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DEVELOPMENT OF A DEVICE TO STUDY FUNCTIONAL FATIGUE ON TI-NI SHAPE MEMORY ALLOY

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Abstract. *This work aims to propose the use of a device, developed at the Mechanical Engineering Department of Federal University of Pernambuco to study the functional and mechanical fatigue in Ti-Ni actuator. Initially, wires of Ti-Ni alloys which exhibits the shape memory effect and 0,89mm in diameter were submitted to heat treatment at 500°C for 24 hours and quenching in water at 25°C. Subsequently, they were subject to differential scanning calorimetry (DSC) in order to obtain the transformation temperatures. With this data, actuators with the form of coil spring were fabricated. Using the proposed scheme, these actuators were subjected to cyclic deformations, with full expansion of 10mm, a programmable thermal bath, at a constant temperature of 85°C, in supereslastic condition, this step is called fast cycle in this work. In order to analyze the effect of these cyclic deformation on transformation temperatures and resilience so the actuators were held one second stage, here called slow cycle. At this stage, the actuators were obtained by successive cycles from the tensile stress equivalent shear stress of 70 MPa applied, within the temperature range between 15°C and 85°C and had the displacement and processing temperatures monitored by a LVDT sensor and a thermocouple, respectively. The fast and slow cycles were interspersed periodically. Thus, there is influence of thermo cycling in the degradation of the shape memory effect.*

Keywords: *Ti-Ni Alloy, Shape Memory Effect, Martensitic Transformation and Functional Fatigue*

1. INTRODUCTION

Studies on functional materials provided the advent of actuators / sensors with application on several fields, such as flow control valves and polymeric actuators used in human muscle simulation (Robertson *et al.*, 2012; Humbeeck, 1999). The development of smart actuators is based on the achievement of elements capable to produce mechanical work from external stimulus. Ti-Ni alloy are an important class of metals that have been used in actuators production with application in mechanical engineering, robotics, aerospace and oil and gas industries. The number of technological application of shape memory alloys, such as Ti-Ni increased with the advances in researches and the dissemination of the shape memory concept in engineering schools. The operation of Ti-Ni actuators and sensors is based on martensitic transformation, such as, shape memory effect and superelastic effect. Work cycles, phase transformation stabilization, the surge of stress fields and phase precipitates can contribute to the degradation of the shape recovery. These phenomena are known as functional fatigue.

Eggeler, *et al*., 2004 classified the shape memory alloy fatigue in structural fatigue and functional fatigue, terms also used by Humbeeck and Stalmans (1998). Figueredo (2006) describes the functional fatigues as the degradation due to cyclic loading on the memory properties such as, recoverable displacement. Structural fatigue refers to conventional fatigue process or mechanical damage accumulated during cycles of load and unloads (Eggeler, *et al*., 2004).

The researches involving shape memory mechanism are considered a great challenge due to the changes on the mechanical and physical properties over the phase transformation. Fatigue on shape memory alloys has two aspects: mechanical and phenomenological. The material is susceptible to fracture mechanisms and or shape memory degradation due to the martensite stabilization (Gonzalez, *et al.,* 2004). This study considered the functional fatigue behavior on Ti-Ni helical springs actuators.

The material response to external stimulus such as electrical current, tension, voltage and temperature variation might be investigate using the DSC (Differential Scanning Calorimetry) technique, mechanical testing and thermomechanical fatigue. Thermomechanical fatigue tests are performed in a device specially developed for this purpose. The device works in a specific range of temperature and simulates efforts to obtain phase transformation over thousands of cycles. The results are discussed according to the behavior of the critical temperatures transformation (A_s, A_f, M_s and M_f), influence of stress fields to try to describe the functional fatigue on the actuators submitted to phase transformation.

2. MATERIALS AND METHODS

The martensitic transformation properties might by characterized by DSC technique, thermomechanical testing, electrical resistivity and dynamic mechanical analysis (DMA). When the shape memory material is used to manufacture actuators, the material is susceptible to fatigue. In the case of helical springs actuators, the mechanical fatigue study is develop by conventional fatigue tests. However, fatigue due to martensitic transformation doesn't have a specific method of analysis. This paper methodology consists in a device proposal to simulate alternate efforts on the actuators and the capture of temperature, thermal hysteresis and displacement data.

