THERMOELASTIC CHARACTERIZATION OF Cu-Zn-Al SHAPE MEMORY ALLOY SPRING ACTUATORS

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Abstract: *This paper present a thermomechanical study of spring actuators made from shape memory alloy wires that can work as actuator and/or as sensor. These habilities are due to a difusionless martensitic transformation that occurs by a cooperative atomic rearrange mechanism. In this work, helical spring actuators were manufactured from Cu-Zn-Al shape memory wires. The springs were submitted to constant tensile loads and thermal cycles. This procedure allows to determine thermoelastic properties of the shape memory springs. Thermomechanical properties were analised for 50 thermal cycles in the temperature range from 20 to 130^{o}C. Results of variations in critical transformation temperatures, thermoelastic strain and thermal histeresys are discussed based on introduction of defects and martensitic transformation theories.*

Keywords: *Shape memory effect, Helical spring actuators, Heat treatment and Training process*

1. INTRODUCTION

Shape memory alloys (SMA) have been used as actuators in various domains of knowledge due to recovery force, thermoelastic deformation and possibility to recover an initial shape when heated through the martensitic transformation (Otsuka et al., 1998). In recent years, many researches have been developed to innovative engineering design using the actuation provided by the shape memory materials (Naganuma et al, 1998; Laurentis et al, 1998). These types of actuators are developed for special cases, as for example: reduction of cost and space, force application, simulation of the human movement (robotic) and surgery (biomedicine) (Machado et al, 2003; Zhang et al, 1996).

Helical spring SMA actuators are very interesting for several technological applications. The reversible thermoelastic strain obtained with SMA coil springs is larger in comparison with the one verified in SMA wires. The last can reach about 5% of recovery strain in relation to its length. Therefore, a SMA spring can be deformed of 1 to 3 times its initial length. After heating, it goes back to the initial position. This fact is due to volume of material utilized in the fabrication of spring (comparing wire and spring of equal lengths) and different state of stress that act in spring.

In most research on this subject, SMA springs are submitted to a constant compression load. In the present work, an specific apparatus was developed to realize thermal cycling in SMA springs under constant tensile load. Temperature and displacement sensors, data acquisition system and a computer allow the storage of the strain versus temperature, critical transformation temperatures versus number cycles and shear stress versus transformation temperature curves. Thermoelastic properties (critical temperatures, thermal histeresys, recovery strain, austenite and martensite elastic constant of the spring) and evolutions of histeresys loops are determined with this apparatus. The aim of this paper is to analyze the variations of properties and loops during thermomecanical “training process” (or education process). This process is applied in SMA to obtain an adequate geometric form for each phase (cool = martensitic phase and heat = austenitic phase). After training, a spontaneous shape change of the SMA is produced, in absence of mechanical loading, when it is heated or cooled (shape memorization) (De Araújo et al, 2001). There is several ways to realize training process, for example: imposition of a load in the martensitic sample, after release of stress, heat and repeat cycle. During cycling, important micromechanics occurs in the SMA, such as rearrangement of dislocations, reorientation of martensite variants, development of internal stresses, elimination of vacancies, reconfiguration of the degree of order in austenite phase after quench and others (Gonzalez et al, 2004).

This work present result of training process for four different loads in springs with 4.0 mm external diameter produced from Cu-Zn-Al SMA wire. The training procedure consists in the application of a constant tensile load on the

SMA spring followed by the realization of 50 thermal cycles in the temperature range from 25ºC to 150ºC. Results of thermoelastic properties and modification of histeresys loops as a function of the number of cycles are discussed and news possibilities for technological applications of this configuration (under traction) of the SMA springs are presented.

