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DEVICE FOR FATIGUE ANALYSIS OF SHAPE MEMORY ALLOY WIRES

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Abstract. *Shape memory alloys (SMAs) have the capability to generate large forces and displacements when subjected to thermo-mechanical loads. This effect occurs due a phase transformation process. In various applications, such as actuators, SMA elements experience cyclic loadings, making the study of fatigue behavior of this material relevant. SMAs have two types of fatigue behavior: functional fatigue and structural fatigue. Functional fatigue is related with actuation capability loss promoted by the decrease in the strain recovery observed with the increase of number of cycles. An experimental device was developed in this study to analyze the fatigue behavior of SMAs wires subjected to thermo-mechanical cycles, which are composed by a constant mechanical load and a cyclic temperature variation. Temperature cyclic variation is obtained using a controlled electrical current source: heating the wire by Joule effect through the application of the electric current, followed by air-cooling by convection. The device can be used to generate experimental curves either for functional fatigue or for structural fatigue. Experimental results show that the system behaved in an appropriate and efficient way to impose fatigue of SMAs wires, exhibiting similar behavior to those found in the literature.*

Keywords: *shape memory alloys, functional fatigue, smart materials, experimental analysis*

1. INTRODUCTION

Shape memory alloys (SMAs) have been widely used in various fields due to their special features such as the capability to recovery large deformations by returning to the original shape after a proper thermomechanical loading. Among the special effects are the shape memory effect that occurs at low temperatures, where large residual deformations promoted by mechanical loadings are recovered by heating after load removing, and pseudoelastic effect that occurs at high temperatures, where the recovery from large deformations promoted by mechanical loadings is achieved by removing the mechanical loading. Its special properties permit the development of innovative applications in various fields including automotive, aerospace, robotics and biomedical (Nava *et al.*, 2014; Jani *et al.*, 2013; Lagoudas, 2008; Song *et al.*, 2006; Petrini and Migliavacca, 2011). Among the various applications stands out use of SMAs elements as actuators and dampers (Aguiar *et al.*, 2010; Follador *et al.*, 2012; Hwang and Higuchi, 2014; Naghashian *et at.*, 2014; Savi *et al.*, 2015). The alloy nickel/titanium (NiTi) stand out because of its good mechanical and functional properties compared to other alloys types.

SMA effect is associated with phase transformation involving two phases: martensite and austenite. For a free stress state, austenitic structure is stable at elevated temperatures whereas martensite structure is stable at low temperatures. Phase transformation can be induced by mechanical or thermal loadings.

Pseudoelastic effect occurs above the critical temperature (A_f) in which there is only the austenitic phase for a free stress state. The application of a mechanical loading promotes a reorientation of austenite phase to detwined martensite. By removing the mechanical loading, reverse phase transformation occurs and austenite phase returns. This effect does not require temperature variation.

Shape memory effect can be one-way (OWSMA) or two-way (TWSMA). For OWSMA the deformed state is retained after the removal of an external mechanical loading and the original shape can be recovered upon heating. For TWSMA the material can remember its shape at both high and low temperatures. However, TWSMA is less applied commercially due to the 'training' requirements and to the fact that it usually produces about half of the recovery strain provided by OWSMA for the same material and it strain tends to deteriorate quickly, especially at high temperatures. (Jani *et al.*, 2013). Figure 1 shows a diagram illustrating both effects.

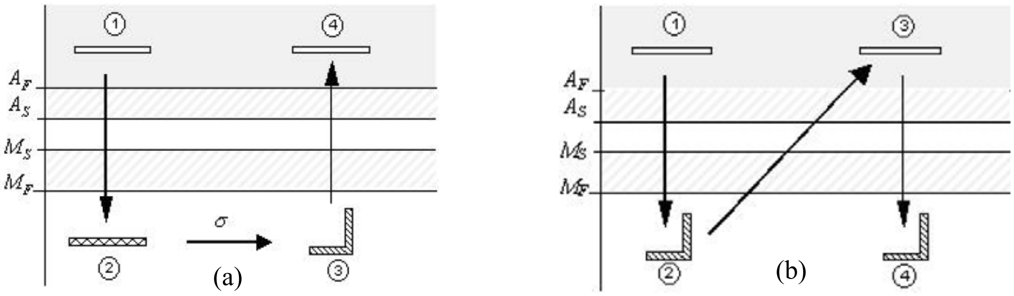


Figure 1. Diagram illustrating: (a) one-way SMA and (b) two-way SMA (Pereira, 2009)

Fatigue of materials refers to the changes in properties resulted from the application of cyclic loads in strain or load control. As SMAs experiments cyclic loadings in several applications as actuators, fatigue analysis is relevant study for these materials. SMAs presents two types of fatigue behavior: structural, or classical fatigue, and functional fatigue (Humbeeck and Stalmans, 1998; Eggeler *et al.*, 2003).

