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STABILITY OF NI-TI SHAPE MEMORY ALLOY WIRE DURING THERMO-MECHANICAL CYCLING USING THE JOULE HEATING EFFECT

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Abstract. *Ni-Ti wires are widely used as thermomechanical actuators that are subject to repeated thermal cycling in a range a temperatures and fluctuating loads. The mechanical stability is a fundamental behavior that need to be understood to project well accurate actuators. Thus, basically the total recoverable strain must to be constant under certain external conditions. In this investigation an apparatus was built to monitor the recoverable strain during prolonged thermal cycles under a constant load. It has been shown that the recoverable strain decrease with cycling. Also, an acceptable stabilization can be found when the wires are heat at 750mA.*

Keywords: *Shape memory alloy, Thermo-mechanical cycling, Mechanical stability.*

1. INTRODUCTION

Shape memory alloy is a class of materials that remember its original shape in such way that when deformed returns to its original pre-deformed shape after heating. Historically, this phenomenon was initially discovered in Au-Cd system by Arne Orlande in 1938 and many years latter in Ni-Ti systems by W.J. Buehler and Wang at the US Naval Ordinance Laboratory in 1963 (Lima, 2008; Schetky, 1979; Worden et al., 2003).

The mechanism of shape recovery is the occurrence of a reversible martensitic-austenitic phase transformation which involves small rearrangement of atoms within the crystal lattice. The martensitic transformation is associated with an inelastic deformation of the crystal lattice with no diffusive process involved (Mishra and Behera, 2012) .

The phase transformation results from a cooperative motion of atoms on distances smaller than the lattice parameters. Upon cooling the material undergoes a phase transforms from austenite to twinned martensite and with heating the twinned martensite, a reverse martensitic transformation takes place and as a result the material transforms to austenite and recover its original shape (Mishra and Behera, 2012). It is important to point out that there are four typical temperatures involved during the phase martensitic-austenitic phase transformations: The martensitic start temperature (M_S) which is the temperature at which the material starts transforming from austenite to martensite. Second is martensitic finish temperature (M_F), when the transformation is complete and material becomes fully in the martensitic. Similar temperatures are defined for reversible transformation during heating. Austenite start temperature (A_S) is the temperature at which the austenite transformation starts and austenite finish temperature (A_F) when it finished.

There are several alloys that display the shape memory effect but the most well-known is the Ni-Ti that can recovery up to 8% of deformation associated with high values of stress (in case of constraining during heating), excellent corrosion resistance, much higher ductility, biocompatibility and damping. Ni-Ti alloys have far greatest attractive properties of commercially available shape memory alloys and for this reason are widely used in the marine industry, aeronautics, aerospace, nuclear, automotive, robotics, household appliances, medicine and dentistry (Castilho and Silva, 2011; Magela, 2010; Lima, 2008). The amount of recoverable strains and the thermal stability of the alloys are the mandatory properties for the development of shape memory products and actuators (Dias, 2005).

For many application the alloys undergoes repeated transformations in a temperature range under constant/variable load. Studies have shown that the functional properties such as: transformations temperatures (M_F, M_S, A_S, A_F), hysteresis, ductility, recoverable strains can change during thermal cycling impairing the material usage. These changes depend on alloy composition and thermomechanical history and stress-strain regime (Bhagyaraj et al., 2009; Perkins and Sponholz, 1984). The present study deals with the mechanical stability of Ni-Ti wire during thermomechanical cycling under constant loading at different temperatures using Joule heating effect.

2. EXPERIMENTAL

Ni-Ti wire of 0.305 mm with a nominal composition of $Ni_{52.95}$-$Ti_{47.05}$ (mass%), supplied by memory Metalle company, were used in the present study. The as-received wires were annealed at 450°C for 360 min followed by water quenching. The transformation temperatures were determined using a TA Q20 DSC instruments at a constant heating rate of 10°C/min under argon inert atmosphere. The tensile properties of the wire in martensite phase were done using Shimadzu 10kN universal testing machine. The tests were carried out on specimens of 50 mm gauge length at a strain rate of 0,5 mm/min. The schematic set up used for thermal-mechanical cycling experiments is shown in the Fig. 1. This apparatus was built at the LaSEA and at the Instrumentation and Control Laboratory of the Electrical Engineering Department from Federal University of Paraiba. 10k

