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Experimental investigation of the influence of the heating rate in an SMA actuator performance

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ABSTRACT

The use of shape memory alloys (SMAs) as actuators has an increasing importance in several areas. In general, the shape memory effect and the two-way shape memory effect are employed in order to produce displacements and/or forces by heating the SMA actuator above the phase transformation temperature. This paper presents an experimental investigation on the heating rate influence on an SMA actuator. Basically, an experimental apparatus is built by considering NiTi wire connected to a steel spring and monitored by sensors. The heating rate varies from 2.9 °C/min to 385 °C/min by applying an electrical current in the SMA actuator. Several situations are investigated highlighting the general thermomechanical behavior associated with the influence of heating rate.

1. Introduction

Shape memory alloys (SMAs) are smart or functional materials that have been used in several applications. This is due to their remarkable properties that are associated with martensitic phase transformations. SMAs have two distinct phases: austenite and martensite. In the martensitic phase, different strains orientations of crystallographic plates define what is known by martensitic variants. On the other hand, austenitic phase has only one variant. Both phases can be induced either by stress and/or temperature.

SMAs have a temperature dependent response that defines distinct thermomechanical behaviors including pseudoelasticity and shape memory effect. Pseudoelastic behavior occurs at a constant, higher temperature, when an SMA specimen is stressed causing inelastic strain above a critical stress [1]. This inelastic strain fully recovers during the subsequent unloading. The stress–strain curve, which is the macroscopic manifestation of the strain mechanism of the martensite, forms a hysteresis loop. Shape memory effect occurs at a lower temperature, where after the loading–unloading process, some amount of residual strain remains after complete unloading. This residual strain may be recovered by heating the specimen [2].

There are several materials that can be classified as SMA. Among others, one can highlight metallic alloys such as NiTi, Cu-based (CuAlNi, CuZnAl), Fe-based (FeCrNiMnSi, FeCrNiMnSiCo and FeMnSiCrNi) [3]. Besides, thin films, composites and polymeric foams also present the shape memory effect. Applications of SMAs are related to several areas as aerospace, automotive, telecommunications, health, among others. In brief, one can cite references [4–7] that discuss applications related to SMAs.

SMAs are usually employed as sensors and actuators in smart systems [8,6,9–11]. In this regard, it is important to evaluate the SMA performance under specific actuation scenarios. This contribution deals with the analysis of a martensitic SMA actuator, employed for linear actuation or torque generation. An experimental set up is built by considering an SMA wire connected to a steel spring. This device is subjected to different temperature changes. The experiment allows the determination of the device's ability to generate force and displacement.

Although martensitic phase transformations are non-diffusive and therefore rate-independent, the heat transfer process is time dependent producing a rate-dependent behavior [12]. In this regard, we used the proposed experimental set up in order to evaluate the influence of heating rate on the actuation performance. Two aspects are of concern: maximum force–displacement and strain energy. Another aspect that is investigated is the device efficiency, developed from the energy point of view measured from the

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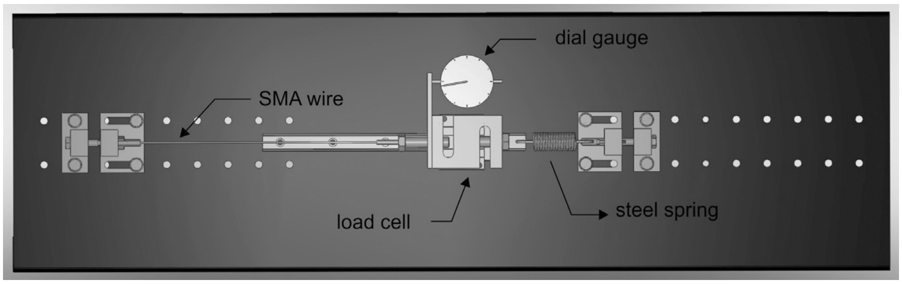

Fig. 1. Schematic picture of the experimental set up employed to analyze SMA actuators.

force–displacement or stress–strain curves. Results show the general tendency of the thermomechanical behavior of SMA actuators related to the heating rate influence.

