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ELECTRICAL ACTIVATION UNDER CONSTANT LOAD OF Ti-Ni AND Cu-Zn-Al SMA WIRE ACTUATORS

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Abstract: *Electrical actuation cycles in shape memory alloy (SMA) wires working against a dead weight (isotonic actuation) have been performed on different wire actuators. Ti-Ni, Ti-Ni-Cu and Cu-Zn-Al SMA wires were studied by means of an experimental set-up specially designed to perform these electromechanical cycles between 10 and 200 MPa. The obtained electrical current versus strain loops as a function of the applied stresses are used to determine important parameters for these actuators, like transformation currents, current hysteresis, electrical current slopes and shape memory effect (SME) under load. Results concerning the performance of the actuators are discussed on the basis of the particularities of each studied SMA.*

Keywords: *SMA actuators; Smart materials; Electrical activation; Shape memory alloys.*

1. Introduction

At present, the materials most attractive for electromechanical force transduction are piezoceramics, piezopolymers, magnetostrictive materials, and shape memory alloys (Fletcher, 1996). Shape memory alloys (SMA) are one of the active materials more promising for use as artificial muscles in robotics and smart structures (Srinivasan and McFarland, 2001). SMA wires are linear actuators that can contract and elongate as a function of temperature due to a reversible solid state phase transformation. The displacement originated by this thermoelastic martensitic transformation is non-linear and present a temperature hysteresis (Otsuka and Wayman, 1998). If SMA are activated by resistive electrical heating, these materials are naturally considered as electrical actuators. In general, actuator motion is controlled as a function of temperature. However, for thin SMA wires temperature is difficult to measure and must be estimated from the electrical current using the static thermal equilibrium equation for the steady-state (Nascimento *et al*, 2004). For these actuators, experimental determination of displacement versus temperature loops is fundamental for the design of smart structures incorporating them. On the other hand, it can be sometimes important to verify the displacement versus current behavior instead of displacement – temperature.

In this work, Ti-Ni and Cu-Zn-Al SMA wire actuators were studied by means of an experimental set-up specially designed to perform electromechanical cycles between 10 and 200 MPa. The obtained electrical current versus displacement loops as a function of the applied stresses are used to determine important parameters for these actuators, like transformation currents, current hysteresis, electrical current slopes and shape memory effect (SME) under load.

2. Experimental procedure

Table 1 show the several types of SMA wire actuators used in this study. As-received SMA wires can present or not the shape memory effect (SME) phenomenon. For wires supplied in the cold-drawing state, SME is not initially verified and a heat treatment is necessary to release the martensitic transformation, as indicated in Tab. 1.

Table 1 – General data of the SMA wires.

Specimens	Alloy	Diameter (mm)	Supplier	Code or market name	Shape memory effect	Heat treatment
TN1	Ti-Ni	0.20	Dynalloy (USA)	Flexinol^{TM}	yes	------
TN2	Ti-Ni	0.37	AMT Inc. (Switzerland)	------	yes	------
TN3	Ti-Ni	0.29	Memory-Metalle (Germany)	Alloy H	no	350°C/20min
TNC	Ti-Ni-5%Cu	0.29	AMT Inc. (Switzerland)	7326 HT	yes	------
CZA	Cu-Zn-Al	0.50	Tréfimetaux (France)	------	no	650°C/15min water quench

The SMA wire actuators were tested using a platform specially designed for this task, as illustrated in Fig. 1. In this platform, wire sample is loaded in a uniaxial constant tensile stress mode while electrical heating – cooling cycles is performed using an Agilent model E3633A DC power supply. Contraction and elongation of the SMA wire actuator is continuously measured by a Solartron model DC miniature DF5 LVDT displacement sensor. All samples had lengths between 95 and 100mm were tested under constant load (dead weight) corresponding to the stress range 10 – 200MPa. To stabilize shape memory properties, each sample of SMA wires shown in Tab. 1 was trained under 150MPa during 100 cycles. Figure 2 show the contraction displacement by shape memory effect (SME) of the TN2 specimen. For the first cycle, SMA wire is in the low temperature position (LTP) corresponding to zero electrical current (i = 0) and the application of a current pulse (i > 0) leads sample to the high temperature position (HTP) by SME contraction, as indicated in Fig. 2. The electrical current is determined experimentally depending of the type of SMA and its diameter.