Structural fatigue usually occurs for several engineering materials and is used to characterize accumulated microstructural damage that promotes the failure of a structure or a mechanical component subjected to cyclic loadings. As SMAs experiments phase transformation during thermomechanical loadings, the structural fatigue of SMAs usually presents a more complex behavior than the one observed in usual engineering materials (Tabanli *et al.*, 1999; Eggeler *et al.*, 2003; Wagner *et al.*, 2004; Pappas *et al.*, 2007; Figueiredo *et al.*, 2010; Gloanec *et al.*, 2010, 2013; Maletta and Furgiuele, 2011; Maletta, 2014).

Functional fatigue is used to characterize the decrease in functional properties observed during cyclic loadings in SMAs (Eggeler *et al.*, 2003; Soul *et al.*, 2010; Mammano and Dragoni, 2011, 2012; Mammano *et al.*, 2013; Song *et al.*, 2014). The cyclic loading can be promoted by variation of temperature or variation of applied load (Miyazaki *et al.*, 1986; Saburi, 1998; Heckmann and Hornbogen, 2003). It should be noted that in many cases first the material experiments a functional fatigue, with the decrease in functional properties, followed by structural fatigue, when a complete fail occurs.

In this work a low cost experimental device based on the one proposed by Bertacchini *et al.* (2003) and developed by Royse (2007) is used to analyze the functional fatigue behavior of SMAs wires subjected to thermomechanicals cycles. The developed device allows the register of the thermomechanical cyclic wire deformation history using a displacement sensor connected to a data acquisition system.

2. EXPERIEMENTAL PROCEDURE

An experimental device was developed in this study to analyze the fatigue behavior of SMAs wires subjected to thermo-mechanical cycles. The device is composed by an aluminum structure that provides a constant mechanical loading of SMA wire applied by a dead weight system. It dimensions are: 700 mm length, 102 mm height and 500 mm in width. A displacement transducer is attached to the wire, that is heated by a controlled current source. Both are connected to a computer that register the SMA wire displacement and also controls the current imposed to the SMA wire. The dead weight system is connected to the SMA wire trough a multifilament yarn that pass to two pulleys. The multifilament wire is fixed to an aluminum plate which is connected to one end of a displacement transducer. The other end of the displacement transducer is connected to the end of the SMA wire using pre-isolated terminals. Finally, the other end of the SMA wire is connected to the structure. Figures 2 and 3 shows, respectively, the developed device and a schematic representation with the components.

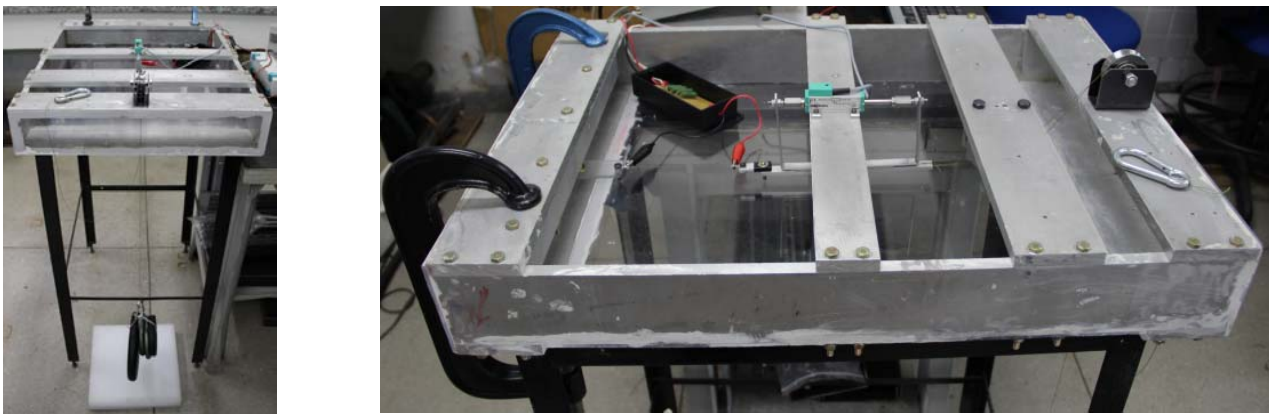


Figure 2. Proposed device for fatigue analysis.