2. Experimental set up

The analysis of SMA actuators is carried out by considering an experimental set up composed by an SMA wire connected to a steel spring. The device has an adjustment for the initial condition, allowing the analysis at different stress levels. The SMA wire is in martensitic state at room temperature and temperature variations cause phase transformation, promoting linear displacement of the assembly. The SMA wire is a NiTi alloy (54.8% Ni and 45.2% Ti) with 1.71 mm diameter, 10 cm long. Continuous phase transformations are achieved by considering heating-cooling cycles using Joule effect for heating and natural convection for cooling. In this regard, the actuator performance is investigated through a series of tests with different thermal loadings and different heating rates. Fig. 1 shows a schematic picture of the device where it is possible to observe that the SMA wire is connected to an adjustment device on one end and to a load cell on the other end. This load cell is connected to a steel helical spring that is connected to a fixed device. The steel spring has a stiffness of 300 kN/m and is responsible for the restoring force of the SMA actuator. Besides, an S type load cell of 250 kN is employed to measure load and a dial gauge with 0.01 mm of resolution is employed to measure displacements.

Although martensitic phase has several variants, one-dimensional media as SMA wires may be described by considering only two variants: the twinned martensite (*M*), which at stress-free state, and detwinned martensite M^+. These variants can be considered as macroscopic phases and, together with austenite (*A*), are enough for the description of the thermomechanical behavior of SMAs.

Fig. 2 presents a schematic picture of the thermomechanical behavior of the experimental set up indicating the heating and cooling process. Initially, the SMA actuator is in a detwinned martensite state, M^+, which means that it is previously subjected to a stress level. The heating process tends to promote the formation of austenite. After the cooling process, the SMA wire is in martensitic phase that could be variant *M* or M^+, depending on the stress level.

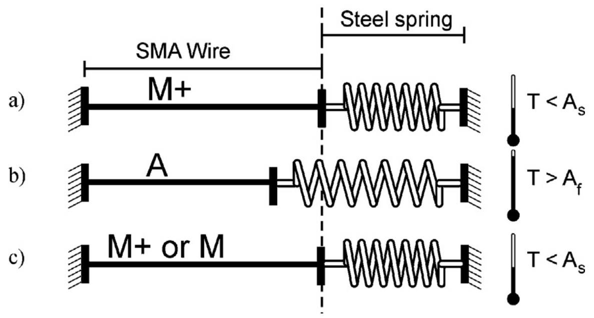

Fig. 2. Schematic picture of the experimental test.

The characterization of the SMA wire is performed with the aid of a digital scanning calorimeter (DSC), NETZCH 200 F3 Maia. Fig. 3 presents results of DSC analysis where it is possible to identify the phase transformation temperatures. By defining M_s and M_f, respectively, the temperature of start and finish of martensitic formation and, A_s and A_f the temperature of start and finish of austenitic formation, the DSC test furnishes the following results: $M_s = 37.5\,^\circ\mathrm{C}$, $M_f = 26.2\,^\circ\mathrm{C}$, $A_s = 78.4\,^\circ\mathrm{C}$ and $A_f = 97.9\,^\circ\mathrm{C}$. It should be pointed out that DSC test shows an intermediate *R* phase during cooling. Since the actuation process occurs during heating, the *R* phase does not influence the actuation process. Nevertheless, this phase may influence the material resistivity [13].

The initial state of the SMA wire is essentially martensitic, associated with detwinned martensite, M^+. Therefore, it is necessary to previously promote the wire reorientation that can be done through a tensile test. Here, this reorientation is imposed by a servo-hydraulic test machine INSTRON 8800 by assuming a controlled displacement rate of 0.02 mm/min. The specimen is trained through cycles of mechanical loading at high temperatures in order to stabilize its thermomechanical behavior.

Heating–cooling cycles are employed in order to induce SMA actuation. Heating is imposed by Joule effect while cooling is imposed by natural convection of the wire. Heating process is imposed through a voltage increase in constant steps, as shown in Fig. 4a. An MCE 8506 source of direct current is employed for this aim. An I410 Fluke ammeter measures the intensity of the current. This voltage increase induces temperature change shown in Fig. 4b, which allows the heating rate calculation. In all tests, the final temperature is 130 °C and the temperature of the wire is measured with