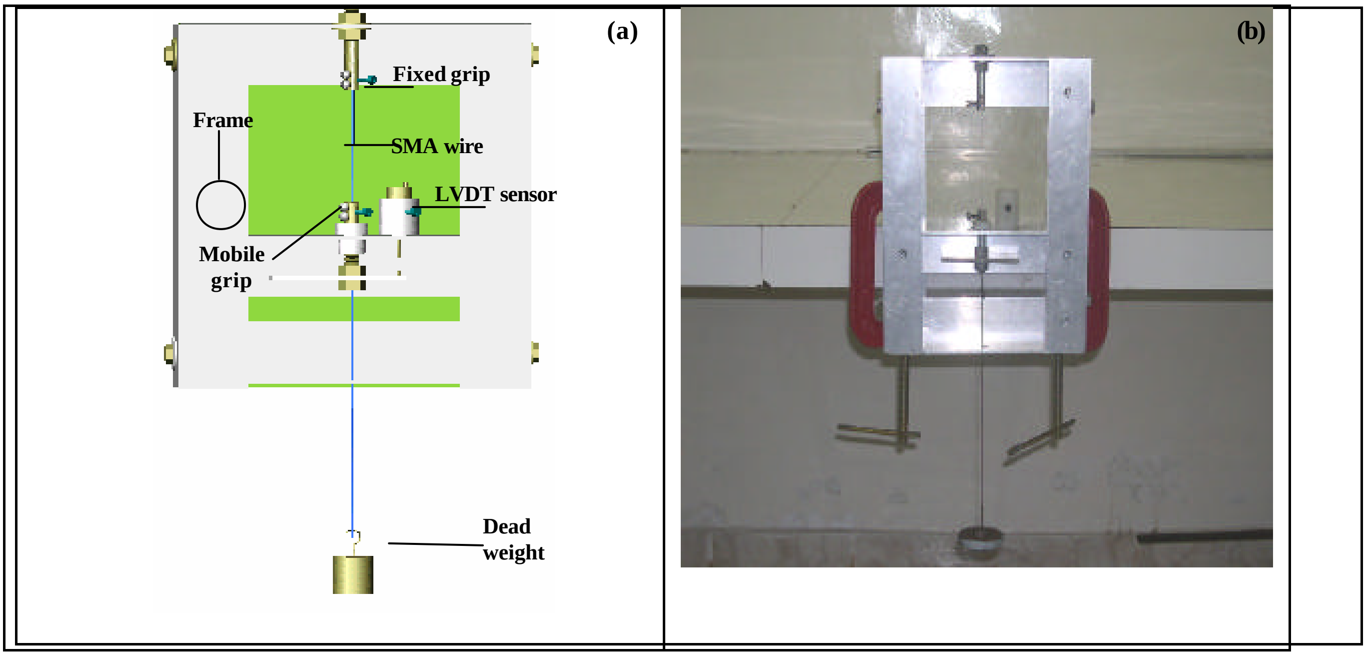

Figure 1 – Experimental test bench. (a) Design. (b) Laboratory construction.

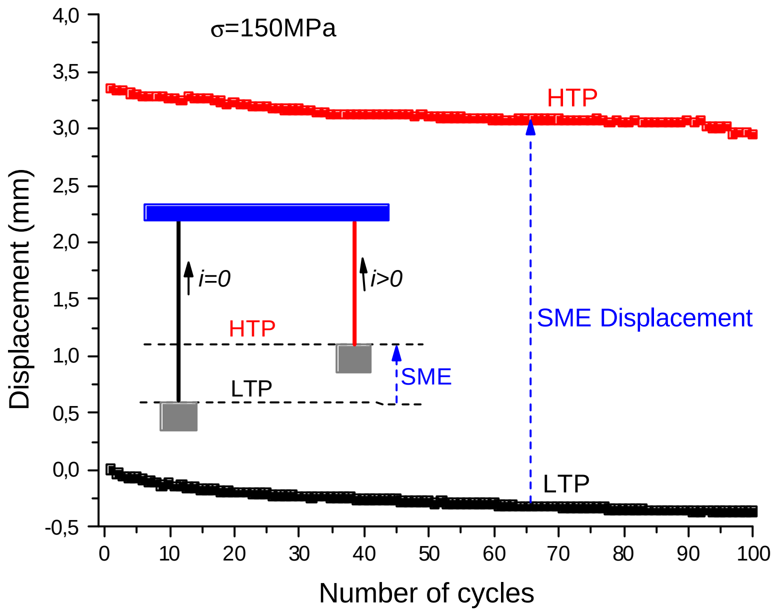

Figure 2 – Training of the SMA wire actuators. TN2 specimen.