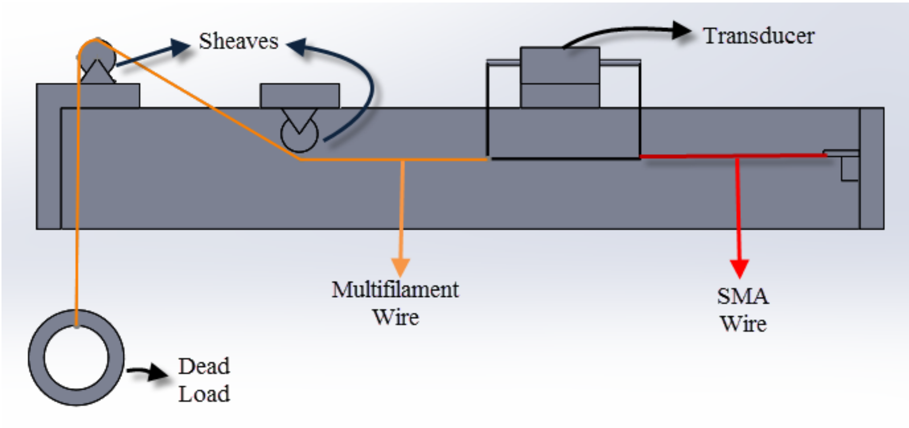


Figure 3. Schematic drawing of the device.

Functional fatigue tests were developed using a martensitic NiTi SMA wire with a diameter of 0.375 mm manufactured by Dynalloy (2015). Table 1 shows the main properties of the SMA wire used in the experiment, its properties and the recommended operating ranges. Data shows a maximum load near 65 N.

Table 1: SMA Wire Properties (Dynalloy, 2015)

Properties Flexinol 375

Physical	Wire Diameter (mm)	0,375
	Minimum Ben Radius (mm)	18,75
	Cross-sectional Area (mm2)	0,11
Electrical	Linear Resistance (W/m)	8
	Recommended Current† (mA)	2,75
	Recommended Power† (W/m)	60,5
Strength*	Max. Recovery Weight at 600 MPa (g)	6,63
	Rec. Recovery Weight @ 190 MPa (g)	2
	Rec. Deformation Weight @ 35 MPa (g)	393
Material	Density (g/cc) 6.45	6,45
	Maximum Recovery Force (MPa)	600
	Recommended Deformation Force (MPa)	35
	Breaking Strength (MPa) 1,000	1.000
	Poisson's Ratio	0,33
	Work Output (Joule/g)	1
	Energy Conversion Efficiency (%)	5
	Maximum Deformation Ratio (%)	8
	Recommended Deformation Ratio (%)	3 to 5
Speed	Typical Contraction Speed†† (sec)	1
	LT Relaxation Speed†† (sec)	13
	LT Alloy Thermal Cycle Rate (cyc/min)	4
	HT Relaxation Speed†† (sec)	10
	HT Alloy Thermal Cycle Rate (cyc/min)	5

		LT Alloy	HT Alloy
Thermal	Activation Start Temp. (°C)	68	88
	Activation Finish Temp. (°C)	78	98
	Relaxation Start Temp. (°C)	52	72
	Relaxation Finish Temp. (°C)	42	62
	Annealing Temp. (°C)	300	300
	Melting Temp. (°C)	1.300	1.300
	Specific Heat (cal/g°C)	0,077	0,077
	Heat Capacity (Joule/g°C)	0,32	0,32
	Latent Heat (Joule/g)	24,2	24,2

	Phase	Martensite	Austenite
Phase Related	Resistivity (µÙcm)	76	82
	Young's Modulus (GPa)	28	75
	Magnetic Susceptibility (µemu/g)	2,5	3,8
	Thermal Conductivity (W/cm°C)	0,08	0,18