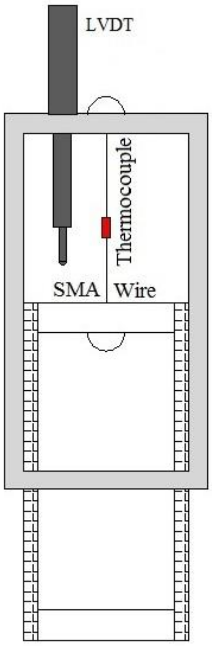

Figure 1. Set up for thermo-mechanical cycling experiments.

The apparatus consists of four parts: mechanical linear guides, linear variable differential transformer sensor, thermocouple and the Ni-Ti wire. The mechanical structure is assembled in a stand (desktop like structure) using a C-shape claw. Upon heating and cooling the wire can slide through linear guide and the total displacement is measure by the LVDT sensor. The wire attached on the superior level of the table and in the end of the wire a constant load is applied. Thus, during the thermal cycling the wire can freely dislocate. The total gage length of the specimen was 100mm and the displacement was monitored using the GCD-SE-1000 LVDT model from Measurement Specialties with resolution of 0.05 mm. The wire temperature was measured by a K-type thermocouple (100 µm thickness).

The electronic set up of the experiments was done using a computer, E3648 Agilent power source, drive circuit and the NI cRIO-9076 data acquisition system from National Instruments (NI 9263 analogical output, NI 9201 analogical input and NI 9213 thermocouple input module), see Fig. 2. The electrical diagram of the drive circuit shown in the Fig. 3 was built to control the actuation of the Ni-Ti wire. This circuit allows to measure the electrical current value in the wire though the voltage drop across the resistor shunt of 0.22 Ω / 10 W. Thus, the voltage drop on the resistor is measured and amplified by 5 times using INA101 amplifier. The output signal of the amplifier passes through a 159 Hz low-pass filter to improve the signal quality.

A Agilent E3648A power source is connected to the circuit to create switched electrical current in the wire by the IRFZ46 transistor with output signal of 5 V. This electrical current heats the sample by Joule effect which make the wire recovery its shape and subsequently this displacement is measured. The acquisition and control of the experimental data were performed by means of the NI cRIO-9076 which communicates to the LabVIEW software.

The graphical interface was done using the LabVIEW software, see Fig. 4, that allows to monitor all experimental parameters and graphs such as: current electrical behavior, temperature evolution, displacements versus time or temperature and so on.