2. EXPERIMENTAL PROCEDURE

A commercial SMA wire with a nominal composition of Cu-25,3%Zn-4,0%Al (% wt) and 0.9 mm in diameter was used in this study. The wire was mechanically constrained on a cylindrical mandrel (screw) having a convenient geometric shape to originate the designed spring. The shape memory effect is only verified in the spring after a betatisation heat treatment of the ensemble (screw and wire). This treatment consist of a homogenisation at 850ºC for 10 minutes followed by quench in water at 100ºC, remaining in this temperature for 15 minutes. This annealing is used to eliminate excess of vacancies and to stabilise the configurational order of the austenitic phase. The main dimensions of the SMA spring obtained by this procedure are: external diameter of 4.0 mm, internal diameter of 3.1 mm, length of 5.0 mm and four active coils.

Critical transformation temperatures of the wire were measured using a differential scanning calorimeter (DSC) Mettler 823 model. For this test, three thermal cycles were realised between 0 and 150 ºC at 10 ºC/min. Figure 1 present a special apparatus developed to determinate thermoelastic properties of the SMA springs under constant tensile stress. The load is applied on the sample through a pulley system. A programmable silicon oil bath is used to realize thermal cycles between -20 and 200ºC. A linear variable displacement transducer (LVDT) and a thermocouple measure the strain and the temperature, respectively. The control and data acquisition system are connected to a computer.

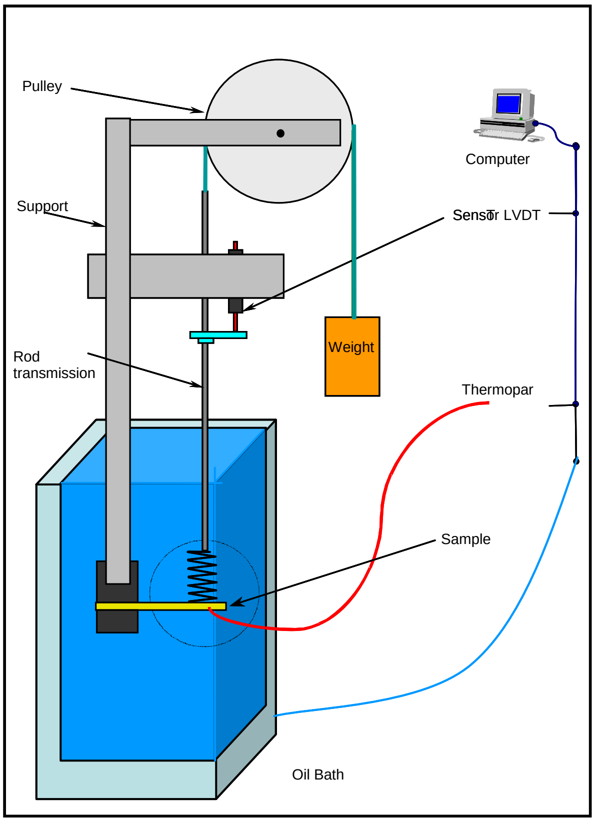


Figure 1. Schematic representation of the thermomechanical apparatus.

The main equations utilized for the spring design are (De Araújo et al, 2001; Otsuka et al, 1998):

$$\tau = Kw \cdot \frac{8FD}{\pi d^3} = Kw \cdot \frac{8FC}{\pi d^2} \tag{1}$$

The equation 2 is used to calculate the elastic constants of the SMA springs.

$$k = \frac{F}{y} \tag{2}$$

the main parameters of these equations are:

τ - shear stress, D - external diameter, d – diameter of wire, F - load applied, C - spring index (C = D/d), *Kw* - Wahl factor (equation 3), y – spring deflection (equation 4).

$$K_W = \frac{4C-1}{4C-4} + \frac{0{,}615}{C} \tag{3}$$

$$y = \frac{8FD^3n}{d^4G} = \frac{8FC^3n}{dG} \tag{4}$$

In this work, samples were individually tested under constant tensile load originating shear stresses of 27, 44, 55, 70, 83 and 111 MPa. For each applied load, the SMA spring was thermal cycled for 50 times between 20 and 150 ºC at 10 ºC/min during heating and 3 ºC/min for cooling. Critical transformation temperatures, thermal hysteresis ($H_t = A_{50}-M_{50}$), thermoelastic strain (ε_t = deformation at A_s temperature – recovered deformation at A_f temperature) are directly obtained from the strain-temperature curves.