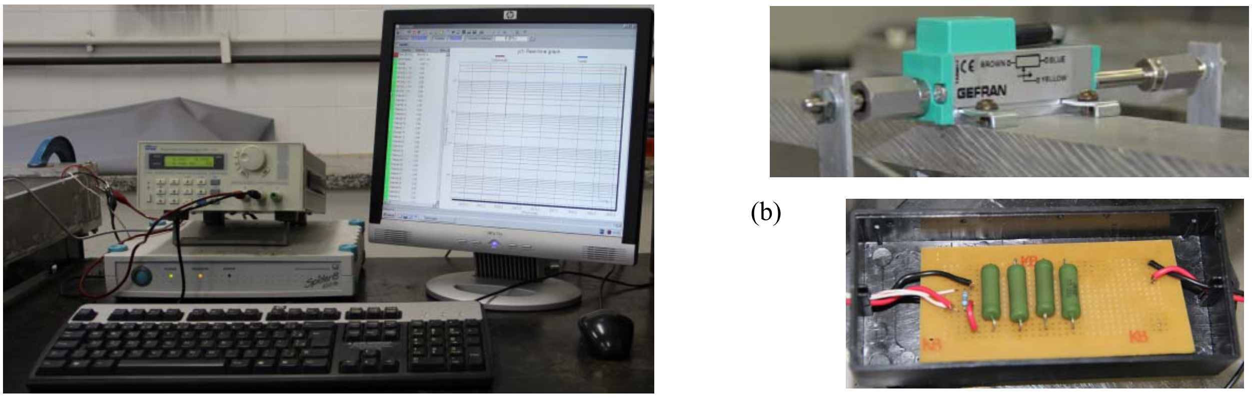
** To obtain force in Newtons, multiply mass in grams by 0,0098*

† In still air, at 20°C

†† Depends greatly on local heating and cooling conditions

SMA wires were subjected to a cyclic thermomechanical loading where a constant load is applied using a deadweight system which maintains a constant mechanical load on the wire. The applied cyclic thermomechanical loading consists of three stages: 1) mechanical loading stage; 2) heating stage; and 3) cooling stage. Initially the wire was in a free stress state with 100% twinned martensite. The mechanical loading stage is obtained through the applications of the deadweight and the SMA wire experiments stress induced phase transformation. Depending on the deadweight value, the twinned martensite experiments a total or partial phase transformation to detwinned martensite. The heating stage consists on heating the SMA wire trough Joule effect by applying a cyclic electric current wave generated by a computer controlled current source. When heated, the wire contracts and recovered the stress induced deformation due to reverse transformation into austenite. Finally, in the cooling stage the computer sets off the electric current and austenite phase present in the SMA wire transforms to detwinned martensite induced by the deadweight.

To study the effect of the constant mechanical load, tests were developed considering several loads: 10, 20, 30, 40, 50, 60, 70, 80, 90 N. The heating-cooling cycle of the SMA wire is achieved by applying an on-off type (square wave) cyclic current using a computer controlled Icel PS-7000 current source. Data from the displacement transducer and the current source were acquired by HBM data acquisition system Spider with the help of HBM data acquisition program Catman. A Gefran PY-2 potentiometric displacement transducer with a maximum range of 150 mm is used to collect data from the system. To avoid damage, SMA wires were connected in parallel to a resistor circuit for reducing the current passing through it. Figure 4 illustrate the data acquisition system, the displacement transducer and the resistor circuit board.

