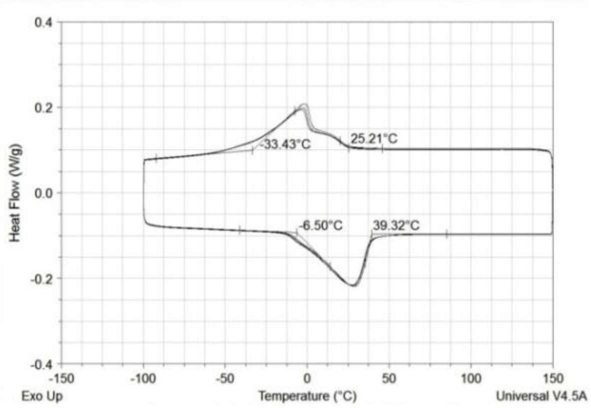

Figure 1 DSC after the thermal treatment

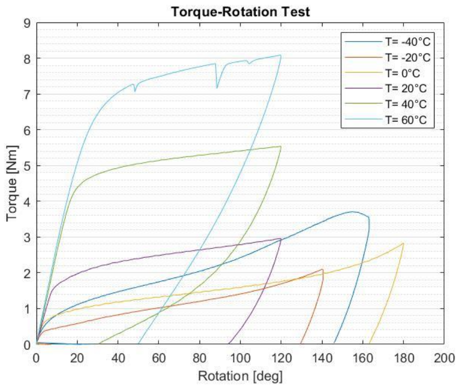

Figure 2 Torque-Rotation test

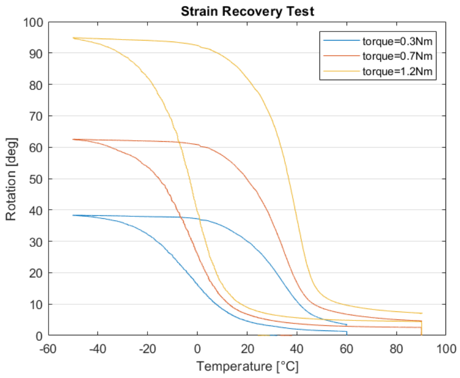

Figure 3 Strain-Recovery Test

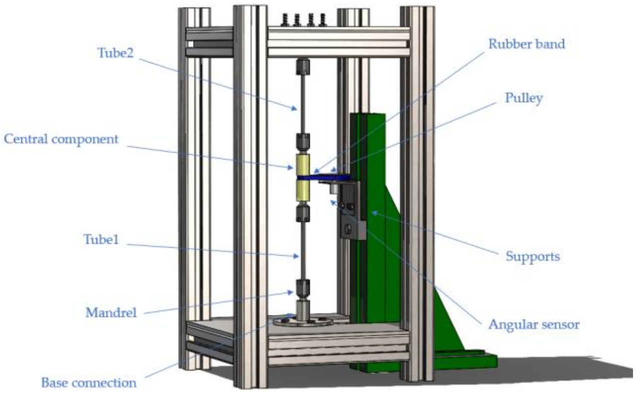

Figure 4 Complete experimental setup

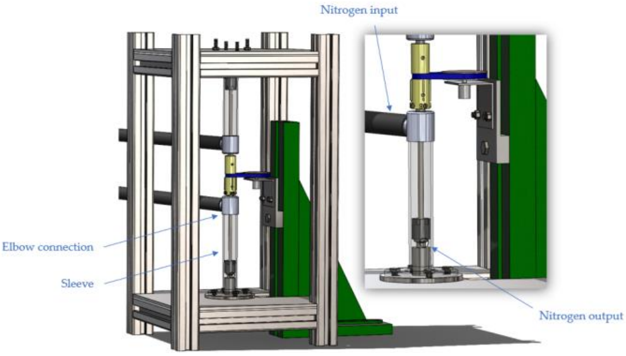

Figure 5 Alternative experimental setup

Figure 6 Final experimental setup

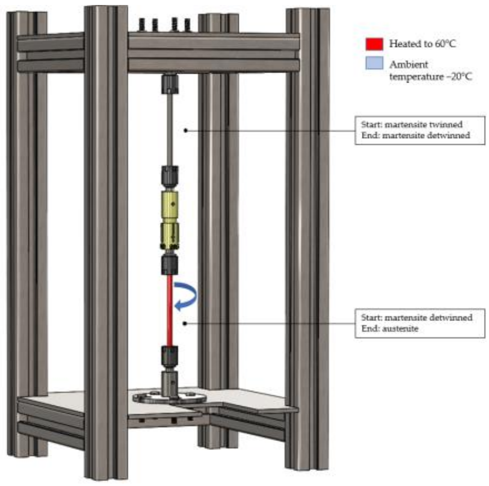

Figure 7 First step of the cycle's sequence

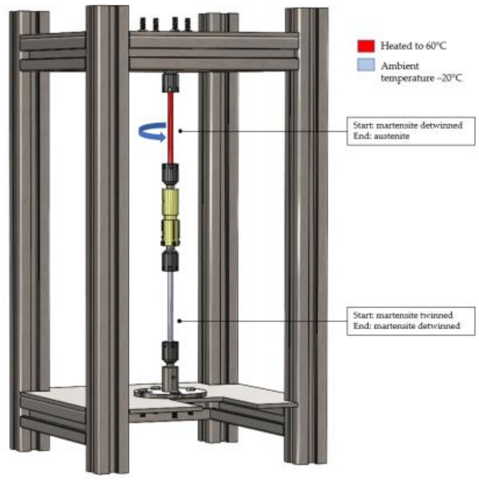

Figure 8 Third step of the cycle's sequence

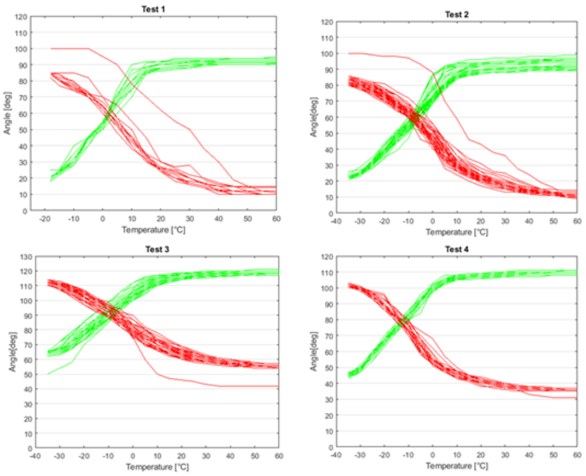

Figure 9 Complete cycling: angle configuration variation with temperature

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