3. RESULTS

3.1. Calorimetric characterization (without load)

Samples of the SMA wire used in this study were heat treated in the same way of the springs (betatisation) and them analyzed by DSC. The aim was to determine the critical transformation temperatures without applied load. Figure 2 shows the calorimetric curves for three thermal cycles and table 1 present critical temperatures for each cycle. In the first heat cycle, inverse transformation temperatures (austenitic phase - A_S and A_f) are larger temperatures (≈ 10^0C) in comparison with the two cycles in sequence. This effect occurs due to a martensitic stabilization process that can pinning the martensite-austenite interface by saturation of quenched-in vacancies and other mechanisms (Gonzalez et al, 2004; Dunne et al, 2004). In the subsequent cycles, the critical temperatures and enthalpies become constant and reproductive (Perkins et al, 1983).

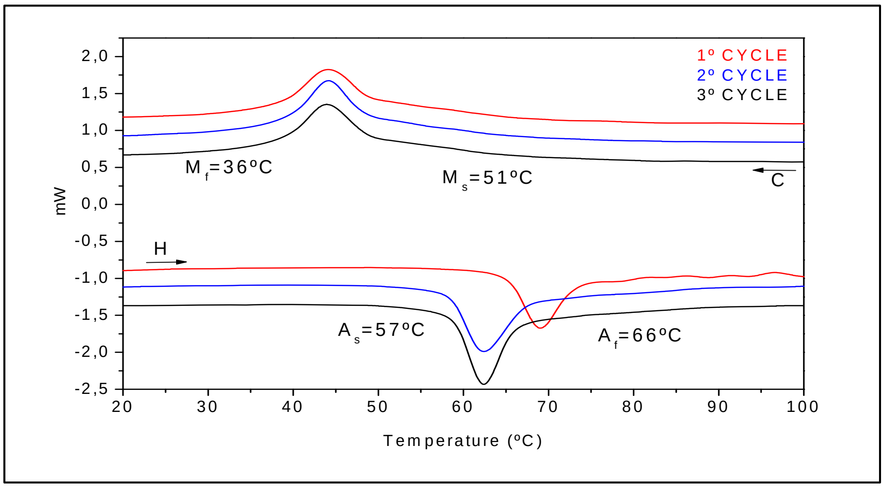


Figure 2. Calorimetric curves for a sample of the Cu-Zn-Al SMA wire used to making the helical springs.

Table 1. Critical temperatures and thermal hysteresis obtained from DSC for the Cu-Zn-Al SMA wire.

Temperature/H_t	**Cycles**		
	1°	**2°**	**3°**
A_s	70°C	63°C	57°C
A_f	78°C	73°C	66°C
M_s	63°C	63°C	51°C
M_f	48°C	49°C	36°C
H_t	19°C	12°C	19°C

3.2. Thermomechanical characterization

Figure 3 show a strain-temperature curve obtained from tests performed with the apparatus described in figure 1. The main parameters that can be determined are: critical transformation temperatures under stress (A_S, A_F, M_S and M_F that are determined using the tangent method (Gonzalez, 2002), thermoelastic strain (ε_t = difference between the deflexions at low and high temperatures), thermal hysteresis (H_t), elastic constants of the martensitic and austenitic phase and vertical displacement of the hysteresis loops (X). This displacement of loops is attributed to the accumulation of true plastic deformation, but others factors also may contribute, as for example: martensitic stabilisation process, martensite needles reorientation process and others.