3. Results and discussions

Figure 3 show the electromechanical behavior of some SMA wire actuators for three different applied loads. These curves reveal some changes occurring in the current - displacement loops as a function of the applied stress as well as the influence of the phase transformation on the current – tension (electrical resistance) behavior during electrical heating and cooling. Improvement of the SME displacement, increasing of electrical currents and reduction of current hysteresis as a function of applied stresses can be observed in Fig. 3(a) for the TN1 SMA wire actuator. The current – tension relationship verified in Fig. 3(a) show three regions corresponding to martensite phase (region I), phase transformation (region II) and austenite phase (region III). Figures 3(b) and 3(c) confirms similar behaviors for TNC and TN2 SMA wire actuators. However, Fig. 3(d) show that the cooper based SMA wire actuator (CZA) has a poor displacement by SME, which is associated with a limited phase transformation as can be observed from its current – tension behavior. For this specimen, the three characteristic regions shown in Fig. 3(a) and detected in all Ti-Ni SMA wires are not present.

Some important shape memory parameters like transformation currents, current hysteresis, electrical current slopes and shape memory effect under load can be obtained from Fig. 3.

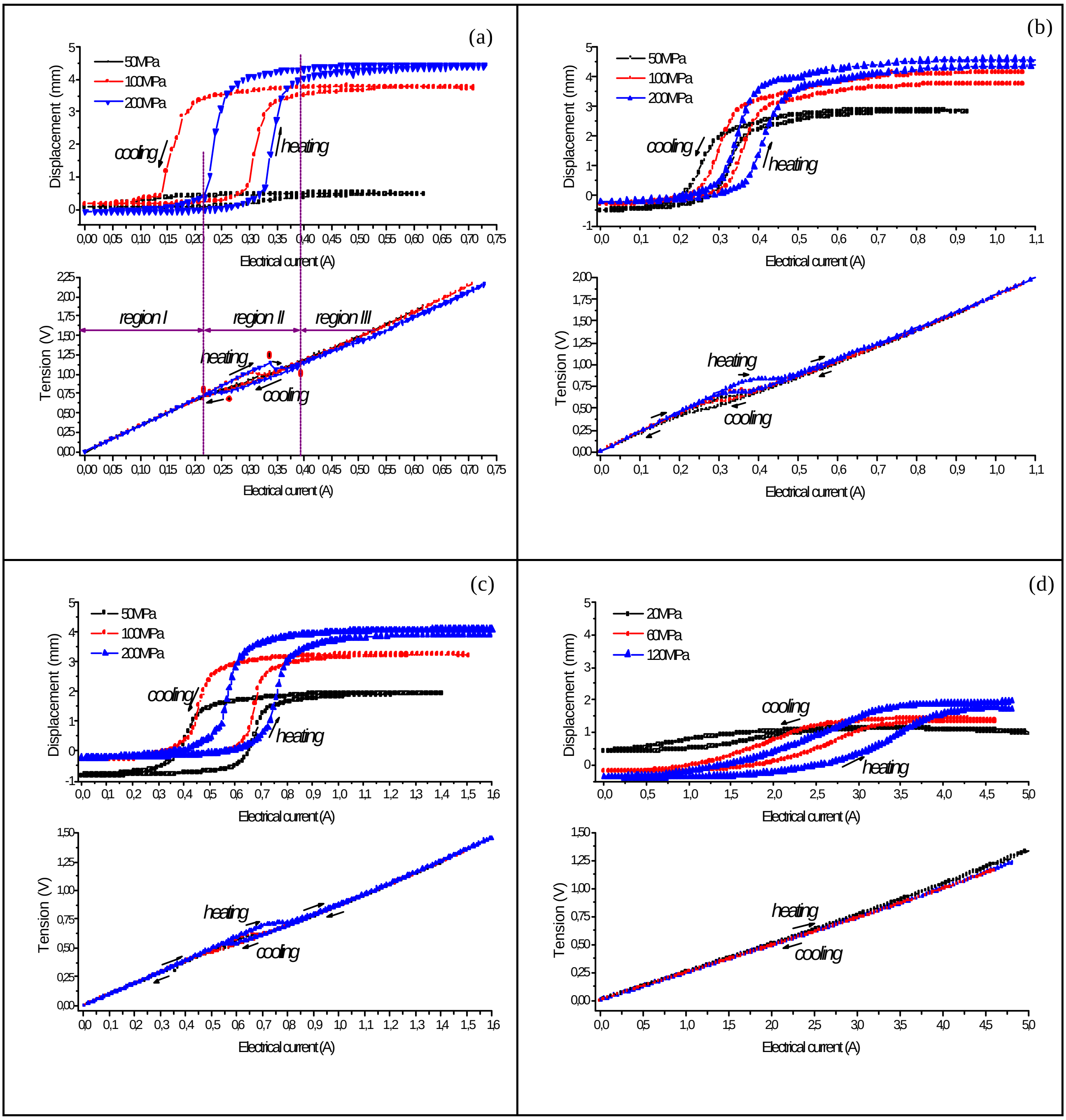

Figure 3 – Electromechanical behavior of some studied SMA wire actuators. (a) TN1. (b) TNC. (c) TN2. (d) CZA.

Figure 4 show the definition of some of these parameters by means of a current – displacement loop associated with a current – tension curve for the TN1 SMA wire under 200MPa. Critical electrical currents, named i_{Ms}, i_{Mf}, i_{As} and i_{Af}, corresponds to the start and finish of austenite to martensite transformation during cooling and to the start and finish of martensite to austenite transformation during heating, as defined in Fig. 4.

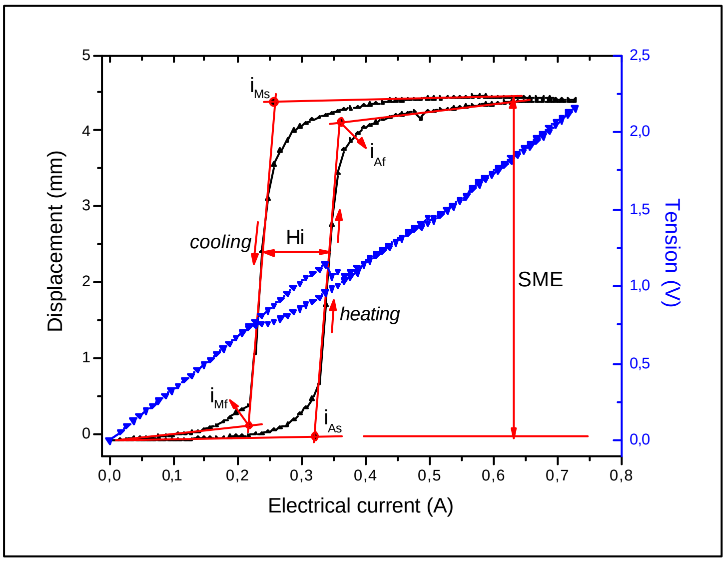

Figure 4 – Main eletromechanical shape memory parameters. TN1 specimen under 200MPa.

Figure 5 show the behavior of these currents as a function of applied stresses for TN1, TNC, TN2 and CZA SMA actuator wires.