Martensitic transformation has important properties that stand out when is used to produce actuators or sensors and are known as superelastic and reversibly shape memory effect. The device designed in this study must simulate alternate effort on the superelastic condition. In superelasticity, phase transformation occurs when the material is in a temperature higher than A_f, in this condition, if the material is submitted to an effort a phase transformation occurs. In this phenomenon, martensite is induced by stress from austenite. The stress modifies the material transformation temperatures and can also change the resistivity. This phenomenon is one of the operating principles of vibration damping systems or earthquake protection systems (Nemat-Nasser and Guo, 2006).

2.1 Ti-Ni actuator

This paper uses Ti-Ni wires with composition Ti-50.4at% Ni. These wires 0.9 mm in diameter were used to manufacture the shape memory spring actuators. The methods to obtain the actuator are well described in the literature (Oliveira, 2010; de Araújo, 2001). The heat treatment used was the homogenization at 500°C, for 24 hours and quenching in water at 25°C. Helical springs were obtained with 8 coils, but 6 active, outer diameter and working length of 6.0 mm.

2.2 DSC tests

The transformation temperatures characteristics of the material in as received and thermally treated condition were determined by DSC technique. The procedure was performed in the range of temperatures between -60 to 100°C, with rate of 10°C*min^{-1} on a Mettler Toledo DSC.

2.3 Fatigue device

The device developed to perform the fatigue tests on spring actuators has a simple dynamics and the objective of simulate alternate efforts in the actuator. The procedure is performed in a programmable thermal bath where the temperature is always held above the austenitic finish transformation temperature (A_f). Figure 1 shows the device and its main parts.

The device operation is based on a four-bar mechanism, similar to a rod-crank mechanism. The anchorage of the actuator is made on the slide sleeve (item 4) and to the movable blade support (item 9). The actuator performs the sliding motion on the sliding shaft (item 14). An engine (item 15) is necessary to make the movement transmission. The dynamic device performs an oscillatory movement that causes the compression and expansion of the actuator. The compression and expansion movement can be fit by modifying the bars position and fixation (rod-crank). The oscillatory movement causes the actuator expansion generating stress on the wire that might be able to induce martensite (superelasticity). The involved stress is the shear stresses in the wire on the movement of compression and expansion (Anadon, 2002). For the device test, it is selected a displacement of 10.0 mm for the actuator. This value is based on the thermomechanical results obtained by Oliveira, 2011.

