

# USE OF COPPER-BASE SHAPE MEMORY ALLOYS IN SEISMIC ENERGY DISSIPATION DEVICES

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### SUMMARY

Shape memory alloys (SMA) are metallic materials that in the martensitic phase state can sustain strains above its elastic limit but when heated return to their original shape. SMAs, when in the austenitic phase state, may exhibit superelasticity; in this case the material automatically recovers its original shape, just by removing the force, without the need for heating. In both cases, energy dissipation occurs through hysteresis cycles.

Although several shape memory alloys have been characterized, few studies have been performed towards seismic applications. In this case, the superelasticity behavior is desirable to occur at room temperature. The material should dissipate substantial seismic energy, through repeated stable cycles at large strains, with little degradation in properties and low sensitivity to frequency in the 0.1-5 Hz range. To ensure that behavior, a great effort has still to be done in order to produce alloys for engineering applications, beyond a lab environment.

This paper examines the suitability of copper-based SMAs for use in energy dissipation devices for civil engineering structures. In particular, CuAlBe and CuZnAl wires and bars, with different compositions and manufacturing procedure, are characterized using several techniques. Mechanical and hysteretic damping properties are determined from cyclic tension-compression quasi-static and dynamic test for different strain amplitudes, frequencies and temperatures.

Single crystal CuZnAl 3 mm diameter rods could stand up to 6-8% strains, the equivalent damping ratio varies from 1.6 to 3.4% depending on the test rate and temperature. Polycrystalline CuZnAl rods have a fragile behavior attributable to a large grain size. Martensitic CuZnAlNi bars and austenitic CuAlBe wires, showed substantial dissipation capacity; equivalent damping ratio for 2% strain, came up to 12% and 4.6%, respectively.

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#### **INTRODUCTION**

The objective of building codes is to establish a minimum standard for protection of life by preventing building collapse. This is normally accomplished by designing ductile structures, that is, structures that are capable of absorbing forces induced by earthquake motions through deformation at carefully detailed critical regions. A ductile behavior does, however, imply damage to these critical regions.

There are other approaches for reducing the earthquake demand on a structural system. One approach suitable for low-rise structures is base isolation [1]. Another approach, appropriate for medium and high-rise structures, lies in taking advantage of the energy dissipation potential of specific devices [2]. Examples of passive supplementary dampers include devices based on metal yielding, friction, deformation of viscoelastic solid material, viscoelastic fluid through an orifice and shape memory alloys (SMAs).

Shape memory alloys are materials that can be deformed at one temperature but when heated return to their original shape. This behavior is due to a transformation from the low temperature form (Martensite) to the high temperature form (Austenite) after the material has been deformed while in its martensitic phase. SMAs also may exhibit superelasticity; in this case a force induces considerable deformation but when the force is removed, the material automatically recovers its original shape without the need for heating. This occurs after the material has been deformed while in its austenitic phase and is also the result of the same phase transformation, but the driving force for transformation is mechanical rather than thermal. In both cases, energy dissipation occurs when the material is subjected to hysteresis cycles. It is well known that although the main factor controlling the phase transformation temperatures is alloy composition, others factors such as heat-treatments, quenching rate and grain size also significantly affect them.

Liu and Van Humbeeck [3] and DesRoches et al. [4] reported several experimental and analytical studies of nitinol bars and wires for Structural Vibration Control, but so far the number of real life applications is very limited. The ISTECH Project [5], sought to develop innovative techniques for the restoration of cultural heritage structures, led to three restoration applications in Italy using Nitinol wires. These were the bell tower of the San Giorgio Church at Trignano, damaged during the October 1996 earthquake, the transept tympana of the Basilica of San Francesco at Assisi, damaged during the September 1997 earthquake and the San Feliciano Cathedral at Foligno.

Studies on mechanical properties and energy dissipation capacity of superelastic copper-based alloys can be found in Ref. [6-8]. Gillet et al. [7], tested for tension, bending and twisting CuZnAlNi wires and CuAlBe sheets; the tests were performed at low frequencies. Torra et al. [8] carried out a long term analysis determining the electrical resistance of prismatic samples of single crystals of CuZnAl in order to determine the evolution of transformation temperature with time. They also developed a one-dimensional model to predict the damping performance of the materials for long-term actions.

