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STUDY OF THE DAMPING BEHAVIOR OF A Cu-Al-Ni SHAPE MEMORY ALLOY USING A DYNAMIC MECHANICAL ANALYZER

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Abstract. *Shape Memory Alloys (SMA), besides exhibiting the Shape Memory Effect and Superelasticity, may present large damping capacity. This fact, together with the engineering necessity to promote energy dissipation in various mechanical systems, has popularized these SMA for use as damping elements. The Cu-Al-Ni SMA arouses great interest because are a less expensive alternative to Ni-Ti and more interesting in many applications. In order to study stiffness and damping characteristics of these copper based SMA, this work aims the investigation of a Cu-Al-Ni SMA manufactured by Trefimetaux Inc (France). For this, it was used a Q800 Dynamic Mechanical Analyzer (DMA) from TA Instruments. For the SMA dynamic characterization, sweep tests were performed in a single cantilever mode varying the following parameters: frequency (1, 2, 5 and 10 Hz), heating rate (2, 5, 10, 15 and 20 °C/min) and tip deflection amplitude (2, 5, 10, 15 and 20 μm). Results corresponding to the optimized parameters to evaluate damping capacity and storage modulus (proportional to stiffness) of these SMA are compared to those found in the literature for Ni-Ti SMA, using the same test conditions.*

Keywords*: Shape Memory Alloys, Cu-Al-Ni SMA, Damping, DMA.*

1. INTRODUCTION

Shape memory alloys (SMA) are advanced metallic materials that present thermoelastic martensitc transformation and functional properties such as shape memory effect (SME) and superelasticity (SE). Many studies have shown that SMA also have a high level of mechanical damping in the low temperature phase (martensite) and during martensitic transformation, being effective in applications for energy dissipation (Chang, 2011). Some of the main SMA are those based on copper (Cu-Zn-Al, Cu–Al–Ni, Cu–Al-Mn,...), as well as that based on Ni-Ti (Ni-Ti-Cu, Ni-Ti-Fe, Ni-Ti-Nb,...) (Otsuka & Wayman, 1998; de Araújo *et al.*, 2009).

The Cu-Al-Ni SMA arouses great interest as an attractive alternative for the Ni-Ti or Cu-Zn-Al SMA. The advantages are the lower cost in relation to the Ni-Ti and thermoelastic properties more attractive when compared to the ones of Cu-Zn-Al SMA. The Ni-Ti are possible of employing only in a temperature range between –200 ^{o}C and 110 ^{o}C while the Cu-Zn-Al SMA are used between –180 ^{o}C and 100 ^{o}C. These latter SMA, whether used at temperatures above 100 ^{o}C, are susceptible to thermal degradation and loss of functional properties.

However, Cu-Al-Ni SMA, due to its lowest costs and higher transformation temperatures, reaching 200 ºC, becomes a potential alternative for developing many industrial applications (Otsuka & Wayman, 1998).

The static thermomechanical properties of Cu-Al-Ni SMA were studied by many researchers (Otsuka & Wayman, 1998). However, in view of potential industrial applications of these SMA, the dynamic aspect of thermomechanical properties became a point of greatest interest (Graczykowski *et al.,* 2010). The high damping capacity presented by SMA is related to the movement of interfaces of twinned martensitic variants. The damping behavior also depends directly of external variables, as the heating and cooling rate, beyond the frequency and amplitude of imposed oscillation. Some internal variables also influence the damping capacity of the SMA, such as grain size, density of martensitic variants and structural defects. For all SMA, it is expected a high damping capacity and low elasticity modulus in the low temperature phase, corresponding to the martensitic state. During the phase transformation from austenite to martensite and its reverse transformation, it is verified the presence of a peak in the damping capacity, accompanied by an increase or decrease of the elastic modulus or stiffness (Cai *et al.*, 2005). The austenitic phase has an elasticity modulus higher than the one of martensite and reduced damping capacity in relation to that phase.

One of the techniques employed to study the dynamic behavior of SMA is the Dynamic Mechanical Analysis (DMA). In this analysis a sinusoidal load is applied on the specimen and the corresponding displacement (strain) is continuously measured to obtain the damping capacity represented by the tangent of the phase angle (*Tan* δ) between the two parameters. The storage modulus, representing the elastic component of the associated complex modulus of the material, can also be measured. In the dynamic test, load is imposed repeatedly so that the elastic modulus can be obtained each time, while stress is applied and strain is measured. Scanning through a range of temperature or frequency allow to determine the elasticity modulus as a function of these parameters (Menard, 1999).