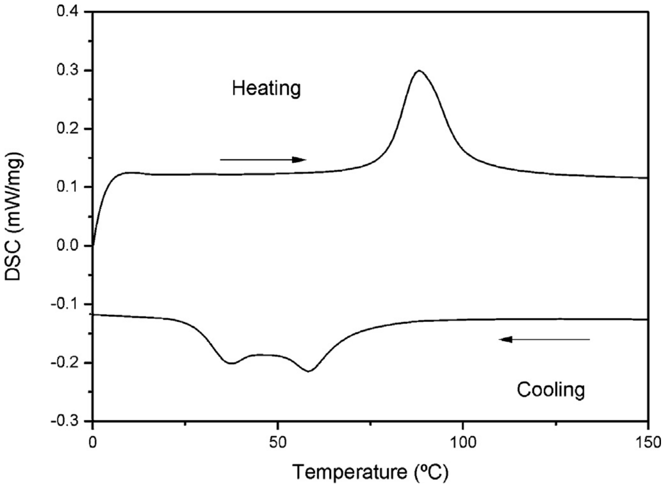

Fig. 3. DSC analysis.

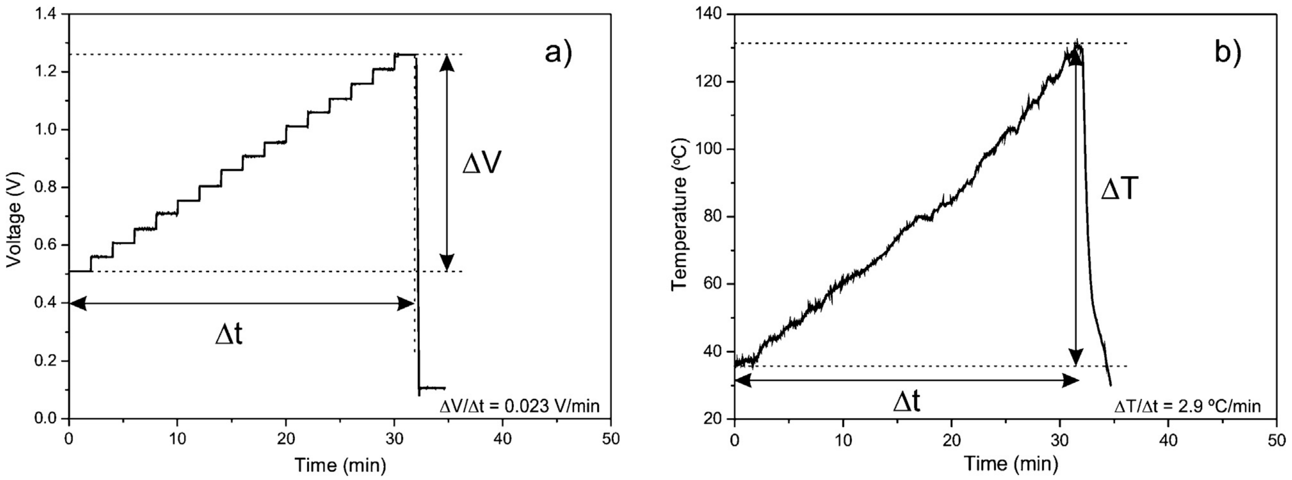

Fig. 4. Heating process: (a) input voltage and (b) temperature response.

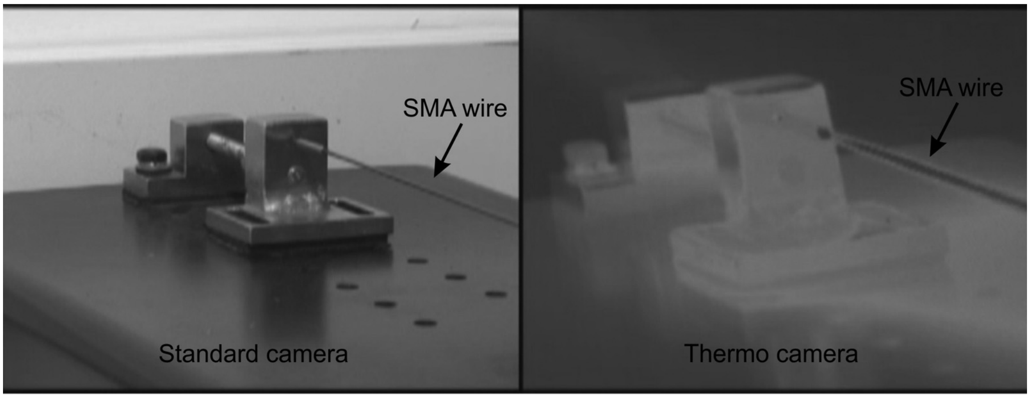

Fig. 5. Image of device during heating test (left) normal camera and (right) thermographic camera.

