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Effect of stress on damping capacity of a shape memory alloy CuZnAl

N. CIMPOEŞU*, S. STANCIU, M. MAYER[a], I. IONIŢĂ, R. HANU CIMPOEŞU
Faculty of Materials Science and Engineering, the "Gh. Asachi" Technical University from Iaşi, Bd. D. Mangeron 61A, 700050 Iaşi, Romania
[a]*Netzsch GerätebauGmbH, Wittelsbacherstrasse 42, Selb /Bavaria 95100 Germany*

A copper based shape memory alloy was obtained by classical melting method. Chemical analyze beside copper, zinc and aluminum reveal small amounts of other chemical elements like iron, lead or nickel that can improve the damping capacity of shape memory alloy. Starting from chemical composition the material was analyzed in deformed and tensioned state by microstructure (SEM), dilatometry (DIL) or calorimetry (DSC) and mechanical-dynamic (DMA) point of view. Results present a nice internal friction peak, in both cases, in transformation temperatures domain with possible practical applications.

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1. Introduction

Damping materials has many applications in all domains connected to amortizations, energy dissipation or even structures rehabilitation. Discovering metallic materials with damping properties improve all the resistance properties of the materials all ready in use for amortization like polymers. High damping capacity has been one of the most important properties of materials used in engineering structures where undesirable noise and vibration are to be passively attenuated. Among the prevalent high damping metallic materials, shape memory alloys (SMAs) could be one of the most promising candidates due to their high damping capacity arising from the reversible martensitic phase transition (MT) and the stress induced reorientation of martensite variants [1,2].

Shape memory alloys are special materials, characterized by two important properties: shape memory effect and super elasticity, but in the last decade is analyzed a new unexploited property, damping capacity, with many applications in civil construction field. It is generally accepted that micro-structural defects should play a dominant role in the damping response of materials [3–6]. From this fundamental concept, a variety of high damping metals and alloys have been developed. From the applications interest, the investigations about the influence factors on damping capacity are of importance. Nowadays, the effects of the temperature changing rate, the frequency and the strain amplitude on the damping capacity have been systematically investigated [7,8].

The SMA energy dissipation devices have been seen in the forms of braces for framed structures [9], dampers for cable-stayed bridges or simply supported bridges, connection elements for columns and retrofitting devices for historic buildings. Experiments or simulations or both have been carried out to explore the potentials of the SMA-based energy dissipation devices in passive structure control. That research focused on three aspects: modeling for dynamic response of the structures with SMA devices, experimentally verifying the feasibility of the SMA devices and optimizing the SMA devices' design in terms of vibration suppression using experimental and numerical methods.

Several different scale prototypes of the devices were designed, implemented and tested. They showed that the proposed devices have characteristics of great versatility, simplicity of functioning mechanism, self-centering capability, high stiffness for small displacements and good energy dissipation capability.

2. Experimental procedure

To obtain the alloy was used a laboratory furnace with graphite crucible using copper, zinc and aluminum high purity materials with reduce percentage of iron, lead and nickel. Chemical composition was determined through spark spectrometry analysis using Foundry Master equipment and EDAX analysis as well. Microstructures, deformed and tensioned states of material, was obtained with a scanning electron microscope (SEM) II LMH by Vega Tescan brand using a secondary electrons (SE) detector.

To investigate the behavior of a material during heating with respect for his physical dimension we use a dilatometer equipment type DIL 402, the measuring system employs two high resolution inductive displacement transducers; with its design using low-expansion invar and broad thermostatic control for highest accuracy, reproducibility and long term stability, it is capable of application temperatures up to 1873 K, the horizontal instrument construction offers specific

advantages, especially for the dual sample arrangement: homogeneous heating of both samples, simple sample insertion, safety during sample decomposition or melting, and effective protection of the measuring system by gas flow. Sample is on cylindrical form with 25.620 mm diameter with perfect parallel ends for a temperature range between 305 and 873 K domain of temperature complete for a nice characterization by the physical dimensions change with temperature.