In this context, despite considering the existence of some knowledge on the high damping capacity of SMA, few data are found in the literature regarding the damping capacity of Cu-Al-Ni SMA. In this work, the stiffness and damping characteristics of a Cu-Al-Ni SMA, manufactured by Tréfimétaux Inc (France), was studied using a commercial DMA analyzer from TA Instruments (model Q800).

2. EXPERIMENTAL PROCEDURES

In this study, a Cu-Al-Ni SMA manufactured by Tréfimétaux Inc. (France) was used. The material was received in the form of strips with rectangular cross section of 3.2 x 1 mm. Figure (1) shown a photographic aspect of these Cu-Al-Ni SMA strips.

Figure 1. Cu-Al-Ni SMA strips processed by Tréfimétaux Inc. (France).

The Cu-Al-Ni SMA strip was initially cut for a length of about 30 mm using a precision cutter machine with diamond cutting disc. Specimen was heat treated at a temperature of 850 °C for 20 minutes with subsequent quenching in water at room temperature (~27 °C). Before DMA analysis, the Cu-Al-Ni SMA strip was first subjected to successive heating-cooling cycles, between 0 °C and 100 °C, to ensure thermal stability of the material. This stabilization process is illustrated in Fig. (2).

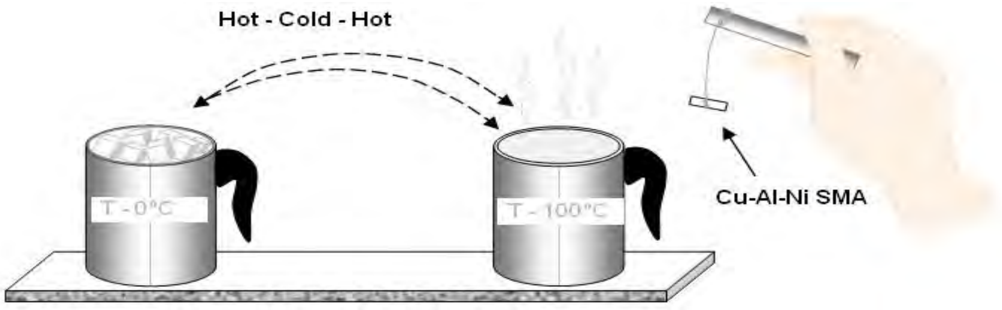

Figure 2. Schematic illustration of the procedure used for thermal stabilization.

For a first thermal analysis of the material, it was used a differential scanning calorimeter (DSC) from TA Instruments (Model Q20). Thus, transformation temperatures of the Cu-Al-Ni SMA, before and after thermal stabilization, were determined. The sample was tested in the temperature range of 20 °C to 250 °C, starting first from the highest to the lowest temperature (cooling) with subsequent reversion (heating). The cooling and heating rate used was 5 °C/min. The temperatures of the beginning and end of phase transformations during cooling and heating were obtained by the tangent method applied at the DSC peaks.

The dynamic tests were performed using a DMA analyzer from TA Instruments (model Q800). According to Silva (2009), in the case of Ni-Ti SMA the standard parameters for the realization of DMA testing in a single cantilever mode are: frequency of 1 Hz, heating rate of 5 °C/min and amplitude of tip deflection of 5 μm. In order to verify the influence of the variation of these parameters on the stiffness and damping properties of the studied Cu-Al-

Ni SMA, the following values were selected for this study: frequencies of 1, 2, 5 and 10 Hz, heating rates of 2, 5, 10, 15 and 20 °C/min and amplitude of tip deflection of 2, 5, 10, 15 and 20 µm. The dimensions of the specimen used in the DMA were effective length of 17.5 mm, 3.2 mm width and 1 mm in thickness.

3. RESULTS AND DISCUSSIONS

Transformation temperatures of the commercial Cu-Al-Ni SMA, before and after thermal stabilization, were determined from the DSC curves as shown in Figs. (3) and (4).