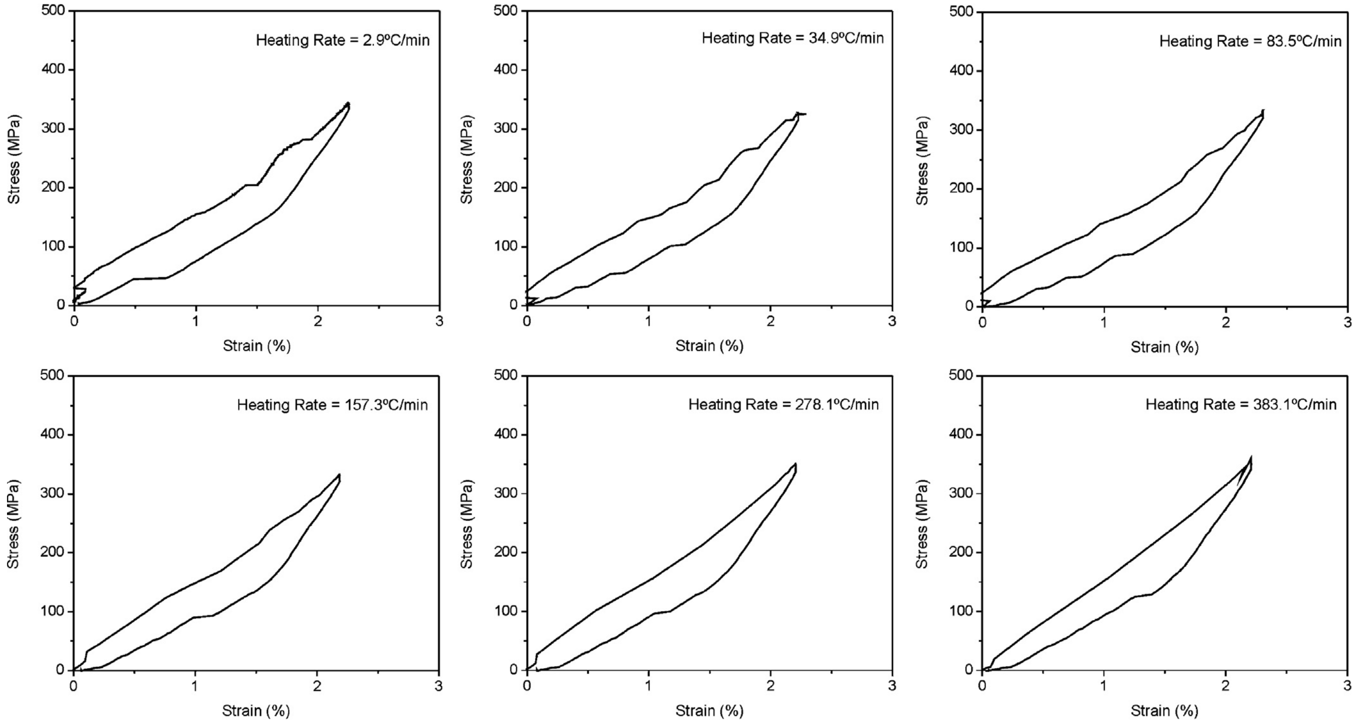

Fig. 6. Stress–strain curves for different heating rates.

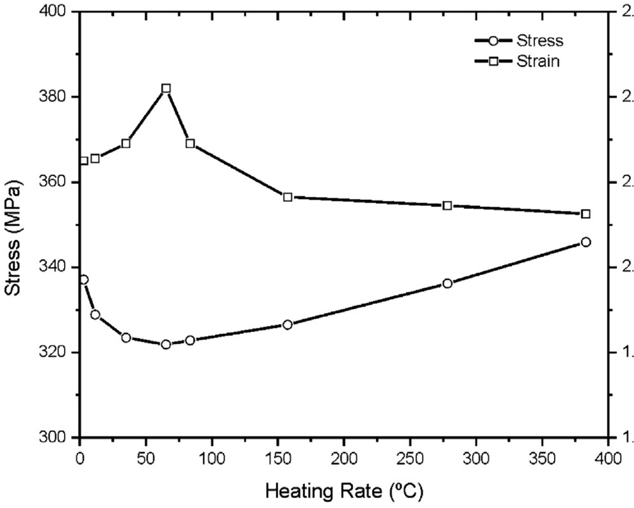

Fig. 7. Stress and strain as a function of heating rate.