The DMA – dynamic mechanical analyzer 242 C operates in the broad temperature range of -170 to 600°C. The low-temperature range is achieved with the proven, low-consumption CC 200 L liquid nitrogen cooling system. The minimal temperature gradient over a sample length of up to 60 mm in the bending mode is unique. An intelligent purge gas system provides for a defined sample atmosphere and protects the measurement electronics from any gases evolving from the sample as well. Frequencies from 0.01 to 100 Hz can be selected and combined with defined stress of up to 16 N and deformation amplitudes of between 0.1 and 240 μm. [10]. Tests was realize in conditions of $Cu_{54.9}Zn_{26.5}Al_{6.44}$ shape memory alloy mechanically prepared with dimensions 20x7,95x0,55 mm and as parameters heaving heating regime 0,5 to 0,5 K, at work frequency 1 Hz and 303 to 573 K range temperature. The material is in melting shape and a water quenched state obtains with a thermal treatment at 800 °C.

The phase angle δ is the phase difference between the dynamic stress and the dynamic strain in a viscoelastic material subjected to a sinusoidal oscillation. The phase angle is expressed in radians (rad). The loss factor tan δ is the ratio of loss modulus to storage modulus. It is a measure of the energy lost, expressed in terms of the recoverable energy, and represents mechanical damping or internal friction in a viscoelastic system. The loss factor tan δ is expressed as a dimensionless number. A high tan δ value is indicative of a material that has a high, anelastic strain component, while a low value indicates one that is more elastic [12].

3. Experimental results

Chemical composition of shape memory brasses is choose function of Ms wanted value between limits: 62-72% Cu, 14-30% Zn, 4-8% Al. Temperatures M_S inferiors are obtain at compositions of 25-30% Zn, 4% Al, and the superiors at concentrations 14-19% Zn, 8% Al. Critical points M_S and A_S can be calculated with some empirical relations [10]:

$M_S = 2212 – 66.9\ [1,355(\%at.\ Al) + (\%at\ .Zn)]$ °C

$A_S = 2177 – 58.79\ (\%Zn) – 149.64\ (\%Al)$ °C

As can be observe, the aluminum concentration influence powerful critical transformation points. We have to mention that aside from alloying elements concentration important influence on critical transformation points are generally for a good quality influence the elaboration technology, plastic deformation and thermal treatment.

Metallic charge components used at elaboration are Cu, Zn and Al all with high purity, minimum 99.99%. To improve the assimilation efficiency of zinc and aluminum can be use pre-alloy (CuZn and CuAl) with standard composition but obtain also from pure elements. For alloys melting was respected next order: Cu, Al, Zn and after cooper melting we introduce the aluminum and a part of pre-alloy solid cooper CuAl to decrease smelting super-heating caused by alumina-thermal reaction between aluminum and oxygen.

Melting temperature is limited at maximum 1200 °C because of evaporation looses and gases solve encouragement. A very important implication on alloy quality has the interaction chemical reactions between metal bath and furnace atmosphere gases. For shape memory alloy elaboration is used vacuum melting [11] and she is executing under pressing or gravitationally to obtain ingots for plastic deformation or to obtain mono crystals.

Melting temperature is adopted function of alloy composition using equilibrium phases diagram and does not have to go upon 50-100 °C past liquids temperature. Casting of shape memory alloys type Cu-Zn-Al must be done by methods that assure a calm flow, without lathering. Can be used filtration procedures as well with filters "en mousse de céramique" which retard micrometrics inclusions [12].

A shape memory alloy from copper-zinc-aluminum system was obtain by melting classical method and chemical composition determined by EDAX analysis, result presented in table 1, and confirm in large line with a spark spectrometer type Foundry Master.

Table 1 Chemical composition of investigated shape memory alloy.