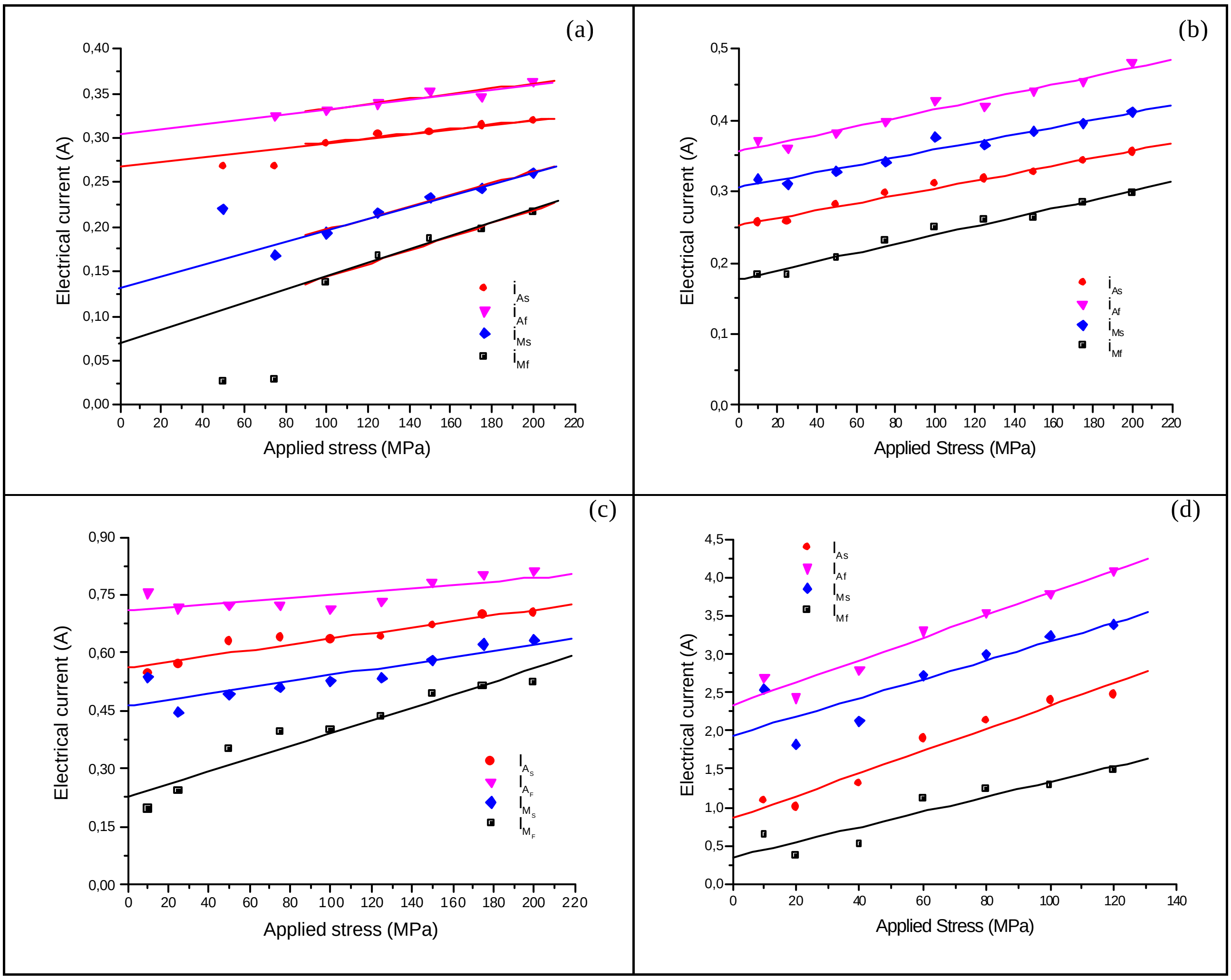

Figure 5 – Linear relationships between transformation currents and applied stresses. (a) TN1. (b) TNC. (c) TN2. (d) CZA.

As expected, a linear relationship between electrical currents and applied stresses is verified, similarly to the results noticed in literature for transformation temperatures (Otsuka and Wayman, 1998). Recently, Wang *et al* (2004) studying electrothermal driving characteristics of Ti-Ni SMA springs have obtained an optimum driving current density between 7.6 and 10.2 A/mm^2 for a good recovery rate by two-way shape memory effect. Activation electrical currents calculated for a current density of 10.2 A/mm^2 leads to the values of 0.32 A, 0.67 A and 1.1 A for TN1, TNC and TN2 specimens, respectively. These currents are sufficient to originate a maximum contraction of the TNC and TN2 SMA wire, but not for the TN1, as can be verified in Figs 3 and 5.