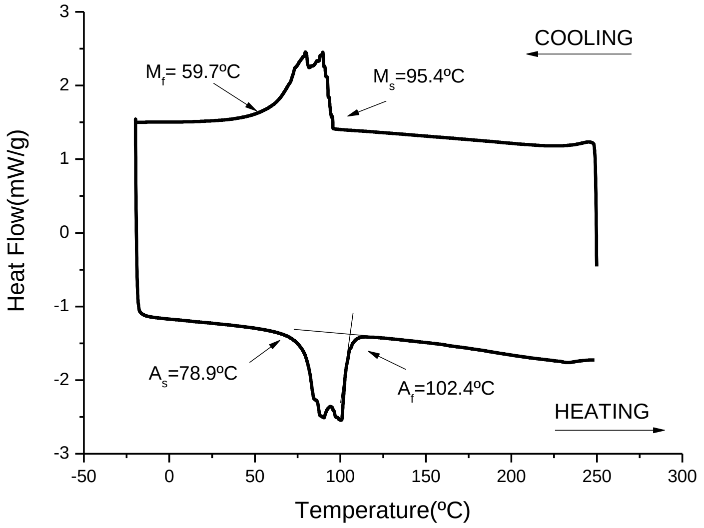

Figure 3. DSC curve of the Cu-Al-Ni SMA before thermal stabilization.

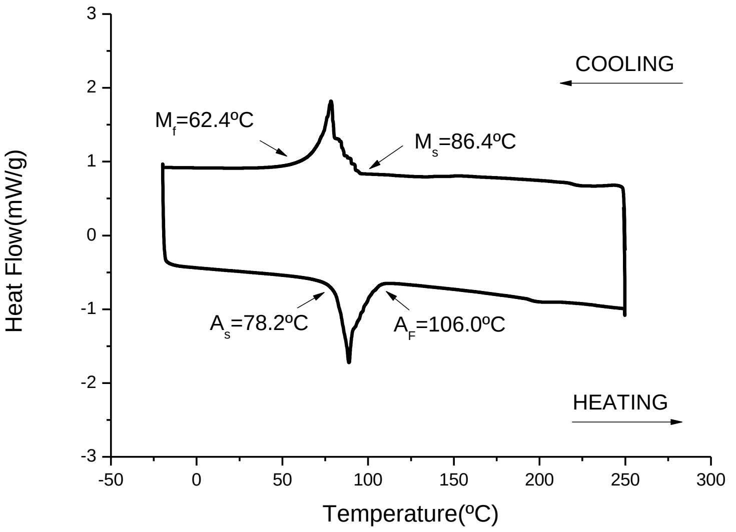

Figure 4. DSC curve of the Cu-Al-Ni SMA after thermal stabilization.

From the analysis of the DSC curve of the Cu-Al-Ni SMA without thermal stabilization, it was determined all phase transformation temperatures: M_s = 95.4 °C, M_f = 59.7 °C, A_s = 78.9 °C and A_f = 102.4 °C. Thus, this SMA presents a thermal hysteresis relatively reduced, of approximately 10 °C.

Figure (4) shows the effect of stabilizing on the DSC peaks and transformation temperatures of the Cu-Al-Ni SMA. It can be verified that the peaks becomes better defined after thermal stabilization with small changes in transformation temperatures.

To verify the influence of DMA test parameters on the damping capacity of the commercial Cu-Al-Ni SMA, the first parameter analyzed was the excitation frequency. Figure (5) shows the influence of this parameter on the damping capacity (Tan δ) for tests with tip deflection amplitude of 5μm and a heating rate of 5 °C/min. It was observed a typical behavior of SMA starting from the martensitic state in response to increasing temperature in DMA analysis. The characteristic DMA curve may be divided into three distinct regions: a first level of damping corresponding to the martensite phase (between 30 °C and 70 °C), a damping peak quite pronounced during the phase transformation (between 70 °C and 130 °C), and a second level of damping with lower values than the first one, corresponding the austenite phase (temperatures higher than 130 °C).

According to the characteristic response of the damping capacity (Tan δ) as a function of temperature shown in Fig. (5), it is observed that higher damping peaks during phase transformation occur for lower values of frequency. Increasing frequencies tend to inhibit the Tan δ peak, reducing the damping capacity of the Cu-Al-Ni SMA. Thus, the frequency of 1 Hz or 2 Hz can be considered optimal to evaluate the damping behavior of the studied SMA.