Elements	Na	Series	Net	[wt.%]	[norm. wt.%]	[norm. at.%]	error in %
Oxygen	8	K-series	3170	7,997291	2,23962	20,01709	0,392909
Aluminum	13	K-series	6697	4,694356	5,349608	6,967403	0,279036
Copper	29	K-series	135543	66,91326	69,57384	42,16825	1,691617
Zinc	30	K-series	29473	16,66711	15,08805	10,20729	0,793381
Lead	73	L-series	8999	6,539313	2,919772	1,447239	0,613761
Nickel	28	L-series	342	2,028704	1,836503	0,436299	1,00442
Iron	26	L-series	424	0,732828	3,543673	0,368373	1,00354
			Sum:	110,4656	100	100	

The material present a small loss of zinc amount after the deformation and tension processes applied and reach with a 2.23 wt% of oxygen.

The alloy $Cu_{69.57}Zn_{15.09}Al_{5.35}$ present a high percent of other elements in composition, like Pb-2.919%, Fe-3.54%, Ni-1.83%, elements that contribute to modification of the thermal characteristics especially the dynamic mechanic behavior improving the damping capacity of the material.

After the dynamic-mechanical behavior analysis of the melted and homogenized alloy realized in [13] we investigate the material characteristics in deformed and tensioned states following the [14] investigations.

The deforming process was realized by hot forging at 1073 K and recovered by heat treatment, heating to 1073 K, maintaining 20 minutes and water cooling. For tension behind the forged samples were prepare laminate sample on a laboratory roller. The tensioned state was obtained on a tension equipment type INSTRON 3382. The elongation-tension variations for different states of materials, for different heat treatments applied, are presented in Fig. 1.

The material behavior under tension is presented in figure 1 with the heat treatments influences on laminate or forged material.

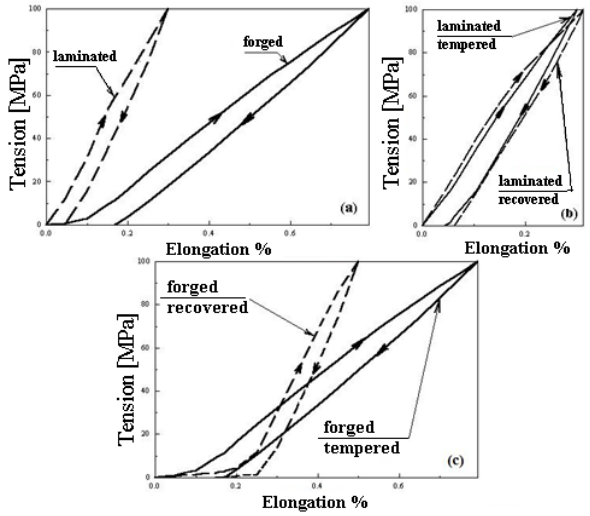

Fig. 1 Summary of elongation-tension variation of the copper based material a) for forged and laminated states, b) laminated and c) forged with different heat treatments applied like recovered or water quenched.

From Fig. 1 is observed that samples present a superelastic behavior characterize by tension plateaus at heating and cooling, phenomena meet at reversible martensitic transformations induce by tension. Can be also observe, from figure 1 a) that forged sample is more ductile then laminate one, heat treatments, recovered and water quenched treatment on laminate sample manifest similar on tension and for forged sample the water quenched improve the ductile properties and increase the mechanical hysteresis and internal friction comparing to recovered sample.

Microstructure of the material realized with a scanning electron microscope (SEM)–Secondary Electrons Detector in deformed and tensioned states, presented in figure 2, reveal a begin of reorientation of the martensitic variants to force applied direction but note yet coherent. The microstructure of alloy was made on 250x250 μm areas with evidence of martensitic variants, characteristic of shape memory alloys. In figure 2 b) can be observed the martesite variants induced by tension.