The characteristic slopes for these currents, here named Ci_{Ms}, Ci_{Mf}, Ci_{As} and Ci_{Af}, are determined as defined in Fig. 5 and summarized in Tab. 2. These slopes reveal the linear increase of transformation currents with applied loads.

Table 2 – Characteristic slopes of transformation currents.

Specimen	Ci_{Ms} (mA/MPa)	Ci_{Mf} (mA/MPa)	Ci_{As} (mA/MPa)	Ci_{Af} (mA/MPa)
TN1	0.65	0.75	0.25	0.29
TNC	0.53	0.62	0.52	0.59
TN2	0.79	1.66	0.75	0.43
TN3	0.17	0.26	0.23	0.31
CZA	12.5	10.4	16.4	14.7

The displacement by shape memory effect under load as well as the current hysteresis defined in Fig. 4 is plotted as a function of applied stress in Fig. 6.

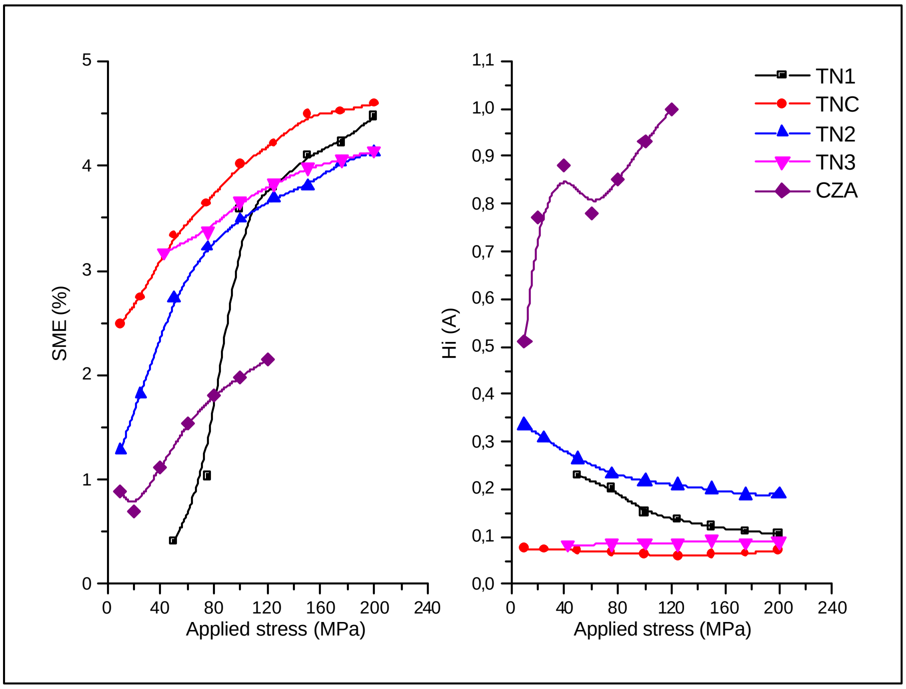

Figure 6 – Shape memory effect and current hysteresis versus applied stress.

Figure 6 allows concludes about the best SMA wire in terms of actuator performance. Despite of cost aspects, maximum SME associated with reduced and nearly constant hysteresis can be considered an optimum operation condition (Huang, 2002). Then, from Figs. 3 and 6, the studied SMA actuators are classified in the following sequence: TNC – TN3 – TN1 – TN2 – CZA. In the studied stress range, TNC specimen demonstrates highest SME associated with a reduced current hysteresis between 10 and 200 MPa while CZA present an opposite behavior.

4. Conclusions

Several SMA wire actuators were studied by electrical activation under constant load aiming to determine some important parameters like transformation currents, current hysteresis, electrical current slopes and stress assisted shape memory effect. These parameters are fundamental for the design of smart systems incorporating these artificial muscles.

As expected, all SMA wire specimens have presented a linear increase of transformation currents as a function of applied loads. Among all tested Ti-Ni wires, Ti-Ni-Cu (TNC) presents a maximum SME associated with reduced and nearly constant current hysteresis between 10 and 200MPa that can be considered optimum operation conditions for these actuators. An opposite behavior was observed in the unique studied Cu-Zn-Al SMA (CZA) that presents a poor SME and an increasing current hysteresis as a function of applied stress.

5. Acknowledgments

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