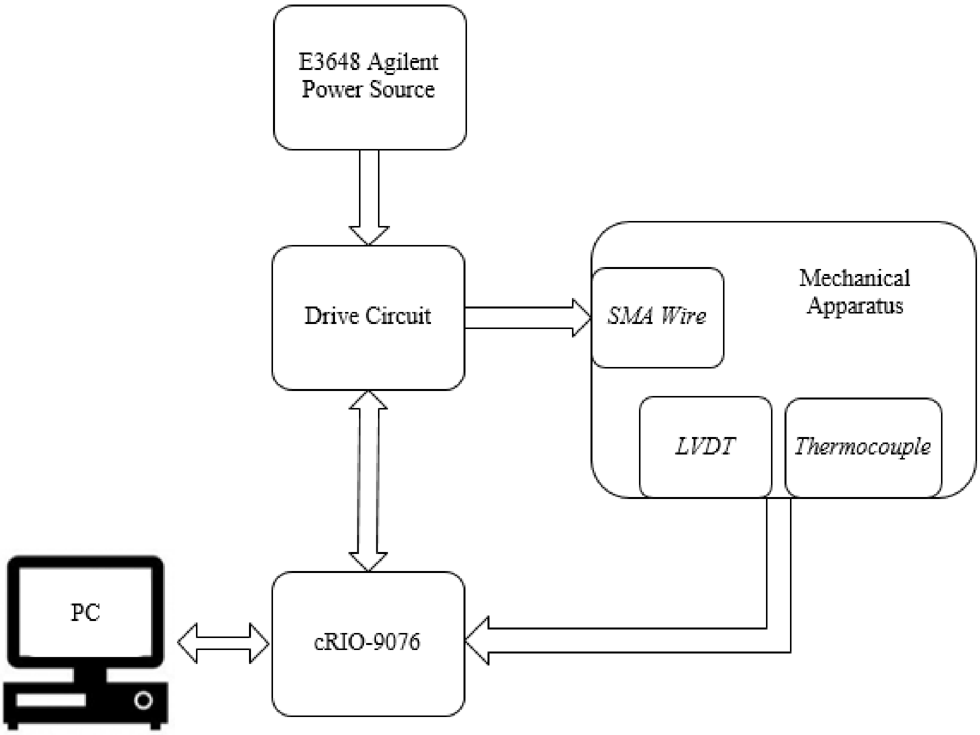

Figure 2. Detailed schematic of the electronic experimental set-up.

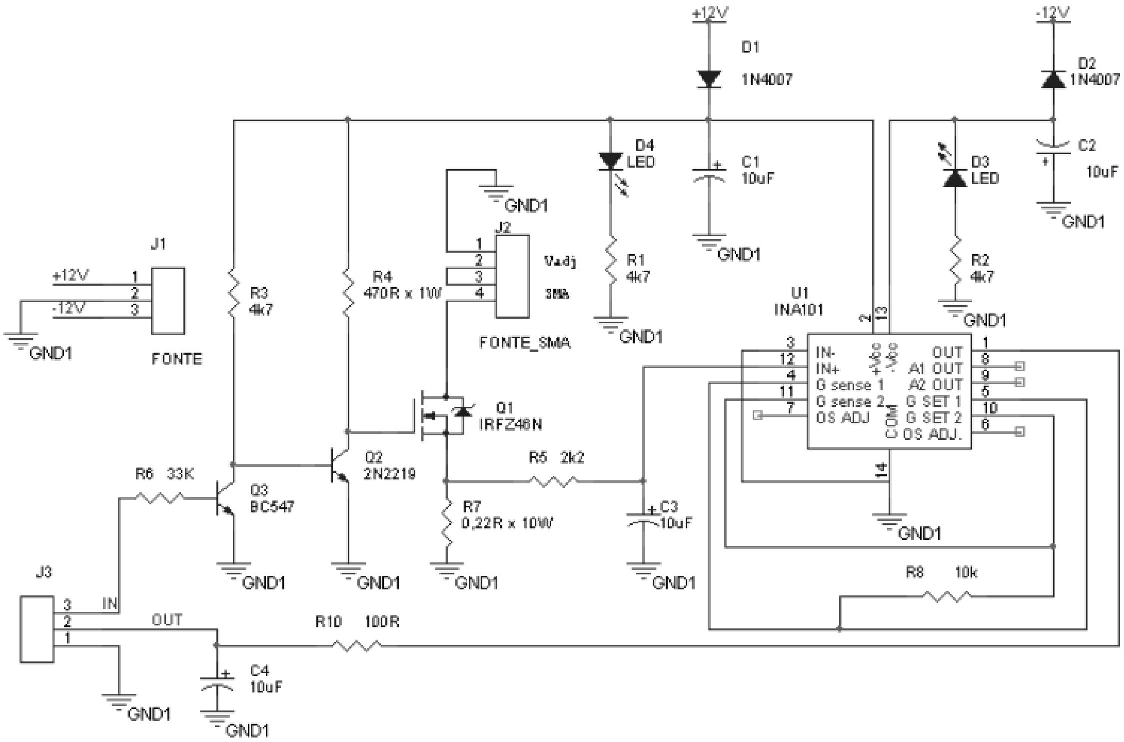

Figure 3. Electrical diagram of the drive circuit.