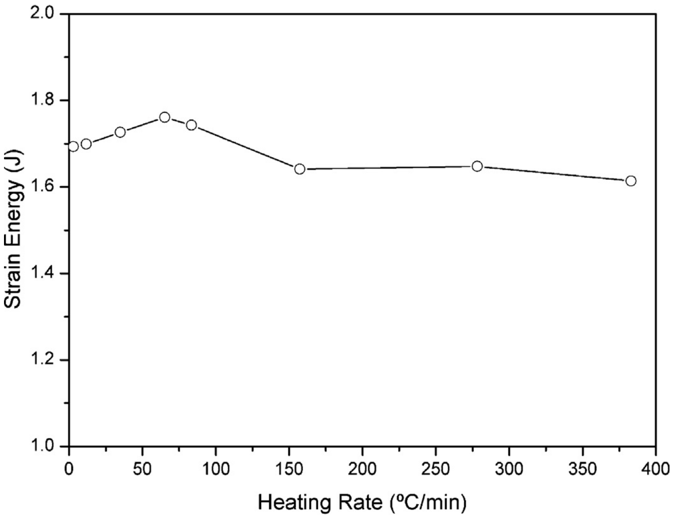

Fig. 8. Strain energy for different heating rates.

the aid of an SC4000 FLIR thermographic camera that allows exporting temperature data of region or point of interest at real time. Fig. 5 shows the thermographic image obtained with the camera.

3. Results and discussion

This section presents results related to the thermomechanical analysis of the SMA wires using the proposed device. Basically, different heating rates are imposed to the SMA actuator evaluating the differences. It should be pointed out that the influence of heating rates is strictly related to heat transfer process. Therefore, changes in convection coefficient, associated with environmental changes for example, are closed related to heating rate changes. Analyses contemplate stress–strain behavior and also strain energy behavior. The study of the device performance is based on two aspects: strain energy and maximum force–displacement. Experimental tests performed allow us to directly determine the device's ability to generate force and displacement. On the other hand, the energy point of view promotes an indirect measurement from the force–displacement or stress–strain curves.

3.1. Heating rate tests

Tests with different heating rates are conducted in order to determine their effect on the actuator performance. Fig. 6 shows stress–strain curves for six different heating rates: 2.9 °C/min, 34.9 °C/min, 83.5 °C/min, 157.3 °C/min, 278.1 °C/min and 383.1 °C/min. Results present slight differences among the