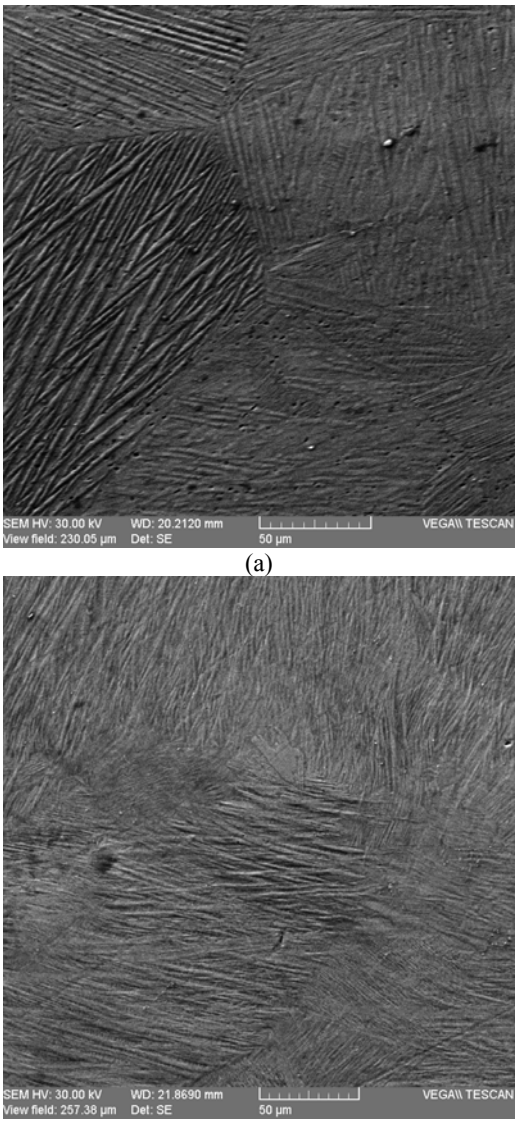

Fig. 2. SEM realized microstructure of shape memory alloy $Cu_{54.9}Zn_{26.5}Al_{6.44}$;(a) deformed by forging state; (b) tensioned state.

Doing a dimensional analyze of shape memory alloy grains and martensite variants between material structure in these two states we observe that, concerning the grains, they change form under tension but didn't modify dimensions, remaining around 250 μm result made from average of 50 measurements , in martensite variants

dimensions appearing a change consist of decreasing them from 1.75 in deformed state to 0.75 μm in tensioned state most of this change being attribute to tensioned induced martensite variants appearance.

Thinking about the internal friction of a material dependence on temperature, [12] the material must be analyzed by heating-cooling behavior point of view.

Because of a clearly dependence of internal friction peak appearance in transformation temperatures domain, based on transition internal friction part, first we have to determine the martensitic transformation range and transformations temperature points of the deformed material during heating.

The dilatogram result, presented in figure 3 is a specific one for shape memory materials, with a contraction of the metallic material during heating that represented the transformation temperatures range. After a normal increasing of physical dimension the martensitic transformation start with a peak of variation at 339 K, with increasing of temperature the material start reduce his linear dimension with almost 20 μm at 369 K.

Conforming to source [13] in this temperatures range the internal friction will exhibit a peak. After 373 K the material exhibit other inflexions of variation, all of them with reduce manifestations, presenting a low interest for practical applications.

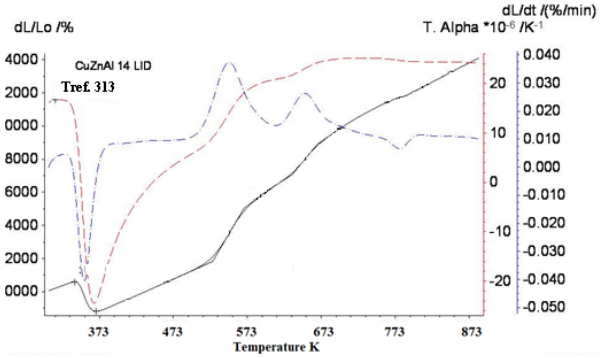

Fig. 3 Variations with temperature of relative thermal expansion (dL/ L_0 with solid line), relative thermal expansion in time d(dL/ L_0) dt) and thermal expansion coefficient (α), on the dilatometry recorded during heating to 600 K of a lamella cut from as-cast SMAs alloy $Cu_{69.57}Zn_{15.09}Al_{5.35}$

The other variations appear on diagram from Fig. 3 are not attribute to martensitic transformation.