This paper examines the suitability of copper-based SMAs for use in energy dissipation devices for civil engineering structures. In particular, results obtained from cyclic tests under tension-compression loading of bars made of different compositions are reported as a function of strain amplitude and frequency. In order to characterize the alloys, several tests were performed: Differential Scanning Calorimetry (DSC), light microscopy observations, fractography, spectroscopy, diffraction RX and static and dynamic testing of  $\phi$  5-14 mm bars and  $\phi$  1.4-3 mm wires.

#### CuZnAl ALLOY

At first, a Cu-Zn 27.%-Al 3.7%-Ni 1.5% (%wt) alloy was prepared locally, in an induction furnace under air, and cast as a vertical plate, [9]. Its phase transformation temperature  $A_f$  was in the range of 60-90°C, depending on the grain size, so it was in martensitic phase at room temperature, condition that was verified metallografically and from DSC analysis. A direct relationship between grain size and phase transformation temperature was detected.

In order to verify the shape memory effect,  $13x8x17 \text{ mm}^3$  specimen rolled at different temperatures, then heated at 800°-850°C for different period of time followed by water quenching, were submitted to several cycles of static compression tests at increasing plastic strain up to 3.7%. After each cycle, the samples were heated to 150°C (>A<sub>f</sub>) to quantify the thermoelastic recovery effect. The one that was hot rolled at 700°C and then annealed during 4 min at 850°C presented the best recovery; 80% at the first cycle, 75% at the second and 38% at the third.

After hot forging the as-cast material, two types of mechanical treatments were applied to prepare the testing samples. Bars L0-L5 were hot rolled at 650°C in 4 passes to a total height reduction of 50%, water quenched, machined to 7 mm diameter rods, annealed for 2.5 min at 800°C and water quenched. Bars E1-E4 were extruded with a 50% area reduction at 900°C, water quenched, machined to 5 mm diameter rods, annealed for 2,5 min at 800°C and water quenched. In the first group the main grain size was 0.2 mm while in the second grain size varied between 0.3 to 0.8 mm.

A MTS machine, 5-ton capacity, was used to perform dynamic tension compression test at room temperature. This machine may be configured to use feedback control of strain or stress to produce a sinusoidal loading on the sample. The strain was measured with an extensioneter of 25 mm gauge length in bars with a 35 mm distance between clamps.

Cycle tests were performed at different frequencies, type of control (strain or stress) and different amplitude of stress or strain. As an example, figure 1 shows stress-strain curves of a hot rolled bar under tension-compression loads in a stress controlled test and of an extruded bar under a strain controlled test. Several features of the strain-stress curves can be observed: (1) The stress-strain loops are asymmetric with respect to the central point (zero stress, zero strain); the stress level during compression is higher than during tension for the same strain amplitude. (2) The cycles are rather stable especially for strains up to 2%. (3) For large stress level only, the stress-strain loops depend on the frequency of the test. (4) The loop shapes are almost independent of the previous thermo-mechanical treatment of the samples, but depends on the type of control of the experiments.

For each test, an average equivalent damping was calculated as  $\Delta W/2\pi W$ , where  $\Delta W$  is the area of each loop and Eq 1 gives W from Liu et al [3]:

$$W = \int_{-\varepsilon_{uc}}^{\varepsilon_{mt}} \sigma_{(T)} d\varepsilon + \int_{\varepsilon_{ut}}^{-\varepsilon_{mc}} \sigma_{(C)} d\varepsilon$$
(1)

where  $\sigma_{(T)}$  and  $\sigma_{(C)}$  are the stress curves during tension and compression;  $\varepsilon_{mc}$  and  $\varepsilon_{mt}$  are the maximum strain attained in each cycle in compression and tension, respectively; and  $\varepsilon_{uc}$  and  $\varepsilon_{ut}$  are the compression and tension strain, respectively, when unloading to zero stress. There is a large dispersion for small strains, but damping values converge to 12% for larger strains, as can be seen in figure 2, ref [10]. The maximum tensile stress attained was 450 MPa for a 3.5 % strain and the maximum compression stress was 350 MPa for a 0.5%. Envelope curves are almost bilinear with yield stress of about 130 MPa. The modulus of elasticity for 0.2% strain varied between 60 to 70 GPa.