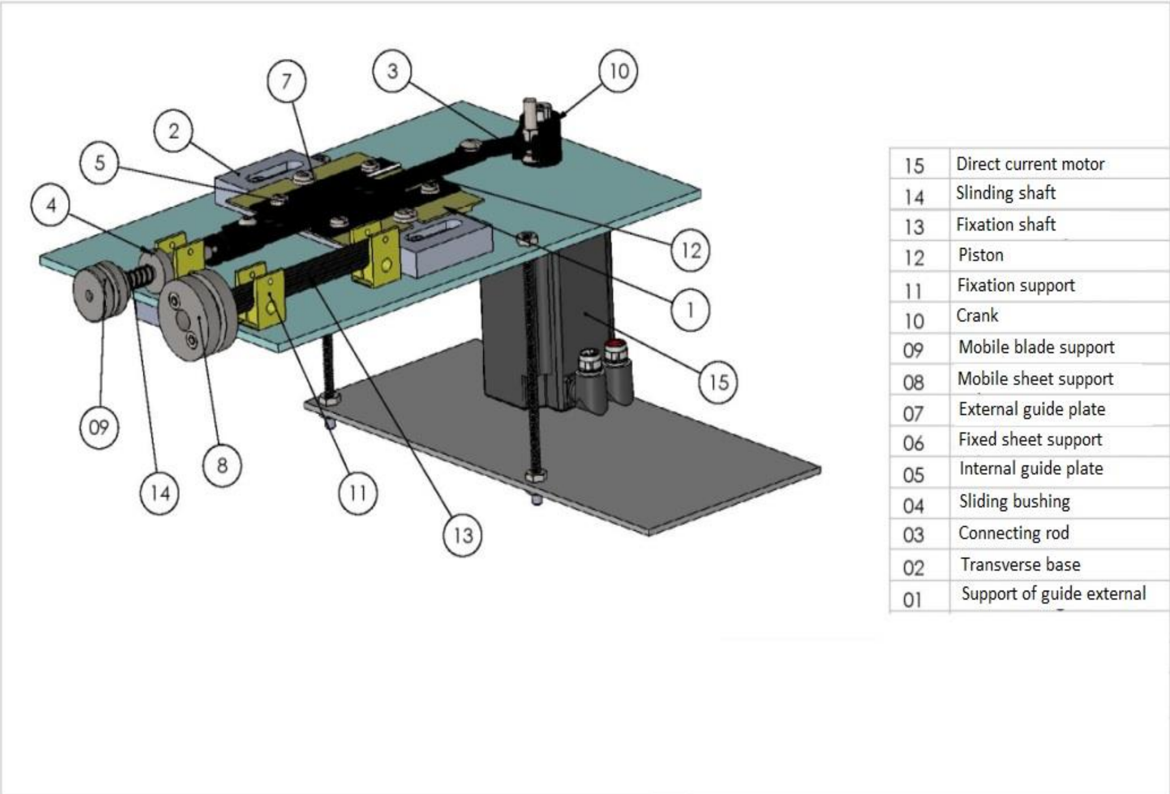

Figure 1. Functional Fatigue Device (Rocha, 2014).

2.4 Fatigue test

The fatigue tests were performed on the device and were divided into two sequences. The sequences were name slow cycles and fast cycles. Each cycle performs the compression and expansion on the actuator. The fast cycles are performed with a frequency of 100 cycles per minute and the slow cycles with a frequency of 0.5 cycle per hour. The elevate rate of the fast cycles makes difficult to determine the transformation temperatures on each cycle. In this research is carried out thousands of cycles. The fast cycles were performed interleaved with slow cycles. Slow cycles were used to obtain critical transformation temperature (A_s, A_f, M_s and M_f), thermal hysteresis, thermoelastic deformation and enthalpy transformation. It were developed 600, 1.2k, 2.4k, 6k, 8.4k, 10k, 20k, 30k, 40k, 50k, 100k, 150k, 200k, 400k, 600k, 800k and 1000k fast cycles interleaved with slow cycles. Parameters like transformation temperatures, thermoelastic deformation and thermal hysteresis were used to characterize the functional fatigue. The two sequences of the fatigue test were performed in a programmable silicone oil thermal bath.

2.4.1 Slow cycles for fatigue test

In order to investigate the shape memory effect behavior on the spring actuators a thermomechanical training technique was executed, experimental procedure perform to obtain the reversibly shape memory effect and to study the phase transformation with tensile or compression stress (Tokuda *et al*., 2001; Yoon, 2008). The slow cycle consists on heating and cooling the actuator during loading with a known stress. In this study, the material was loaded with a stress equivalent to a shear stress of 70 MPa. The shear stress is measure in the wire cross-section. The test is carry out in a programmable thermal bath, where heating and cooling rates were estimate in 7°C*min^{-1} and 2°C*min^{-1}, respectively. Slow cycles were conducted within the temperature range between 15°C and 85°C. The actuators displacement was monitored by a LVDT sensor and the temperature by a thermocouple. The data were stored in a data acquisition system and were used to identify the transformation temperatures, thermoelasticity and thermal hysteresis on each slow cycle.

2.4.2 Fast cycles for fatigue test

The fast cycles were performed in the developed device. The device is submerged into the thermal silicon oil bath. The main objective is to produce a high number of compression and expansion cycles at a controlled temperature. The procedure is able to induce phase transformation between the austenite and martensite phases, the procedure also induce propagation of internal stress fields in the material. The fast cycles were carried out in a constant temperature of 85°C, with the material completely in the austenitic phase. The actuator expansion causes an increase on the shear stress in the actuator wire; which in this case goes from 0 to 70 MPa and reaches the total expansion of 10.0 mm. The gradual increase of the shear stress reaches values capable of inducing martensite nucleation in a thermoelastic behavior known as superelasticity.

3. RESULTS

3.1 DSC results

The calorimetric tests for Ti-Ni samples, heat treated at 500ºC, allowed the identification of the transformation temperatures. Figure 2 shows the heat flow versus temperature graph, where two peaks of transformation are identified, one along the heating segment and other along the cooling segment. The presence of only one peak in each segment suggests that the transformation occurs without R-phase transformation. The values for enthalpy were 25 and 26 J/g for endothermic and exothermic peaks, respectively. The transformation temperatures were identified as A_s=57°C, A_f=74°C, M_s=39°C and M_f =26°C. The thermal treatment applied in the material exhibit in response a transformation from austenite to martensite in near ambient temperatures and the domain of austenite phase on temperatures above 75ºC.