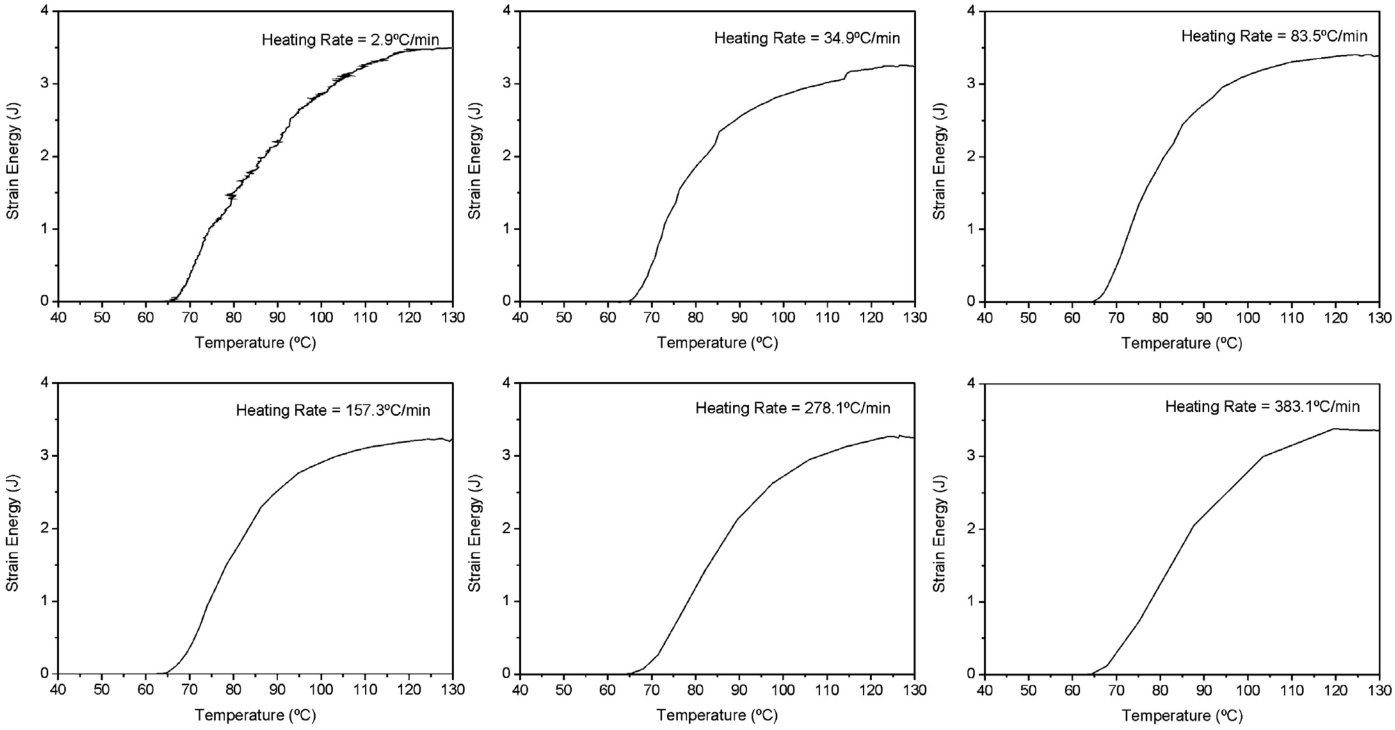

Fig. 9. Strain energy generated by each heating rate.

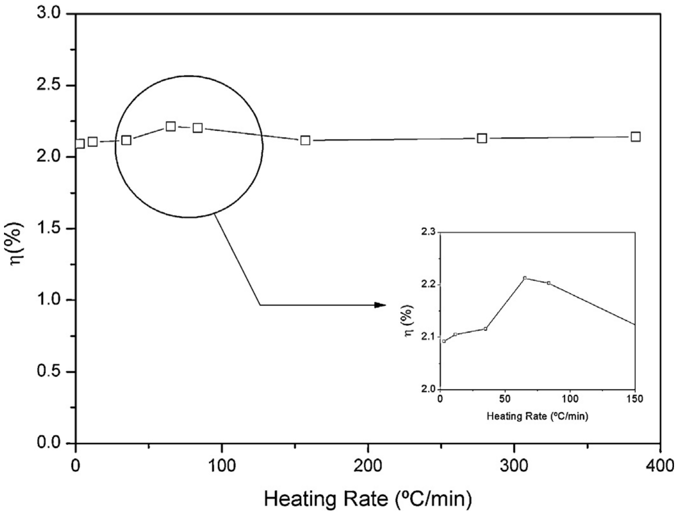

Fig. 10. Actuator efficiency for different heating rates.

curves. Although the total area of the stress–strain curves remains almost constant, meaning that there is small variation in strain energy for different loading rates, stress and strain behaviors are affected for the heating rates, as shown in Fig. 7. Note that when the strain reaches its maximum value the stress reaches its minimum. The strain variation shows an increase of 13.8% over the minimum value and the stress variation shows an increase of 7.4% over the minimum. The extreme values are the following: 2.42% of strain or 2.42 mm of displacement; 321 MPa of stress or 735 N of force. These values correspond to a heating rate around 65 °C/min. Besides heating rate, this maximum value is influenced by geometrical aspects and chemical composition of the SMA actuator.

In order to analyze the amount of energy related to the actuation process, it is defined the strain energy density, E_{Strain}, which is calculated by the integration of stress–strain curves presented in Fig. 6, during the heating process. Fig. 8 presents the strain energy as a function of heating rate. Although this curve presents small variations of the strain energy, it has the same qualitative behavior of the stress and strain curves, presenting a maximum value.

Fig. 9 presents the strain energy density as a function of temperature. Note that the phase transformation temperatures are clearly defined. For all cases, phase transformation starts around 65 °C and finishes around 130 °C. It should be highlighted the difference between these values and the ones defined by the DSC tests ($A_s = 78.4\,^\circ\text{C}$ and $A_f = 97.9\,^\circ\text{C}$). This difference is due to the stress level of the SMA actuator imposed by the spring.