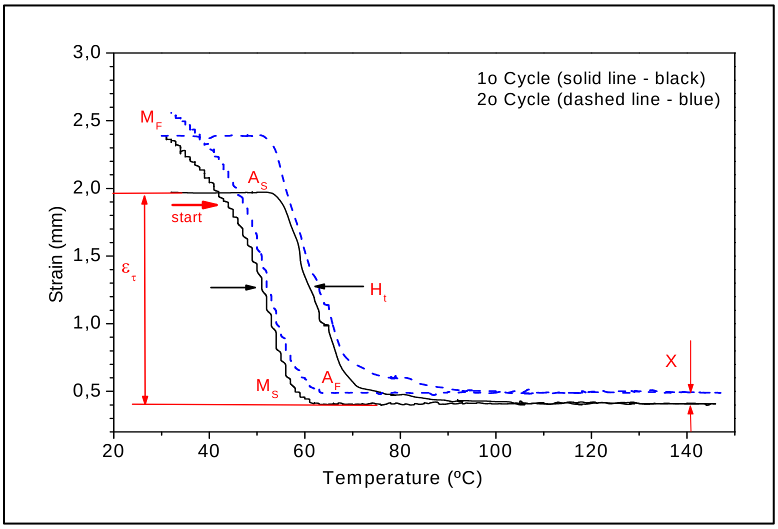


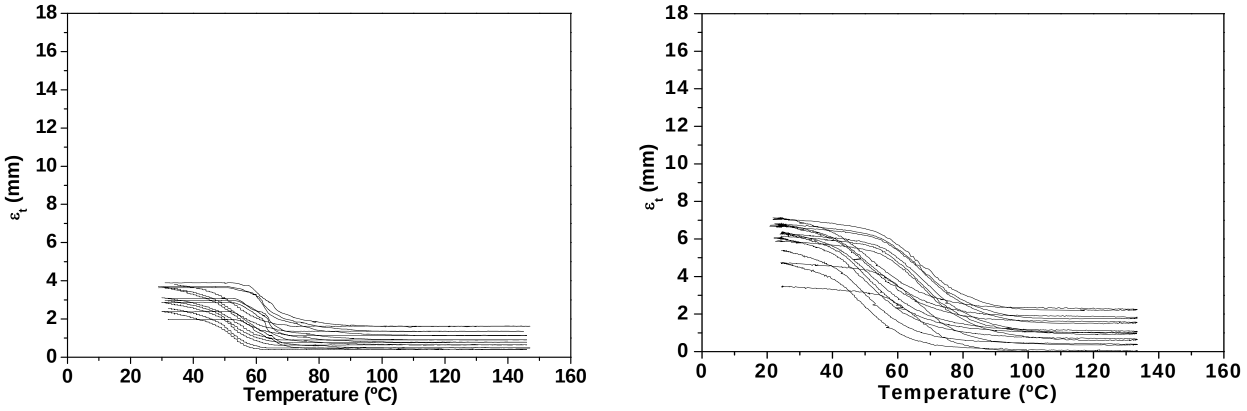
Figure 3. Representative strain versus temperature curves obtained from a test of thermal cycling under constant load in the SMA springs.

Figure 4 show the strain – temperature loops for the cycles 1, 5, 10, 20, 30, 40 and 50 obtained for springs loaded with shear stresses of 27 MPa, 44 MPa, 55 MPa, 70 MPa, 83 MPa and 111 MPa. Weight was applied in SMA spring at temperature below of M_F where an initial deformation (deflection) is observed. After, the temperature control system is started for heating of spring and when the temperature reach A_S, the shape recovery process is initiated and progress until the A_F temperature. During cooling, the thermoelastic deformation process begin when the temperature reach M_S and is finalised at the M_F temperature, corresponding to an expansion of the SMA spring. The deformation produced and the evolution of hysteresis loops depend of applied load. Main contribution for the strain observed is due the thermoelastic martensite variant reorientation process. In this process, the martensite variants favored by the shear stress grow or increase while the others shrink or decrease. An excess of load can produce a true plastic deformation in the SMA spring and reduce the recovery shape.