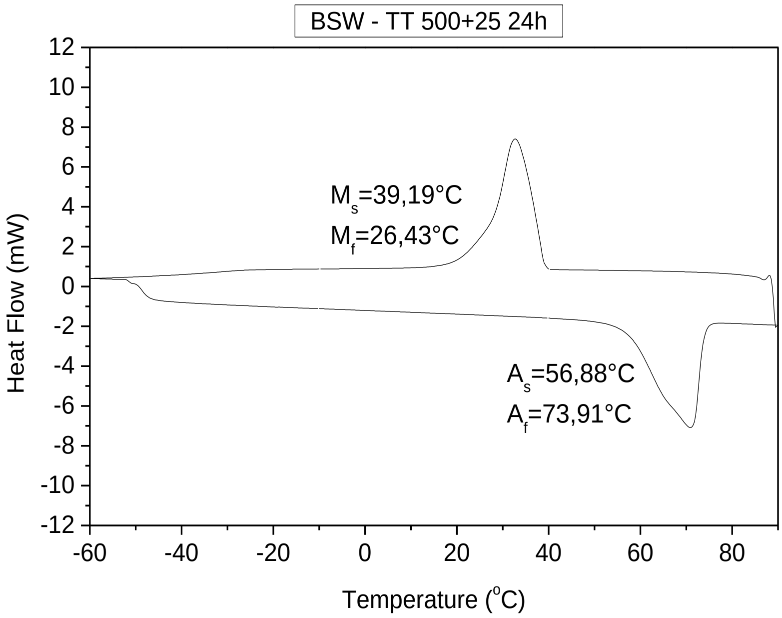

Figure 2. DSC curves for wire heat treated at 500ºC for 24 hours.

3.2 Fatigue results

The shape memory properties degradation is influenced by external elements and by the own martensitic transformation. Among the external elements there is the stress applied, strain amplitude, the number of cycles performed and temperature variation. These elements might change the material thermoelastic properties. The successive martensitic transformations, over many cycles, are capable of inducing defects, creating fields stress and increasing the density of internal defects (Otsuka and Ren, 1998). Others elements may influence the actuator behavior, as for example, the material composition that may provide favorable conditions to the appearance of precipitated like Ti_3Ni_4 that favors the R- phase transformation and that may influence the degradation of thermoelastic properties (Otsuka and Ren, 2005; Otsuka and Wayman, 1998). These elements are included in the study of functional fatigue in Ti-Ni actuator. Figure 3 shows the results of transformation temperatures behavior during the slow cycles with the application of a shear stress of 70MPa.

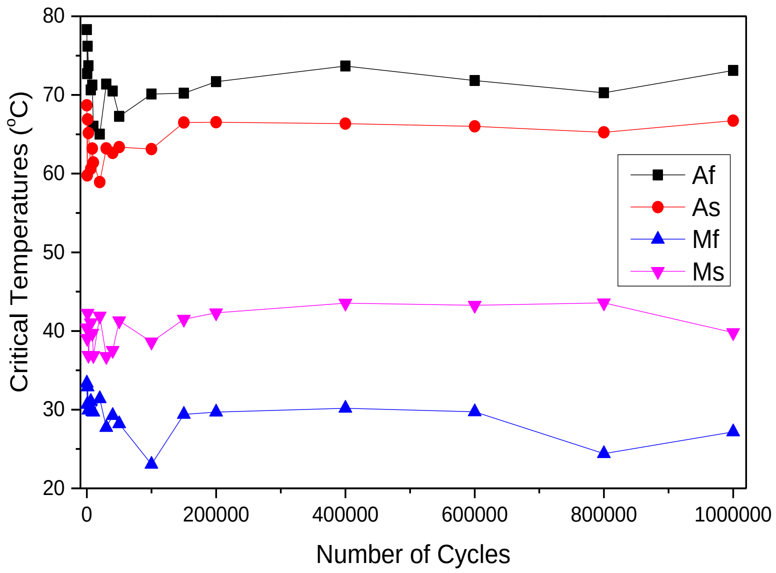

Figure 3. Critical Temperatures by Number of Cycles.