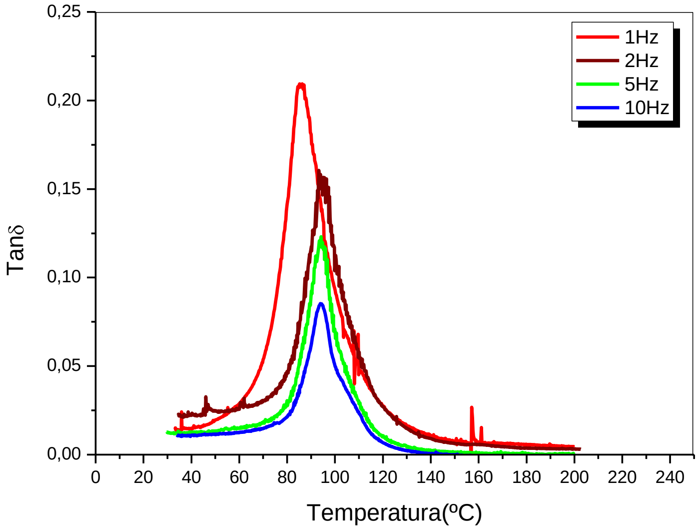

Figure 5. Behavior of damping capacity with frequency variation (1 to 10 Hz).

In relation to damping capacity by varying the heating rate, Fig. (6) shows the DMA results for a excitation frequency of 1 Hz, tip deflection amplitude of 5 μm and heating rate ranging from 2 to 20 °C/min. It is noted that the increase in the heating rate changes the damping peak position to highest temperatures, but not affect the damping capacity in the martensitic phase (Tan δ for temperatures between 30 °C and 70 °C). Then, heating rates above 10 °C/min leads to damping peaks with noisier signals. According to Chang & Wu (2008), the values of Tan δ peaks for the Ni-Ti SMA decreases when the heating rate is reduced. This same behavior was observed in this work for the Cu-Al-Ni SMA.

Vilar (2010) has also found that the heating rate is the parameter of most relevance to evaluate the phase transformation temperatures of a Ni-Ti SMA ribbon derived from DMA characteristic curves in tensile mode. This occurs due to the presence of a temperature gradient in the SMA specimen related to considerable mass and thermal conductivity of the clamps. Thus, to ensure that the SMA specimen is at the temperature indicated by the thermocouple of the DMA analyzer, it is important to use the lowest heating rate possible. In view of this fact, regarding Fig. (6) it was found that a heating rate of 5 °C/min leads to relatively rapid tests with representative damping curves.

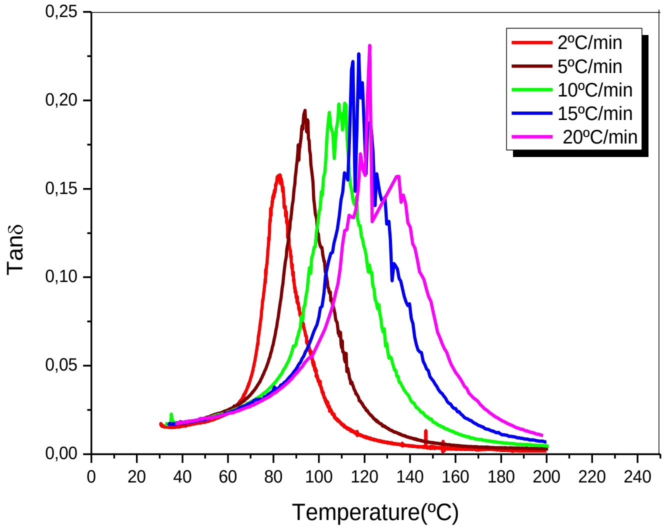

Figure 6. Behavior of damping capacity with variation of heating rate (2 to 20 °C/min).

It was also verified the effect of the oscillation amplitude (tip deflection at the end of the strip specimen) in the DMA tests, which were carried out with excitation frequency of 1 Hz and heating rate of 5 °C/min. Tip deflections used at the end of the cantilever beam sample ranged from 2 to 20 μm. Figure (7) show the obtained damping capacity as a function of temperature for this case. It can be observed that low amplitude leads to a response signal with more high noise in the peak, which can provide uncertain peak damping values, as can be seen for the amplitude curve corresponding to 2 μm. However, for this case, it was observed that the damping capacity in the martensitic phase (Tan δ for temperatures between 30 °C and 70 °C) increases with increasing tip deflection amplitude. For amplitudes greater than or equal to 10 μm, the response of the Cu-Al-Ni SMA remains stable.

