Cu-Al-Ni Shape Memory Single Crystal Wires with High Transformation Temperature

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Abstract

CN-250X is a new material with higher performance than Nickel-Titanium Shape Memory Alloy (SMA). For space mechanisms, the main disadvantage of Nickel-Titanium Shape Memory Alloy is the limited transformation temperature. The new CN-250X Nimesis alloy is a Cu-Al-Ni single crystal wire available in large quantity because of a new industrial process. The triggering of actuators made with this Cu-Al-Ni single crystal wire can range from ambient temperature to 200°C in cycling and even to 250°C in one-shot mode. Another advantage of CN-250X is a better shape recovery (8 to 10%) than Ni-Ti (6 to 7%).

Nimesis is the first company able to produce this type of material with its new special industrial process. A characterization study is presented in this work, including the two main solicitation modes for this material: tensile and torsion. Different tests measure the shape recovery of Cu-Al-Ni single crystals wires during heating from room temperature to a temperature higher than temperature of end of martensitic transformation.

Introduction

Shape memory alloys (SMA) are recognized as reliable and efficient materials particularly to design actuators. The major drawback of these shape memory actuators is the trigger temperature that is lower than 100°C with standard Ni-Ti alloys. The new Nimesis Cu-Al-Ni single crystal wire (Figure 1) shows a transformation temperature higher than 100°C and they are available in round section with a diameter from 0.5 mm to 20 mm. The state of the art and a detailed characterization work made for CNES demonstrated that a Cu-Al-Ni single crystal wire is a very good candidate for space applications that need trigger temperatures between 100°C and 200°C.

Figure 1. Cu-Al-Ni single crystal Ø2.2-mm wires made with special Nimesis process

Experimental Approach

Single crystals were produced by a Nimesis special industrial process that is derived from the Bridgman process [(1) (2)]. Dimensions of wires were 2 mm in diameter, and 70 to 300 mm in length. The advantage in using single crystals is that the preferred orientation of these crystals (close to [001]) obtains a maximum

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reversible strain of about 8 to 10% [3] [4]. This preferred orientation is due to the high elastic anisotropy of the material.

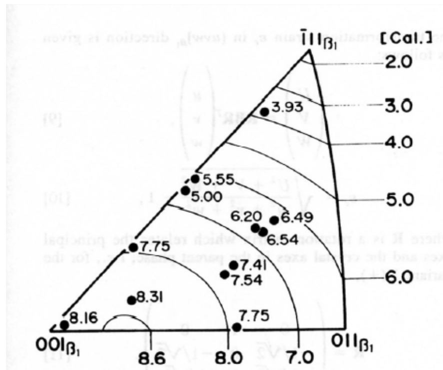


Figure 2. Relation between transformation strains and crystal orientation [3]

Some Cu 82.4wt%-Al 13.5wt%-Ni 4.1wt% single crystal samples were mainly tested in tensile and torsion mode. The evolution of the deformation during a thermal cycle and with imposed force (shape recovery) was measured. This test was performed for more than 10 thermal cycles. Transformation temperatures were controlled by DSC (Differential Scanning Calorimetry) until 25 cycles.

Thermomechanical tests

The objective of these tests is to obtain data relative to thermomechanical behavior of the Cu-Al-Ni single crystal wire produced in industrial conditions.

DSC tests Results

Table 1 shows the evolution of transformation temperatures (As, Af, Ms, Mf) for polycrystalline (before monocrystallization process) and single crystal (after monocrystallization process). There is a small variation of transformation temperatures during the monocrystallization process.

Table 1. DSC results on Cu-Al-Ni polycrystal and single crystals.

description	M_f (°C)	M_s (°C)	A_s (°C)	A_f (°C)
Cu-Al-Ni polycrystal	118	152	149	163
Cu-Al-Ni single crystal	134	153	157	163

Figure 3 shows the evolution of temperatures during thermal cycling between 25 to 250°C and between 25 to 200°C. The transformation temperatures are more stable in cycling when the maximum temperature is limited to 200°C.

Tensile Test Results

Wire samples are manufactured and tests are done with a tensile testing machine equipped with special grippers and extensometer. Heating is achieved with a direct power supply (Joule Effect) of the sample. Temperature is measured at three different locations: in the center of the sample, just above the extensometer and just below the extensometer. This ensures heating the test zone of the sample homogeneously.

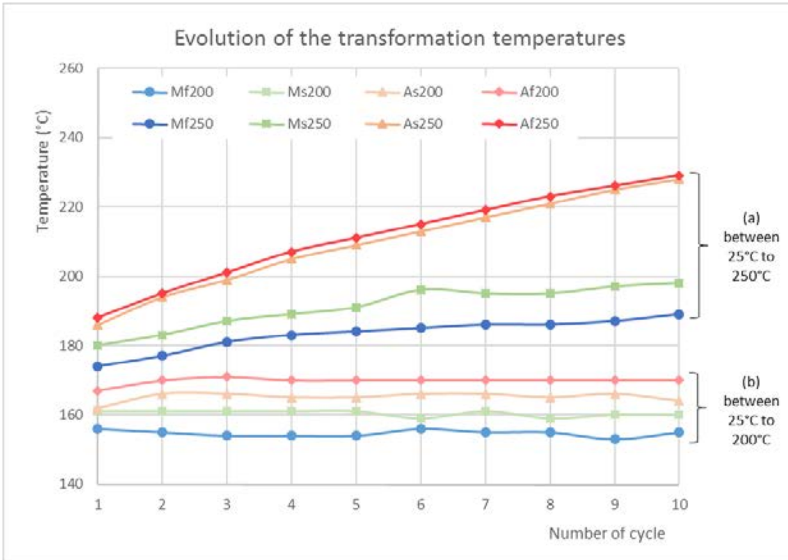


Figure 3. Evolution of transformation temperatures during thermal cycling (a) between 25 and 250°C, (b) between 25 and 200°C

Two preliminary tests allowed to evaluate the behavior of the material at room temperature and at 220°C, Figure 4 shows results of tensile tests at room temperature and at 220°C.