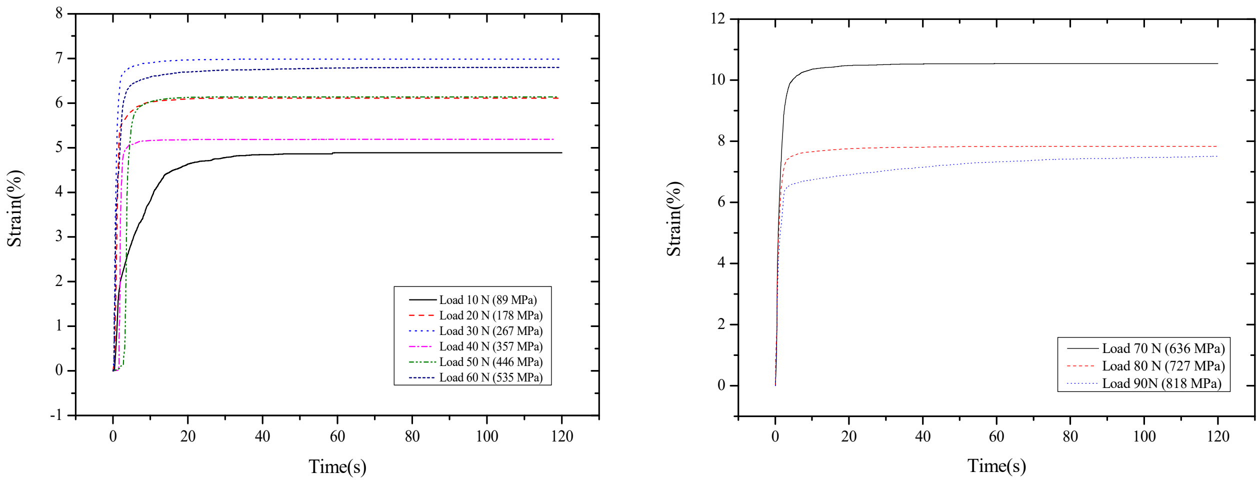


(a) (b) (c)

Figure 4. (a) Data acquisition system, (b) displacement transducer and (c) resistor circuit board.

A procedure is used to guarantee that the SMA wire is in 100% twined martensitic state at room temperature before each test. A small current is applied to the SMA wire to remove residual deformation associated to the presence of detwined martensite promoted by any prior load. An initial length of 90 mm is adopted for the SMA wires.

As the phase transformation temperatures depends on the stress levels, a study was developed to assess the cooling and heating times required to complete the phase transformations. Figure 5 shows data associated to the required cooling time for the deadweights used in the tests. The developed tests consist in register the displacement evolution during the cooling stage. Results show that higher load values are associated with smaller required cooling times.



(a) (b)

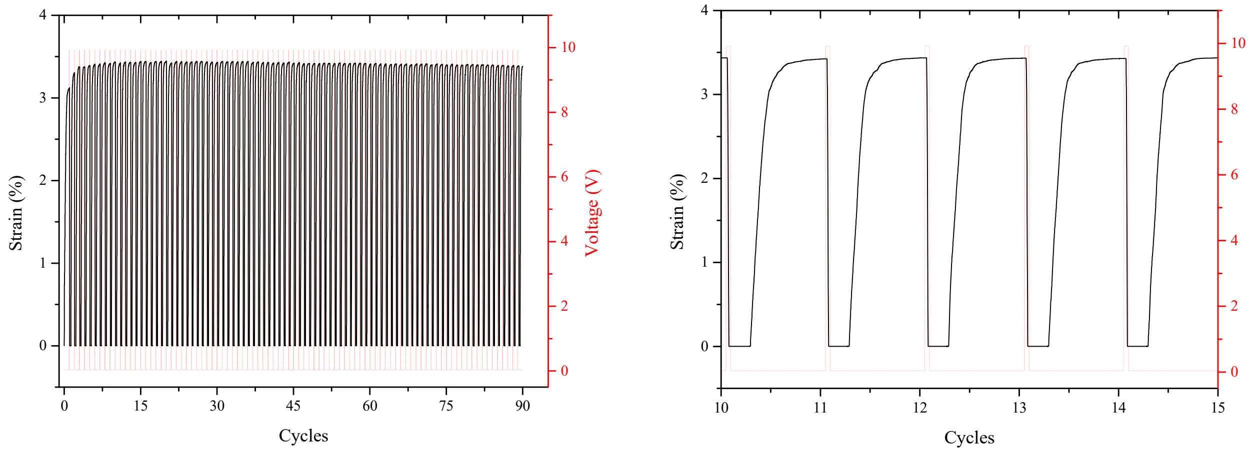
Figure 5. Displacement evolution during the cooling stage. Applied loads: (a) bellow and (b) above the maximum load recommended by the manufacturer (65 N).

At this point the developed tests are described. Initially the martensitic wire is positioned in the device without application of deadweight. A cyclic electric voltage square wave of 0-10 V loading program generated by the current source is applied to the wire. This setting results in an electric current square wave of 0-1.46 A. Displacement and voltage data are registered by the data acquisition system. The deadweight is then applied and the current source cyclic loading program is turned on. When the SMA wire temperature reaches austenitic phase transformation temperature the residual deformation induced by the deadweight is recovered, approaching its initial length. After 90 cycles the program is turned off. Before starting a new cycle, the SMA wire is heated without the weight so it could return to its original shape without the presence of residual deformation.