Over the data in Figure 3, it is observed the transformation temperatures behavior (A_s, A_f, M_s and M_f). The A_s temperatures exhibit an intense fall on initial cycles until 10k cycles. This temperature shows an evolution from 63ºC, at 10k to values near 65ºC at 600k. After 800k cycles the temperature reaches values near 68ºC. The M_s Temperatures also exhibit a fall on initial cycles and a growing behavior until 800k cycles. The M_s temperatures shows evolution from 40ºC at 10k to 43ºC at 800k cycles, after this temperature behavior it is observed a great fall to values near 40ºC at 1000k cycles. The expected results were the A_s temperatures reducing and the M_s temperatures increasing during cycles evolution. This behavior has influence on the thermal hysteresis. In the case where A_s is decreasing and M_s is increasing the thermal hysteresis exhibit a decreasing, behavior that might indicate the efficient of the training process. The difference between the expected and obtained behavior for A_s and M_s suggests that more energy is necessary to complete the martensitic transformation (Gonzalez *et al*., 2010).

This research also considered the deformation evolution and the influence of the fast and slow cycles in superelasticity. Fast cycles induces martensite from austenite by stress over thousands of cycles; the slow cycles were used to obtain the martensitic transformation parameters and to verify changes in phase transformation throughout the experiments. Figure 4 shows the thermoelastic deformation behavior (thermoelasticity-E_t) along 1000k performed cycles. The thermoelasticity (E_t) represent the amount of shape recovery in the actuator during slow cycles.

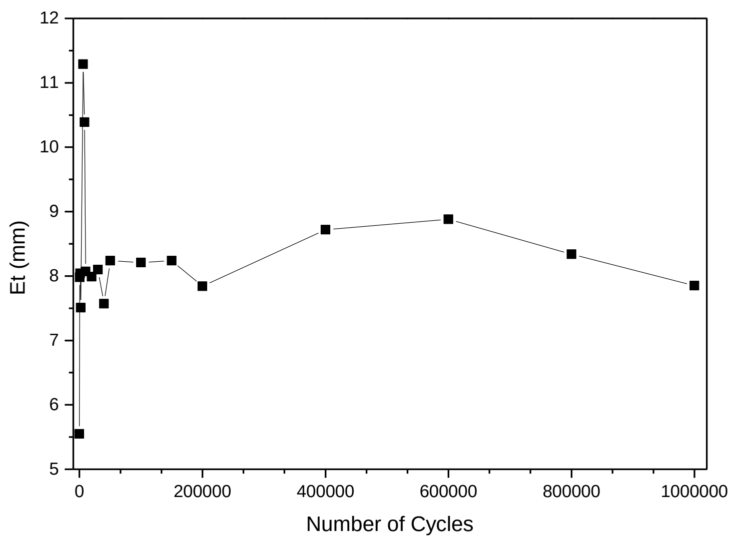

Figura 4. Thermoelastic Behavior by number of cycles using 70 MPa.

The information presented by figure 4 shows a strong evolution in the values of thermoelastic deformation for the first 10k cycles, in this case, E_t stars in 5.5 mm in the first cycle, reach 11.3 mm on cycle 6k and reduced to near 8.0 mm on cycle 20k. The E_t with 8.0 mm persisted until cycles close to 400k and reduced again to 7.5 mm for cycles close to 1000k. This behavior indicates that deformation due to martensitic transformation showed an initial reduction that should be involved with the initiation martensite variants orientation to the preferred direction of the applied effort. It might generate reconfiguration of stress fields and rearrangement of dislocations in more strained regions of the wire. After this period the oriented variants, hold the increase behavior on the actuator thermoelastic deformation to cycles close to 600k, when it began to present a fall. Considering that the material started to require more energy to accomplish the complete transformation from austenite to martensite, condition observed by the increase on A_s temperature, it is believed that the evolution observed for E_t is function of the martensite variants activation in other regions of the wire. The regions whose variants were initially oriented can experienced a process of degradation due to stress and number of cycles. Figueiredo (2006) describes the functional fatigue as degradation on the phase transformation due to cyclic loading. In the studied case, the developed number of cycles was not enough to cause the actuator wire failure, but it suggests that modification on martensitic transformation such as the increase on A_s and M_s temperatures and behavior observed on E_t indicate that it is necessary further studies to reach additional concrete conclusions.

4. CONCLUSIONS

By the obtained results, it can be conclude that the proposed device for functional fatigue study was efficient to obtain the evolution on the transformation temperatures and E_t during the training cycles. The test identified changes in transformation temperatures, especially for the A_s and M_s. The evolution of these parameters suggests that the procedure causes changes in the phase transformation inducing the increase of the thermal energy necessary to complete phase transformation in the actuator. The results suggest an indication of shape memory degradation after cycles above 800k, but the number of experiments wasn’t enough to break the wire and to obtain further and additional specific conclusions for the functional fatigue.

5. ACKNOWLEDGEMENTS

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