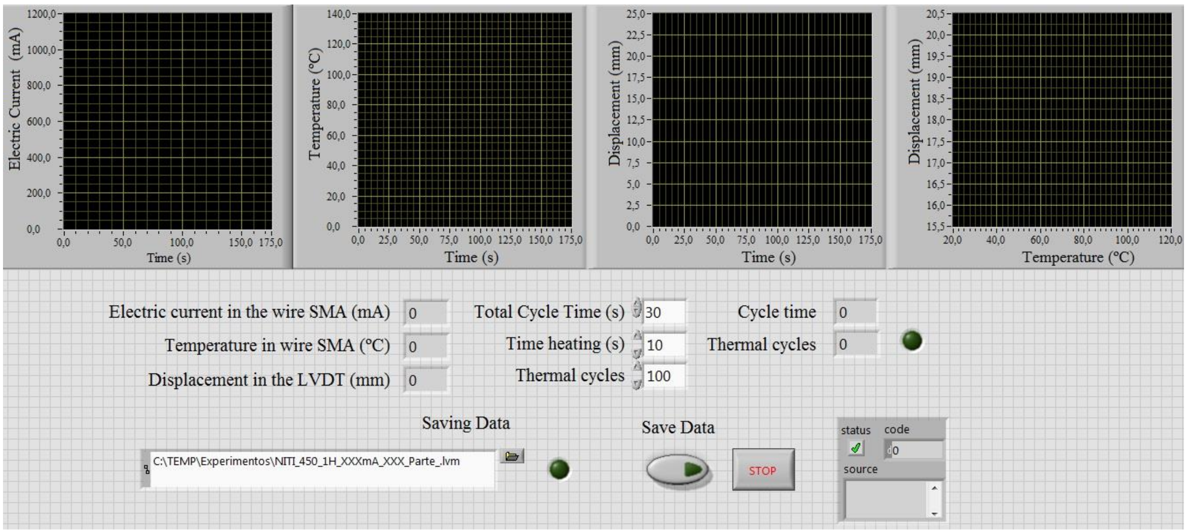

Figure 4. Frontal panel done in the LabVIEW software.

3. RESULTS AND DISCUSSION

The stress-displacement curve for as-quenched Ni-Ti wire is shown in the Fig. 5. The typical properties are: yield stress of 170 MPa, ultimate stress of 1057 MPa and maximum strain up to rupture of 39.4 %.

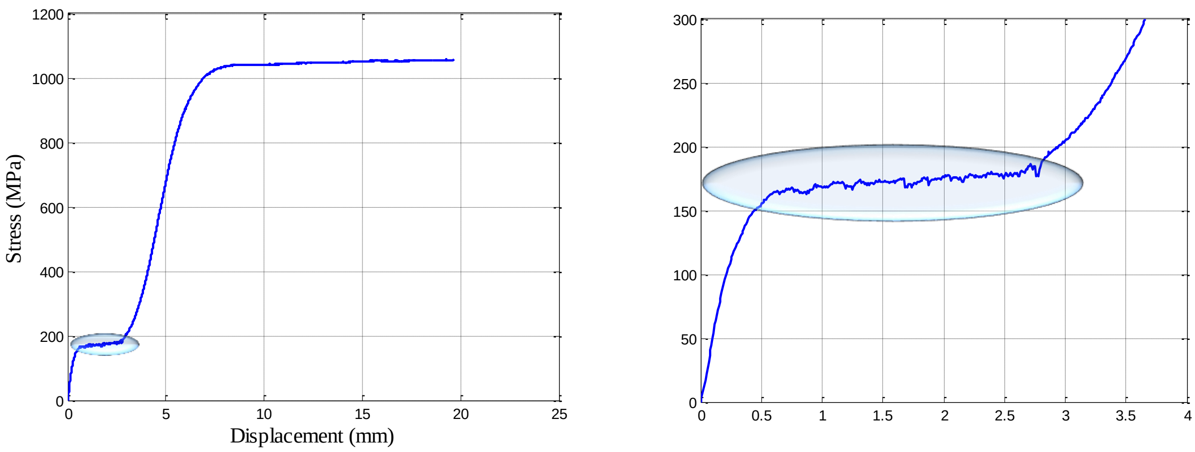

Figure 5. Tensile test for as-quenched Ni-Ti wire.