These factors have a great influence on the behaviour of hysteresis loops during training, mainly in the twenty initial thermal cycles. After, the thermomechanical behaviour becomes almost stable. The displacement of loops in the vertical direction is also reduced. During thermal cycles, the hysteresis loops are modified taking to variations in critical transformation temperatures, thermal hysteresis, thermoelastic strains and slope of curves (for high loads). This inclination observed in the strain – temperature curves is due to the fact that more energy is required to realize the transformation. Thus, the thermal amplitudes, defined as the difference between A_F and A_S for heating and the difference between M_S and M_F for cooling, becomes larger in comparison to small loads.

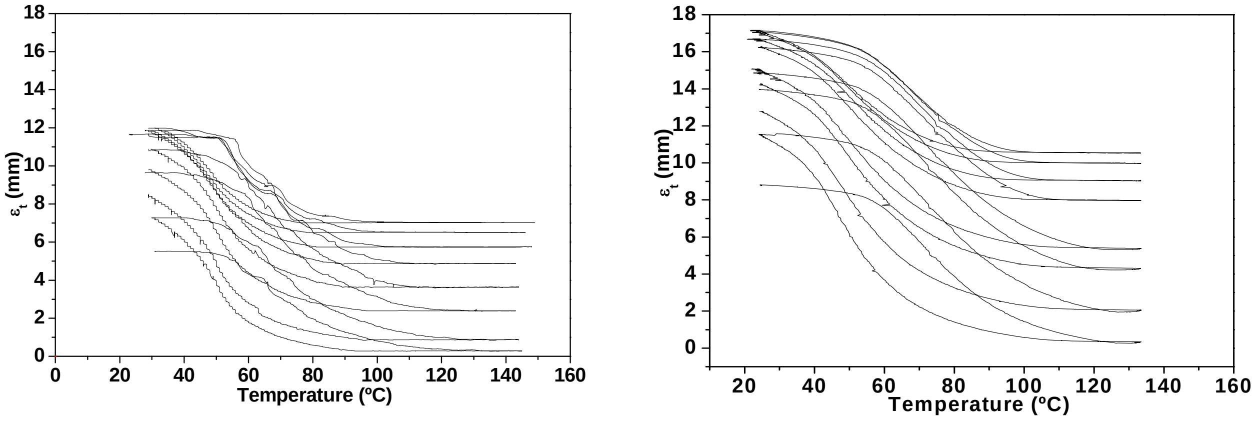
During thermal cycles, martensite variants reorientation and reconfiguration of pre-existent dislocations are active processes in the first cycles. The reconfiguration of dislocations promotes internal stress fields that facilitate the martensitic transformation. Critical temperatures and thermal hysteresis tend to decrease during the 20 first cycles. After these cycles, the new configuration of dislocations stabilizes the values of thermoelastic properties (Gonzalez et al, 2004).

Table 2 summarizes the deformation obtained in initial loading and the thermoelastic strain (ε_t) for each cycle. From equation 4 and using the shear modulus for martensitic phase (8,7GPa), the deflection obtained in initial loading is very close to the one measured for 27, 44 and 55 MPa. For the other applied loads, the values are not close. Probably for loads larger than 55 MPa, a true plastic deformation processes occurs. In the test for 27 MPa, the recovery strain increase after each cycle. For the following load (42MPa), the strain reaches a maximum and later decrease progressively. With this load the best result for recovery strain (4.6 mm) is obtained. For other loads, the strain reach larger maximum values but decrease progressively during thermal cycles. The dislocations induced for the excess load and accumulated during thermal cycles originate a mechanical hardening of the SMA spring. This hardening process stabilizes the martensite variants and degradate the thermoelastic properties.