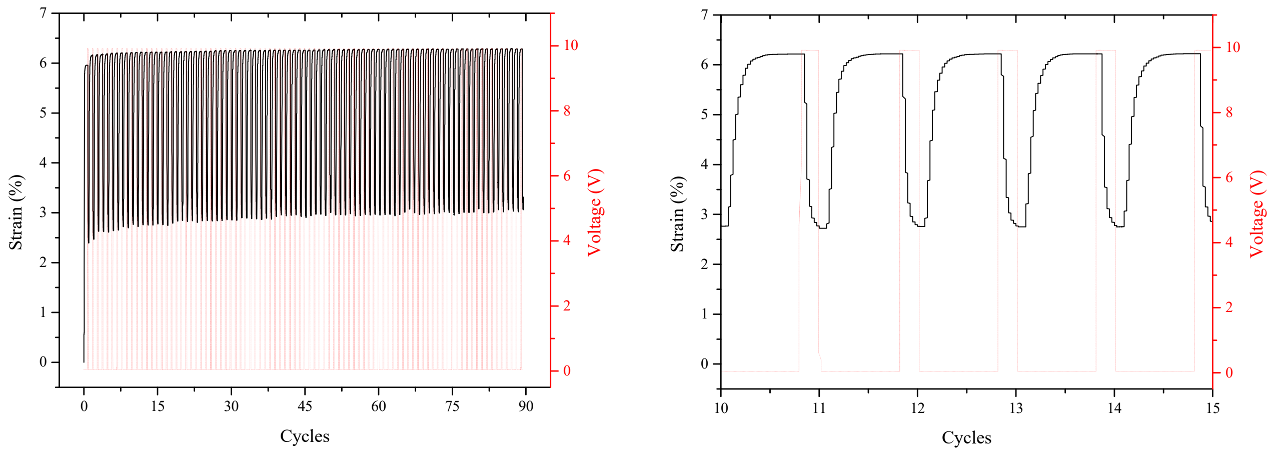
The same wire was used in a sequential order for the tests for loads bellow the maximum load recommended by the manufacturer (65 N): 10, 20, 30, 40, 50 and 60 N. This loading range is the recommended by the manufacturer for best performance of the material. For loads above this value, a new wire was used for loads: 70, 80 and 90 N. SMA wire with 90 N fail just after a few cycles.

3. RESULTS AND DISCUSSION

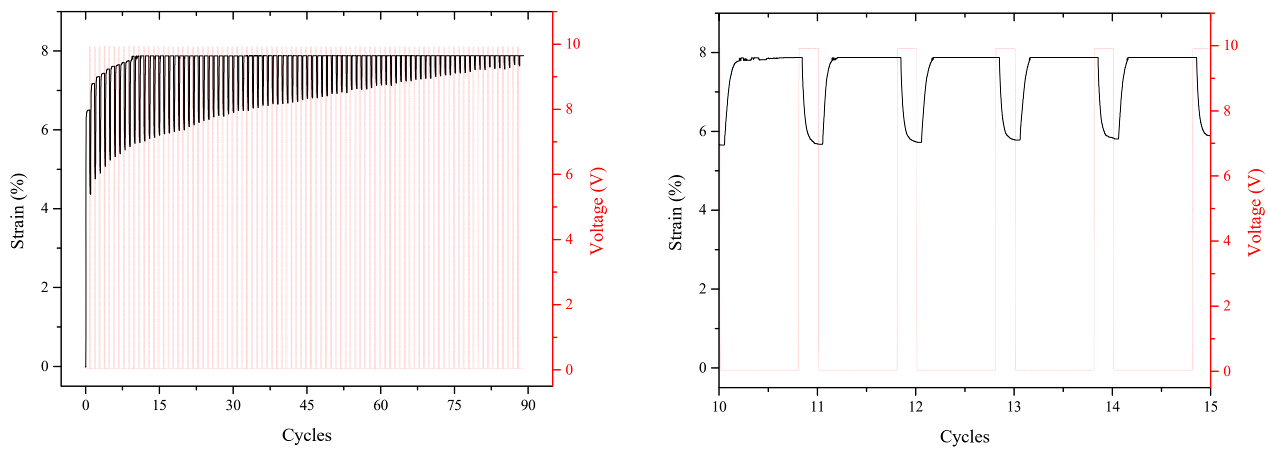
This section presents the results from the tests described in the prior section developed to identify functional fatigue of a 0.375 mm NiTi SMA wire. Figure 6 shows the displacement (black line) and electric voltage (red line) evolution for 3 tests: 10 N, 50 N and 80 N.