The DSC scans of the as-quenched Ni-Ti wire are shown in the Fig. 6. The chacteristics transformation temperature are: A_S = 88.4ºC, A_F = 99.7ºC, M_S = 63.7ºC, and M_F = 54.4ºC. This experiments were done to guide the set up of the thermal mechanical experiments that experiments as done as follows:

- Condition 1. Constant stress of 85 MPa and electrical current of 900 mA;
- Condition 2. Constant stress of 17 0MPa and electrical current of 900 mA;
- Condition 3. Constant stress of 85 MPa and electrical current of 750 mA;
- Condition 4. Constant stress of 170 MPa and electrical current of 750 mA.

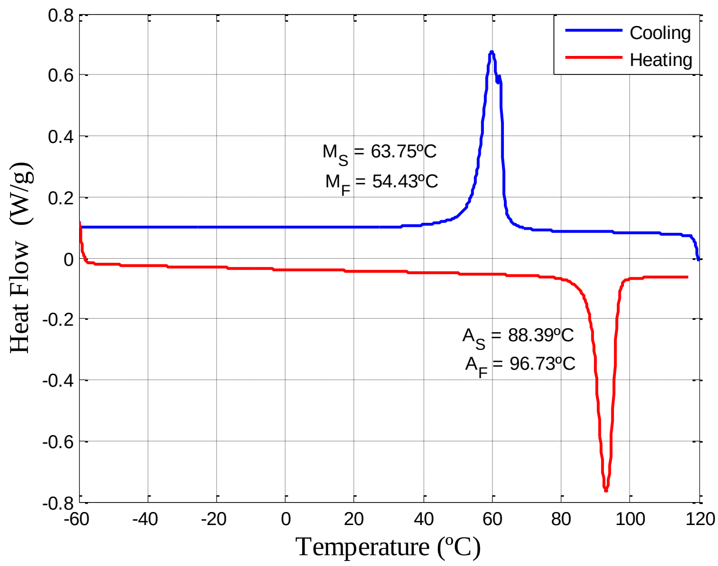

Figure 6. DSC thermogram of the as-quenched Ni-Ti wire.

The Figure 7 and 8 show the displacement versus time curves and its envelop curves for samples in the condition 1 and 2, respectively, In these conditions the wires was submitted to 11.000 thermo-mechanical cycles. The heating was reached by applying an electrical current for 10s while the cooling for 20 s using a square wave of 900 mA. It is import to point out that with both 750 mA and 900 mA, the wire reach a fully austenite transformation on heating.

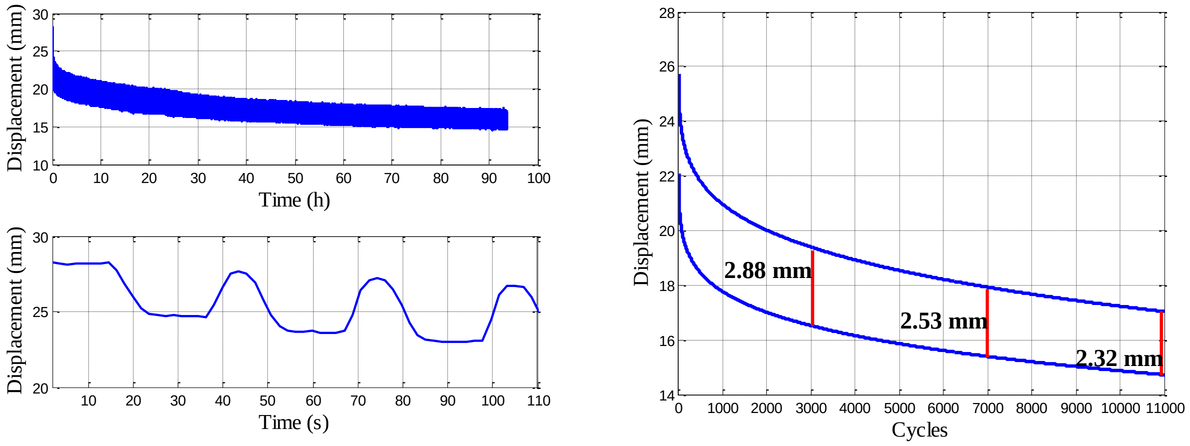

Figure 7. Displacement versus time curves and its corresponding envelope curves for samples submitted to 11.000 cycles (Stress of 85 MPa and electric current of 900 mA).