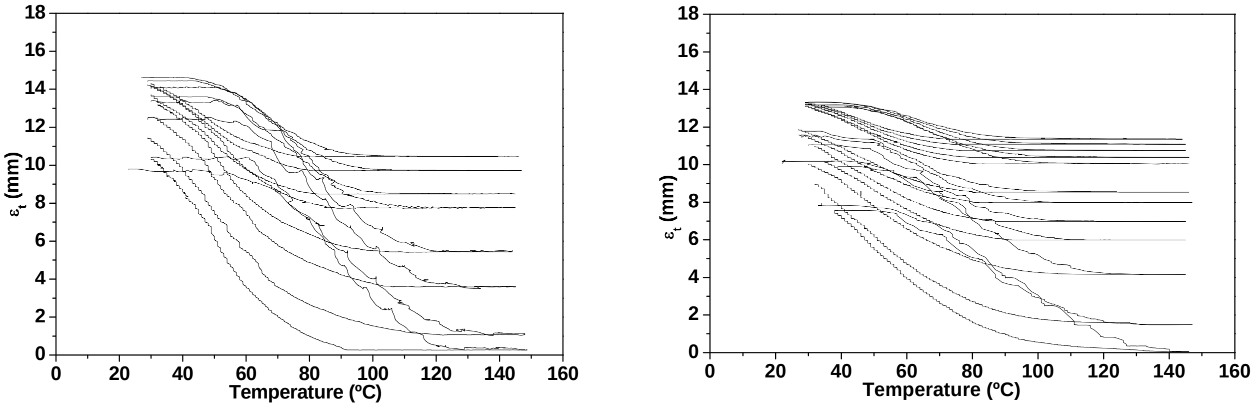
a) Test for constant shear stress of 27 MPa.

b) Test for constant shear stress of 44 MPa.



c) Test for constant shear stress of 55 MPa.

d) Test for constant shear stress of 83 MPa



e) Test for constant shear stress of 83 MPa.

f) Test for constant shear stress of 111 MPa.

Figure 4. Strain-temperature loops for thermal cycling of the Cu-Zn-Al SMA springs. Tests for constant shear stress of a) 27 MPa, b) 44 MPa, c) 55 MPa, d) 70 MPa e) 83 MPa and f) 111 MPa. The loops represented are 1, 2, 5, 10, 20, 30, 40 e 50 for each load applied.

Table 2. Thermoelastic deformation for each shear stress applied and various number of cycles.

Thermoelastic Deformation (mm)									
Cycles	loading	1	5	10	15	20	30	40	50
Spring - 4,0 mm									
27 MPa	0,6	2,0	2,9	3,0	3,1	3,1	3,6	3,7	3,9
44 MPa	1,7	5,2	7,2	7,2	7,2	7,0	6,2	5,0	4,6
55 MPa	4,2	3,4	5,1	5,2	5,1	5,2	5,0	4,9	4,7
70 MPa	4,6	9,4	8,8	7,9	7,0	6,6	5,1	4,6	4,2
83 MPa	5,0	8,4	9,6	9,4	8,7	8,1	7,5	7,0	6,5
111 MPa	8,2	6,6	6,1	4,0	4,0	3,4	3,0	2,4	2,0

Figure 5 show the evolution of M_S temperatures during the fifty cycles. It was observed a progressive augmentation of M_S for springs tested with shear stress of 44 MPa and 55 MPa. For tests performed with larger loads, the tendency for the M_S evolution is of decrease. Other important observation is that the M_S temperature increase almost lineally with loading presenting a slope of 1.85 ºC/MPa (figure 6). For stress above 83 MPa, this relationship is not more valid. Reduction of M_S and deviation of the linearity in slope (in ºC/MPa) for larger loads reinforce the hypothesis that martensite transformation is hindered by the increase in the dislocation density and consequent hardening mechanism (Oliveira, 2007).