(a)



(b)



(c)

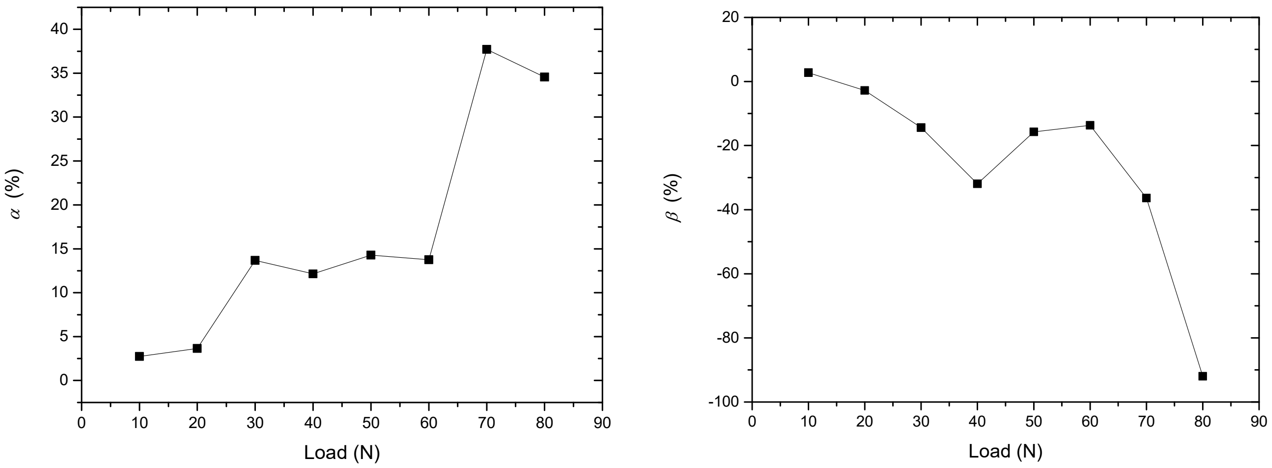
Figure 6. Displacement (black line) and electric voltage (red line) evolution for 3 tests: (a) 10 N, (b) 50 N and (c) 80 N. Full history is presented at the left and an amplified view at the right.

Results show that for larger loads higher mean deformation and higher amplitude reduction are observed. As expected, functional fatigue strongly depends on the applied loading. This behavior can strongly affect the performance of SMA elements as actuators. To study the behavior of a SMA wire, two parameters are introduced:

$$\alpha = \frac{\bar{u}_f - \bar{u}_i}{\bar{u}_i} \tag{1}$$

$$\beta = \frac{\Delta u_f - \Delta u_i}{\Delta u_i} \tag{2}$$

where $\bar{u}_i$ and $\bar{u}_f$ are the initial and final mean displacement, respectively, and Δu_i and Δu_f are the initial and final amplitude displacement, respectively. Therefore, α represents the variation of the mean deformation and β the variation of the amplitude reduction variation with the applied load. i index is associated to the second cycle while f index is associated to the last cycle. Figure 7 shows the dependence of both parameters with the applied load. Results show that for applied loads larger than the maximum load recommended by the manufacturer (65 N), the SMA wire performance can be strongly affected, as amplitude reduction after 90 cycles can be larger than 40%.



(a) (b)

Figure 7. Dependence with the applied load of the variation of: (a) mean deformation and (b) amplitude reduction.

4. CONCLUSIONS

The proposed device is a low cost apparatus that can be used to generate experimental data to characterize functional fatigue on SMA wires. Experimental results show that the system behaved in an appropriate and efficient way to analyze functional fatigue of SMAs wires, exhibiting similar behavior to those found in the literature. The system permits to record the wire displacement and electric current time evolution, allowing to compare the response of wires subjected to different types of loadings. Experimental results show that larger loads promote lower recovery phase transformation induced deformation, consequently, resulting in a loss of actuating effect, that tends to be amplified as the number of cycles increases. Due the good repeatability of the equipment, the device can be also used to study classical fatigue of SMA wires.

5. ACKNOWLEDGEMENTS

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