It can be observed in the Fig. 8 and 9, that independent of the applied load the deformation does not reach a stable plateau during the thermal cycles. In both cases it tends to continually decrease, probably as a result of introduction of defects in the microstructure. Additionally, the total deformation observed on the envelop curves decrease with increasing the load. The fitting tool from the MATLAB allows obtaining the flowing equation for envelop curves:

For condition 1:

$$y_{superior} = -1.602x^{0.2001} + 27.35 \quad (1)$$

$$y_{inferior} = -2.042x^{0.1639} + 24.1 \quad (2)$$

For condition 2:

$$y_{superior} = -0.803x^{0.2274} + 30.64 \quad (3)$$

$$y_{inferior} = -0.6045x^{0.2354} + 27.55 \quad (4)$$

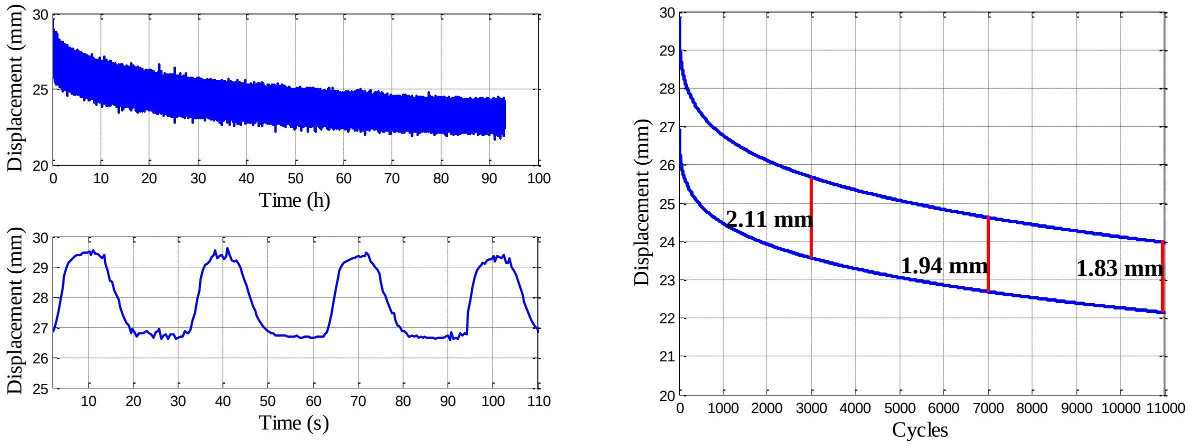

Figure 8. Displacement versus time curves and its corresponding envelope curves for samples submitted to 11.000 cycles (Stress of 170 MPa and electric current of 900 mA).

The Figure 9 and 10 show the experimental curves carried out at 750 mA under 85 and 170 MPa, respectively. In these conditions, the electrical current was applied for 15 s, during the heating and cooling cycles.