The actuator efficiency is defined as a relation between the supplied thermal energy, E_{Thermal}, and the generated strain energy, E_{Strain}, as follows:

$$\eta = \frac{E_{\text{Strain}}}{E_{\text{Thermal}}} \tag{1}$$

The thermal energy is given by:

$$E_{\text{Thermal}} = mc\ \Delta T + \Delta H(\sigma), \tag{2}$$

where ΔH is the enthalpy variation between phases, m is the mass, c is the specific heat, and ΔT is the temperature variation. SMA actuator has the following parameters: $m = 1.48$ g; $c = 520$ J/(kg K); $\Delta T = 105\,^\circ\text{C}$; $\Delta H = 1867$ J/kg. This definition neglects energy exchanges with the surroundings and also the dependence of the enthalpy with respect to the stress [15], assuming a constant value.

Fig. 10 shows the system efficiency for different values of heating rate, presenting the maximum value at 65 °C/min. This variation is approximately 5.7% over the minimum.

4. Conclusions

The aim of this paper is to study the influence of heating rate in actuating process. As a result of this study we observed a heating rate that maximizes force and/or displacement of the actuator. Although different geometries or alloys present different values of critical heating rate, it is important to show that a performance analysis is important for the actuator design. This contribution proposes two different ways to perform this analysis in terms of force and displacement efficiency or combinations of them. An experimental set up connecting an SMA wire with a helical spring is developed for this aim. Several tests are carried out indicating the importance of the consideration of heating rate when designing an SMA actuator. In general, there are heating rates around 65 °C/min that maximizes the displacement of the actuator, although reducing its force. The maximum variations are observed around 14% in displacement and 7.5% in force. At high heating rates (>100 °C/min) we observed a force increase with a significant decrease of actuator displacement. Concerning energy analysis, we observed that higher heating rates provide lower energy consumption and better performance. As a result of this study we observed a heating rate can maximizes force and/or displacement of the actuator. The efficiency analysis shows an increase of 5.7% at the same heating rate that maximizes strain. This value depends directly on the product of the displacement and force of the actuator, which is proportional to the strain energy.

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Biographies

Paulo Cesar da Camara Monteiro Junior has a degree in physics from the State University of Rio de Janeiro (1999) and a masters in physics from the State University of Rio de Janeiro (2002). He has experience in the area of cosmology with emphasis on black holes and gravitational waves. He holds a doctorate in naval and oceanic engineering (2007), with emphasis on theoretical and experimental analysis of structures, shape memory alloys and smart structures. He is currently a post-doctoral researcher working in the field of smart materials and systems, specifically in energy harvesting. He is currently a researcher at the Laboratory of Submarine Technology COPPE/UFRJ.

Luciana Loureiro da Silva has a degree in physics from the State University of Rio de Janeiro (2000), master degree in physics from the State University of Rio de Janeiro (2002). He has experience in solid state physics in semiconductor nanostructures and spintronics and a doctorate in Metallurgical and Materials Engineering from Federal University of Rio de Janeiro (2007). She is currently a post-doctoral researcher working in the field of smart materials and systems, specifically in energy harvesting. She has experience in materials engineering and metallurgy, with emphasis on nondestructive testing and mechanical properties of metals and alloys.

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Marcelo Amorim Savi is a doctor in mechanical engineering (1994). Nowadays, he is professor at Federal University of Rio de Janeiro (Department of Mechanical Engineering, COPPE/Poli) where develops research and teaching activities. He is the author of several scientific papers published in international journals, proceedings and books, over 300 publications. He is involved with several research projects sponsored by the main Brazilian agencies (CNPq, CAPES, FAPERJ), and also international agencies (NSF, AFOSR). Scientific exchanges with research centers in Brazil and all over the world should be highlighted. He has participated in consulting activities in different aspects of mechanical engineering. He is involved as advisor of undergraduate and graduate students, summing more than 90 works. He is member of academic societies including ABCM, where participates of the committee of dynamics, smart materials and structures, and nonlinear phenomena and chaos. Research interests are related to nonlinear phenomena and chaos where it should be highlighted smart material and structures; nonlinear dynamics, chaos and control; biomechanics and environmental systems.