The dynamic mechanical behavior of the material in deformed state is analyzed using DMA equipment.

The result presented in figure 4, reveal that an internal friction peak appears having a nice value of 0.11635 at temperature 362.73028 K, placed in the transformation temperatures range determined early by dilatometry.

According to ISO 6721-1 the storage modulus E′ represents the stiffness of a viscoelastic material and is proportional to the energy stored during a loading cycle. It is roughly equal to the elastic modulus for a single, rapid stress at low load and reversible deformation, and is thus largely equivalent to the tabulated figures quoted in DIN 53457 [15]. In the same ISO standard, the loss modulus E′′ is defined as being proportional to the energy dissipated during one loading cycle. It represents, for example, energy lost as heat, and is a measure of vibration energy that has been converted during vibration and that cannot be recovered. According to [16], modulus values are expressed in MPa, but N/mm^2 is sometimes used. The real part of the modulus may be used for assessing the elastic properties, and the imaginary part for the viscous properties [17-18].

Concerning the internal friction values of material in martensitic or α equilibrium state can be observed a small decrease of damping capacity, from 0.02 to 0.01, with the temperature increasing.

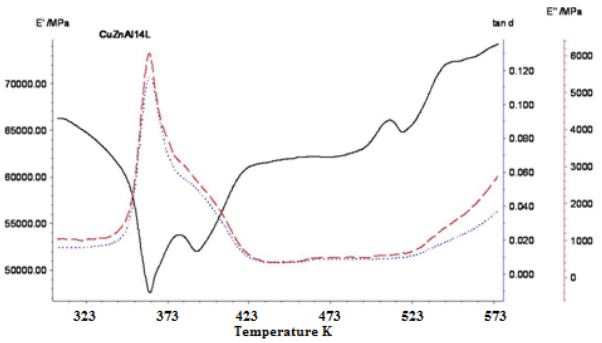

Fig. 4. Internal friction tand, storage modulus E'and amortization modulus E'' variations with temperature

Dynamic elasticity modulus E' (storage modulus) decrease from a value of 67000 MPa at room temperature until a value of 47554.41 MPa at 369 K, just before the internal friction peak, and increasing until a value of 78 000 MPa at 573 K. The link between the maximal value of internal friction and the minimum value of elasticity modulus is the common causes that produce them [19].

E" "loss modulus" represent an amortization term describing the energy dissipation capacity in heat when a material is deform and appear named imaginary modulus as a part of complex elasticity modulus, E=E'+E".

In the storage modulus variation with temperature after the decreases that appear with internal friction variations we can observe some other manifestations at 503 or 543 K connected to variations observed on dilatometry result.

After analyze of deformed state of shape memory alloy investigated, tensioned 4% samples was obtain for thermal investigations, differential scanning calorimetry for temperatures martensite transformation points and dynamic-mechanical behavior for internal friction variation manifestation.

As can be observed, from DSC result presented in figure 4, the martensitic transformation is considered completely reversible, being observe at cooling as well presenting a move to lower temperatures from the peak exhibit at 325.4 K at heating characterize by an

transformation enthalpy of 5.89 j/g to a peak at 313.1 K of 5.826 j/g. It's interesting to observe the transformation temperatures range decrease comparing to deformed state of material, in this sense the transformation range decrease from 339-369 K values to 313-350 K. Comparing to material behavior in melted state [13] or deformed state, in tensioned state the transformation range get near to room temperature exploiting the advantage of directly use of material.

Heating the material to 473 K temperature is avoided the risk of martensite transformation loosing by reaching the equilibrium α state. Even that the peak shape at heating and cooling are different from geometrical shape point, can be observe that the enthalpies are almost equal.

Tensioned samples was investigated with DMA (dynamic mechanical analyzer) under rectangular shape 30x10x0.5 mm by heating to 473 K during 2 cycles of heating and one of cooling to observed the cyclic behavior of the material under different solicitation.