Figure 1 Stress-strain curve, martensitic CuZnAlNi



Figure 2 Equivalent damping as a function of strain amplitude

Moreover, a Cu-Zn 20.36%-Al 5.2%-B 0.04% alloy and a Cu-Zn 15.6%-Al 8.8%-Ti 0.11% (% wt) were prepared with the same previous procedure. B and Ti were added for grain refinement. Through metallography it was verified that both alloys were in austenitic phase at room temperature. Machining the as-cast material 5 mm diameter test samples were produced. The maximum tensile stress attained in static test was 300 MPa for 2.3% strain in the B alloy sample, while the Ti alloy samples fractured at low stresses. Based on these experiences, a second melting of CuZnAlB alloy was prepared in an induction furnace under control atmosphere at 1100°C and cast as a 3 cm diameter cylinder, 30 cm long. The solidification and cooling was performed inside the furnace. To eliminate porosity a new melting was performed in a resistance furnace, objective that was only partially attained, [11].

Bars 10 and 15 mm diameter were extruded with a 60 and 35% area reduction at 850°C. Later they were machined to 3 and 7 mm diameter rods, annealed for 10 or 15 min at 825°C and water quenched. Strain controlled tension cycle tests were performed at different frequencies. Figure 3 shows an stress-strain curve of a 3 mm rod tested at 0.5 Hz; although the alloy is in austenitic phase at room temperature, it does not show superelastic behavior. As residual deformations exist for 0 stress, the machine trying to come back to the original position, applies significant compression stresses. All 7 mm bars broke at a low level of deformation.



Figure 3 Stress-strain curve, austenite CuZnAlB

Finally, single and polycrystal CuZnAl were prepared at the Bariloche Atomic Center (CAB). The nominal composition was Cu-Zn 16.91%-Al 7.72% (% wt). Phase transformation temperature  $A_s$  and  $A_f$  were between  $-6^\circ$  and  $-11^\circ$ C and between  $-3^\circ$  and  $-8^\circ$ C respectively, so the alloy was in austenitic phase at room temperature. Through machining 3 mm diameter rods were prepared and subjected to static tension test at different temperature and frequency. In single crystal rods up to 7% strain was attained, with an equivalent damping of 3.4%. Figure 4 shows stress-strain curves for two different conditions; superelasticity is observed in both but the transformation stresses and equivalent damping values are quite different, (1.74 and 3.39% respectively). Polycrystal subjected to similar conditions had brittle behavior.



Single crystal rods were also subjected to dynamic cycles attaining up to 8% strain and 1.52% equivalent damping. Hysteresis loops are compared in figure 5 for tests performed at 22° C and 4% strain with different test rates; the quasi static case shows the largest area, while almost no difference are detected between 0.5 or 1 Hz. Transformation stress exceeds 800 MPa in all cases. Figure 6 shows a hardening effect over a 7% strain in a test performed at 1 Hz.



Figure 5 Dynamic stress-strain curve, CuZnAl



Figure 6 Hardening effect on CuZnAl rod

Figure 7 shows equivalent damping values for one single crystal sample tested in tension at different frequencies and strains; equivalent damping diminishes when frequency increases and the values are rather low.



Figure 7. Equivalent damping CuZnAl single crystal rod

#### **CuAlBe ALLOY**

A Cu-Al 12.8%-Be 0.6% (%wt) alloy produced by Trefimetaux has been studied. The mechanical properties strongly depend on the metallurgical state and according to the manufacturer's data in the asdrawn state, the ultimate tensile stress is  $\sigma_u = 900$  MPa; the conventional elastic limit at 0.2% strain is  $\sigma_{0.2} = 500$  MPa; and elongation percent to fracture is A = 12%. On the other hand, after a heat treatment of 15 minutes at 650°C, followed by quenching,  $\sigma_u = 500$  MPa,  $\sigma_{0.2} = 300$  MPa, and A = 5%. The transformation temperature A<sub>s</sub> was reported as -110°C.