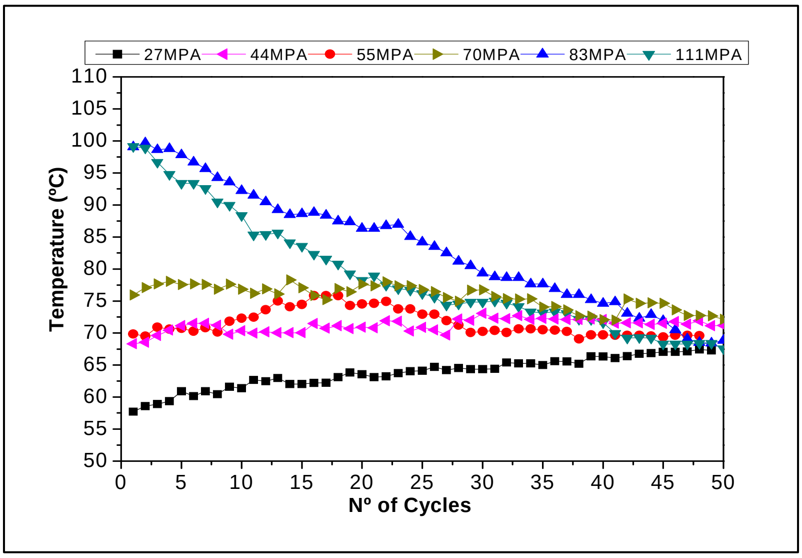


Figure 5. M_S temperature versus number of thermal cycles for each applied shear stress in Cu-Zn-Al SMA springs.

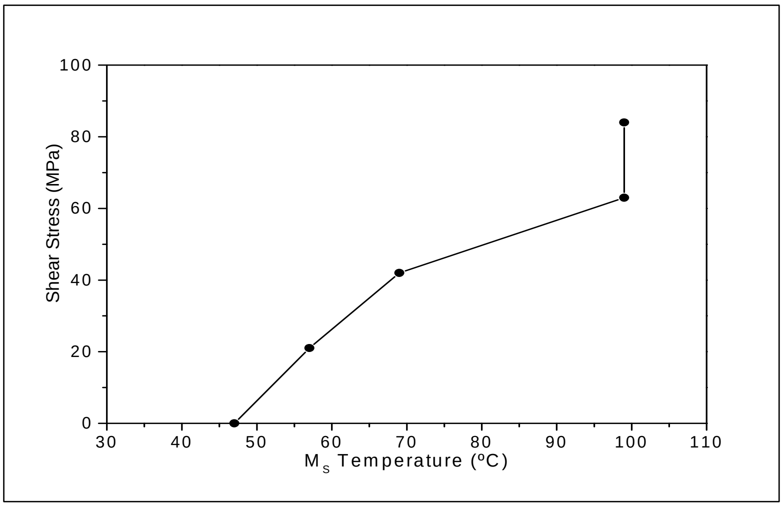


Figure 6. M_s temperature versus shear stress for the Cu-Zn-Al SMA springs.

4. CONCLUSIONS

In this work, Cu-Zn-Al shape memory alloys springs were studied under constant tensile load and some thermomechanical properties were determined. During training process, the thermoelastic parameters of SMA springs are modified for the initial cycles. This evolution is due to the conjunction of various phenomena directly related amongst themselves, as martensite variants reorientation process, creation of internal stress fields, reconfiguration of dislocations, accumulation of true plastic deformation and martensitic stabilisation processes. It was observed that after about 20 cycles the thermoelastic properties of the Cu-Zn-Al SMA springs tend to stabilize. For applied loads lower than 55 MPa, the M_S temperature increases during thermal cycling. In the case of loads higher than 55 MPa an inverse behavior was observed and M_S decrease progressively. In the first case, the applied load changes the thermoelastic properties slowly during cycling. In the second case, large loads induce excessive increase of the dislocation density causing stabilization of the shape memory effect. For SMA springs employed in this study (4,0 mm in external diameter and 4 coils), the ideal training condition was obtained for a shear stress of 55 MPa which present a thermoelastic strain of 4.7 mm.

5. ACKNOWLEDGEMENTS

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