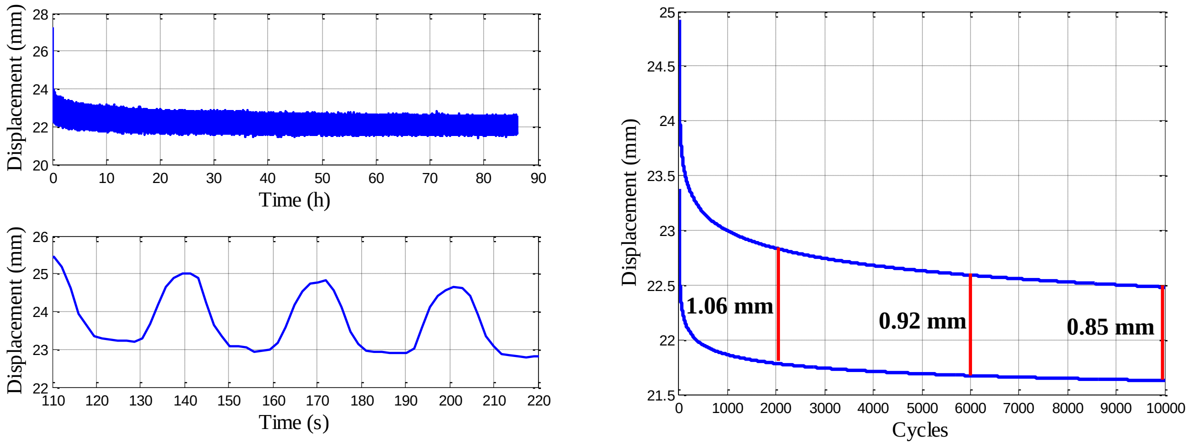

Figure 9. Displacement versus time curves and its corresponding envelope curve for samples submitted to 10.000 cycles (Stress of 85 MPa and electric current of 750 mA).

The result is similar for samples heated at electrical current of 900 mA. That is, in both cases the total deformation is not constant with thermo-mechanical cycling and has the tendency to decrease with time. However, in these later case, that is with smaller electrical current, the slope of the envelope curves are clearly lower indicating that the temperature has as important role on the stabilization of the thermomechanical behavior of the Ni-Ti wire. The equation of the envelope curves are bellow:

For condition 3:

$$y_{superior} = 7.046x^{-0.046229} + 17.88 \quad (5)$$

$$y_{inferior} = 2.313x^{-0.1547} + 21.07 \quad (6)$$

For condition 4:

$$y_{superior} = 7.046x^{-0.046229} + 17.88 \quad (7)$$

$$y_{inferior} = 2.313x^{-0.1547} + 21.07 \quad (8)$$

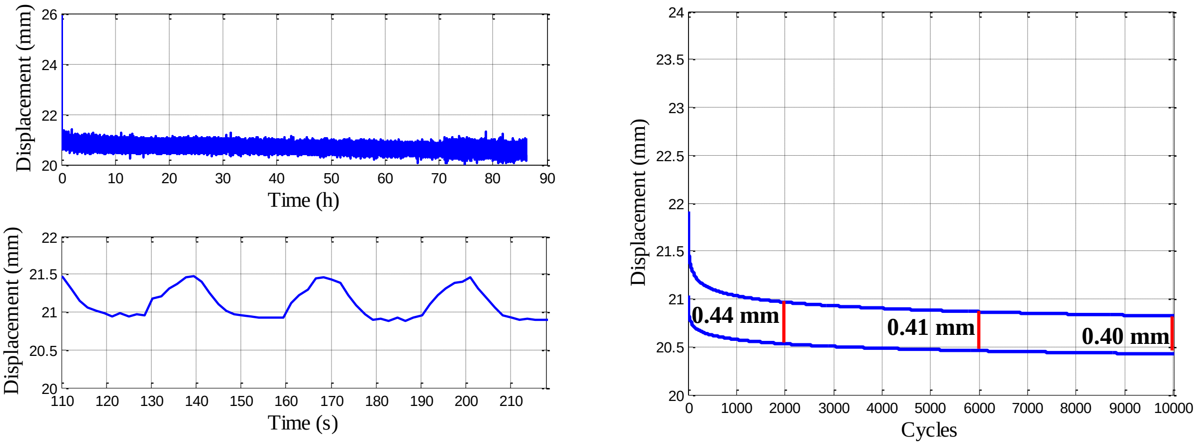

Figure 10. Displacement versus time curves and its corresponding envelope curve for samples submitted to 10.000 cycles (Stress of 170 MPa and electric current of 7500 mA).

4. CONCLUSIONS

In this study the mechanical behavior of Ni-Ti wires were investigated under thermo-mechanical cicles using the Joule heating effect on different conditions of load and temperatures. The main conclusion can be summarized as follow:

1. Irrespective of condition the Ni-Ti wire has shown an unstable behavior when subjected to thermal cycles. The key is to find out the optimal condition to minimize the decreasing of the recoverable deformation, i.e., to stabilize the strain.
2. For samples heated with 750 mA the wire displays a more stable shape recovery.

5. ACKNOWLEDGEMENTS

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