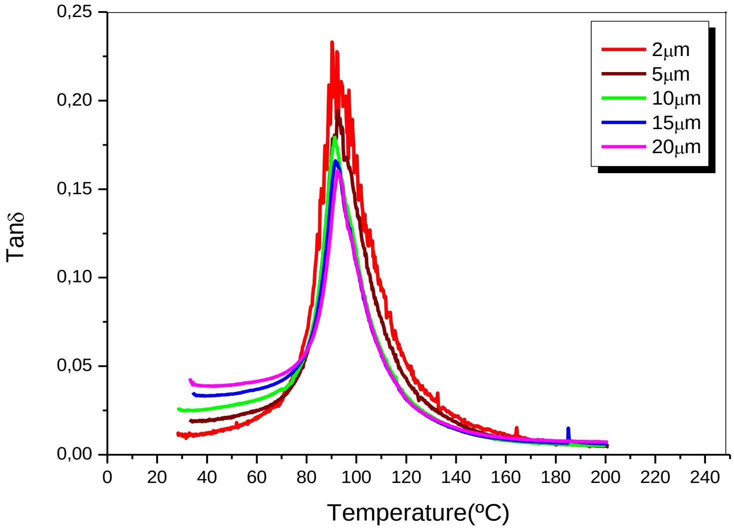

Figure 7. Behavior of damping capacity with variation of tip deflection amplitude (2 to 20 μm).

Figure (8) show the characteristic curves that correlate the storage modulus (E) and damping (Tan δ) with temperature for optimized parameters, defined as 1 Hz, 5 °C/min and 10 μm. It can be observed that the value of E, corresponding to the elasticity modulus of the material, practically did not change significantly between the martensite and austenite phases, except during the phase transformation, when there is an inverted peak of E. This behavior inversely proportional to the Tan δ behavior indicates that the studied Cu-Al-Ni SMA presents small variation of stiffness between the martensite (30 °C) and austenite (180 °C) phases. This behavior was opposed to the one verified by Silva (2009) with a NiTi SMA, also because in the phase transformation region a reduction of about 37 % in elasticity modulus (peak value of E at about 90 °C) compared to the martensite phase at 30 °C was observed for the Cu-Al-Ni SMA. This result can be relevant when this SMA is considered for dynamic applications, especially those whose purpose is to remove a mechanical resonance condition by varying the stiffness of the system with temperature variation.

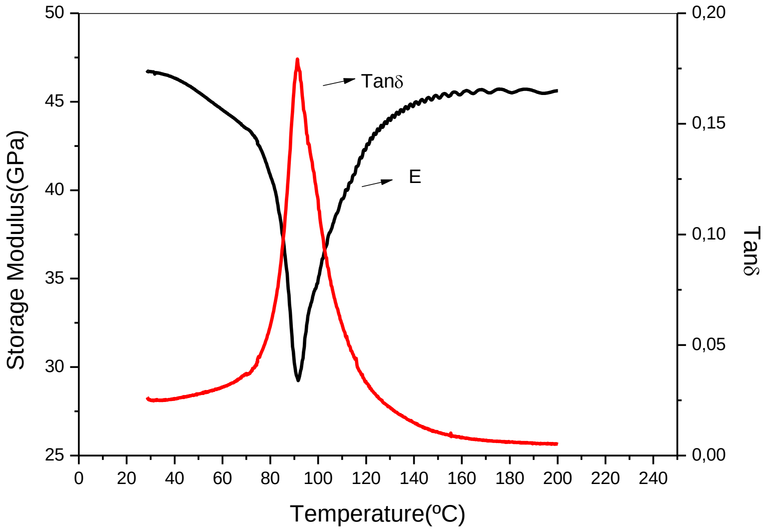

Figure 8. Behavior of the storage modulus (E) and Tan δ as a function of temperature for the optimum DMA parameters.

It is important to notice that Graczykowski et al (2010) and Silva (2009) found maximum Tan δ values of approximately 0.1 for a frequency of 1 Hz in Cu-Al-Ni and Ni-Ti SMA, respectively. On the other hand, verifying all results for Tan δ of this work, in the range of 0.15 to 0.2, it can be confirmed the better damping behavior of the studied Cu-Al-Ni SMA.

4. CONCLUSION

In this study, the damping and stiffness characteristics of a commercial Cu-Al-Ni SMA were determined using a Dynamic Mechanical Analyzer (DMA).

Based on the obtained results it can be concluded that the optimum parameters for the evaluation of the damping capacity in Cu-Al-Ni SMA with commercial DMA analyzers correspond to frequency of 1 Hz, oscillation amplitude of 10 µm and maximum heating rate of 5 °C/min.

An anomalous behavior corresponding to a high loss of stiffness (about 37% of reduction in elasticity modulus) during heating from the martensite state, followed by an increase that allows recover the initial stiffness, was observed and need further studies.

5. ACKNOWLEDGEMENTS

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