Several tests were performed in order to characterize  $\phi 14$  mm bars, in the as-drawn and heat treated states and 1.4 mm wires, [12]. The thermal treatment reported by the manufacture consisted of 30 minutes at 700°C and water quenching. Micrographs show that both materials are in austenitic phase at room temperature, and that the grain size of the heat-treated material is smaller than that of the as-drawn one.

The bars have superelastic behavior at room temperature with stable cycles when subjected to dynamic tension tests. The maximum tensile strain attained was 4.4% with maximum tensile stress of 500 MPa at a frequency of 0.1 Hz. For higher frequencies the strains attained were much smaller. Average elastic modulus was about 70 GPa. Fracture occurred by a brittle intergranular mechanism at about 500 MPa. Figure 8 shows the stress-strain curve for a stress controlled test at a frequency of 0.5 Hz; equivalent damping ratio is 1.704% and the secant stiffness is 36631.4 MPa.



Figure 8 Superelastic behavior of CuAlBe bar

The equivalent damping varied between 0.5-3.7 %, which is a low value for the application pursued in this project. Nevertheless the superelastic effect has advantages in addition to damping which make it useful for seismic protection.

When applying exactly the same heat-treatment informed by Trefimetaux to the as-drawn bars, the microstructure and mechanical properties were different than the original heat-treated bars, so some other procedures should be tried.

Later, 5.6 mm bars and 3 mm wires with the same nominal composition but from a different melting were analyzed. The alloy again was in austenitic phase at room temperature ( $A_s = -9^{\circ}C$  and  $A_f = -4^{\circ}C$  for 3 mm diameter and  $A_s = -12.38^{\circ}C$  for the 5.6 mm bar). The 5.6 mm bars were subjected to static tensile test attaining up to 30% strain and 730 MPa stress. When the 3 mm wires were subjected to dynamic, stress controlled, tensile test, the hysteresis cycles were much larger than those of the previous melting and the martensitic transformation occurred at a much lower stress. Figure 9 compares stress-strain curves for the 3 and 1.4 mm wires and Table 1 compares the equivalent damping obtained from tension cyclic test of CuAlBe wires 3 and 1.4 mm diameter.



Figure 9. Hysteresis cycle CuAlBe wires

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diameter	Frequency	Maximum	Maximum	Residual	Damping
	Hz	stress	strain	strain	%
		MPa	%	%	
φ 3 mm	0.1	170	0.8	0.	4.08
	0.5	170	1.4	0.	4.06
	0.5	200	2.0	0.05	4.61
	0.5	230	2.85	0.35	5.34
	1.0	200	2.0	0.25	4.91
φ 1.4 mm	0.5	301	1.0		0.54
	0.5	356	1.5		0.95
	0.5	410	2.0		1.23
	1.0	410	1.0		0.66
	1.0	445	1.5		0.99
	1.0	477	2.0		1.13

Table 1. Equivalent damping of CuAlBe wires

Finally, figure 10 compares stress-strain curve for a CuAlBe 3 mm wire and a single crystal CuZnAl of the same size (3 mm diameter) tested in tension at 0.5 Hz and a maximum strain of 2%. The equivalent damping ratio are 4.61 and 1.26% respectively.



Figure 10 Stress-strain curve for CuAlBe and CuZnAl rods

#### DISCUSSION AND CONCLUSIONS

Different composition, manufacturing process and thermo-mechanical treatment on copper based-alloy have been presented. At this stage the CuAlBe alloy has shown a more promising behavior although the CuZnAlNi in martensitic phase shouldn't be discarded. In effect, although the equivalent damping values of the latter alloy have a large dispersion for small strains, they converge to 12% for larger strains. This value is larger than the one reported in [3] for martensitic Nitinol bars for strains of the same order of magnitude.

With respect to CuZnAl, different nominal compositions have been prepared in single or polycrystal samples. Although most of them are in austenitic phase at room temperature as can be seen from metallographic plates, only single crystal have shown superelastic behavior. Equivalent damping ratios are rather low. Martensitic transformation stresses varies significantly with temperature. More efforts have to be done to improved its behavior.

In all cases the frequency of the test has little influence on the damping values This is part of continuing research program at the University of Chile to find appropriate materials to use in seismic dissipation devices.

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