In results diagram are presented internal friction variation with temperature with dashed lines and storage modulus with filled lines. The calorimetric investigation, realized previously, contribute to dynamic-mechanical behavior temperature range, being in this case set from 223 to 473 K, the main domain being around 323 K. At the first heating cycle internal friction exhibit a peak at 331,4 K, also form by two parts, as the calorimetric test show, a previous part at 326,6 K with a smaller value of 0.08 and the final peak with a value of 0.1. The higher values of internal friction in martensitic domain can be also seen comparing to austenitic state of the material, still with reduce values, 0.04 respectively 0.008.

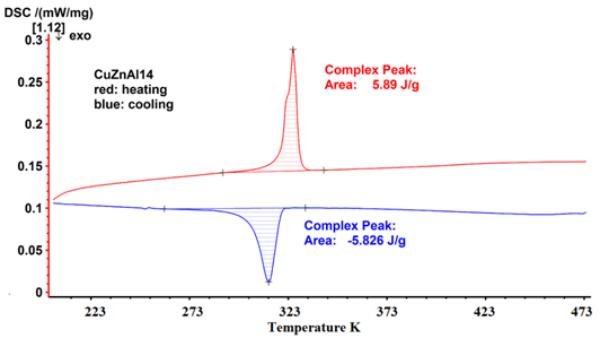

Fig. 5. DSC thermogram recorded during a heating cooling cycle up to 473 K of fragments cut from tensioned 4% sample of CuZnAl shape memory alloy .

The storage modulus, E' corresponding to first heating cycle decrease very much in the transformation range, almost in the same time with the internal friction peak earlier with 3.6 K, from 45000MPa to approximate 2000MPa.

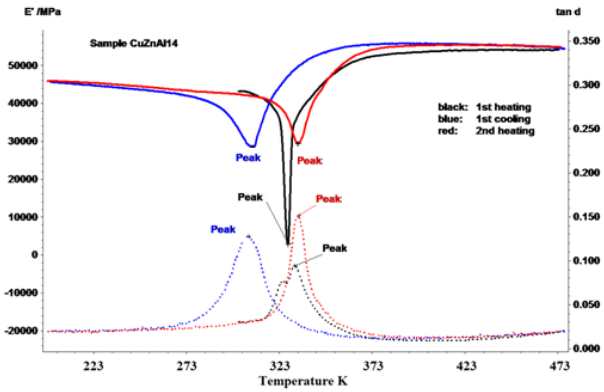

Fig. 6. Variation diagram of internal friction, tand and storage elasticity modulus E' of a shape memory alloy type $Cu_{68,1}$ $Zn_{13,2}$ $Al_{4,85}$, with temperature first heating cycle being represented with black color, cooling with blue and second heating cycle with red .

On cooling cycle similar to DSC diagram the internal friction move's to smaller temperatures reaching a higher value of internal friction of 0.14 at 306,4 K. The peak obtain is still a large one but continuously. Concerning the storage modulus in this case the decrease is not that big only until 28000MPa at an appropriate temperature, before the internal friction peak appearance. Second heating present a bigger internal friction peak with 0.1607 values near to first peak appearance, smoother and also thin.

4. Conclusions

- A shape memory alloy from copper-zinc system was obtaining by classical method, and after investigations reveals nice shape memory effect and good damping properties.
- Using combined equipments thermal behavior was analyze for determination of a nice memory effect in deformed and tensioned states.
- Small value of internal friction at room temperature of the shape memory alloy characterizes the martensitic state of the material. Contrarily the same alloy present an important peak of internal friction around temperature 363 K, in transformation points range, value of 0.11635 for deformed point and 0.1607 in tensioned state at 333.8 K which can be use for practical applications.
- Critical transformation point's domain move's to the left on temperature ax with deformation and tension of sample "taking" the internal friction peak appearance in the same direction.
- Storage modulus variation exhibit a contrarily internal friction manifestation connects them to some common causes.

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*Correspondent author: nicanornick@yahoo.com