Other tests are done with a preload of 150 MPa before heating. Successive thermal cycling from 25°C to 250°C results in measuring evolution of the strain of the martensitic transformation. During the cycling, transformation temperatures were recorded.

Figure 5 presents transformation temperatures and strain as a function of the number of thermal cycles. Contrary to other High Temperature Shape Memory Alloys, deformation and transformation points remain constant until 25 cycles and probably over (test to be done).

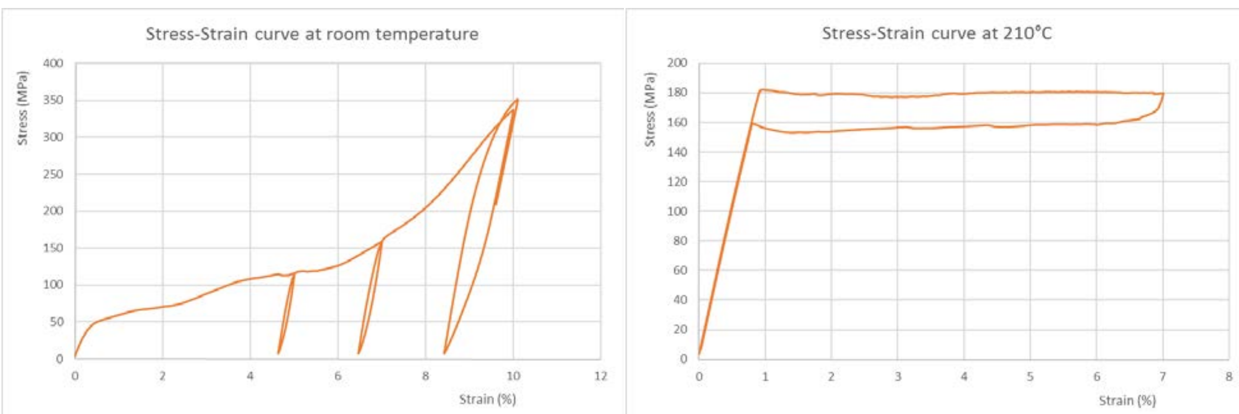


Figure 4. Tensile tests of Cu-Al-Ni single crystal samples at room temperature (martensitic state) and at 210°C (austenitic state)

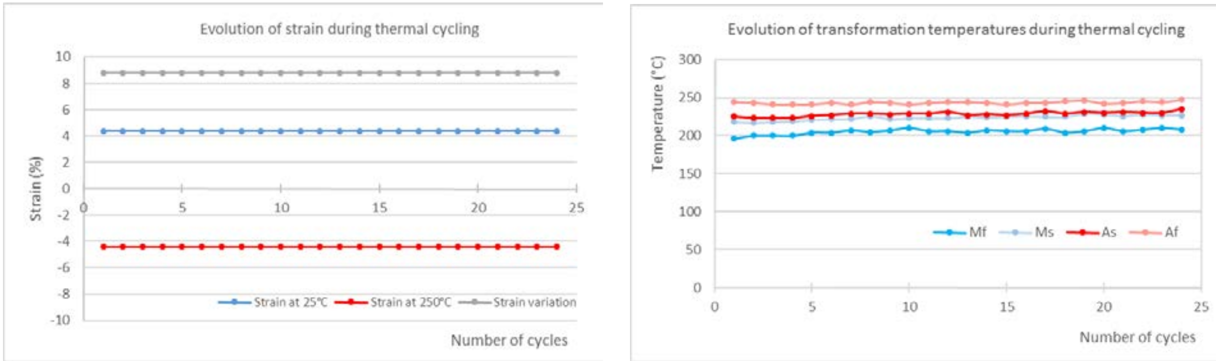


Figure 5. Evolution of (a) strain and (b) transformation temperatures for a prestressed Cu-Al-Ni single crystal (150MPa) and during thermal cycling from 25°C to 250°C

Torsion tests

Torsion tests were made with Cu-Al-Ni polycrystalline samples, Cu-Al-Ni single crystal samples and Ni-Ti samples for comparison. Length of each sample was 70 mm. Each sample is fastened between one fixed end and one end on which a bulk is set in order to induce a torque. Torque value varies between 0 and 0.5 N-m. Heating is achieved by a heat gun able to reach a temperature up to 200°C. Torsion angle is measured initially at room temperature and then after heating at 200°C after recovery shape. Shear strain γ and shear stress τ are calculated from these data. Results of these tests on Ni-Ti are in accordance with those in the literature [5][6]. This establishes a comparison between Ni-Ti and Cu-Al-Ni in torsion. Recovery shape rate is globally the same between Ni-Ti samples and Cu-Al-Ni polycrystalline samples. But $\Delta\gamma$ is lower for Cu-Al-Ni single crystals.

Thermomechanical behavior

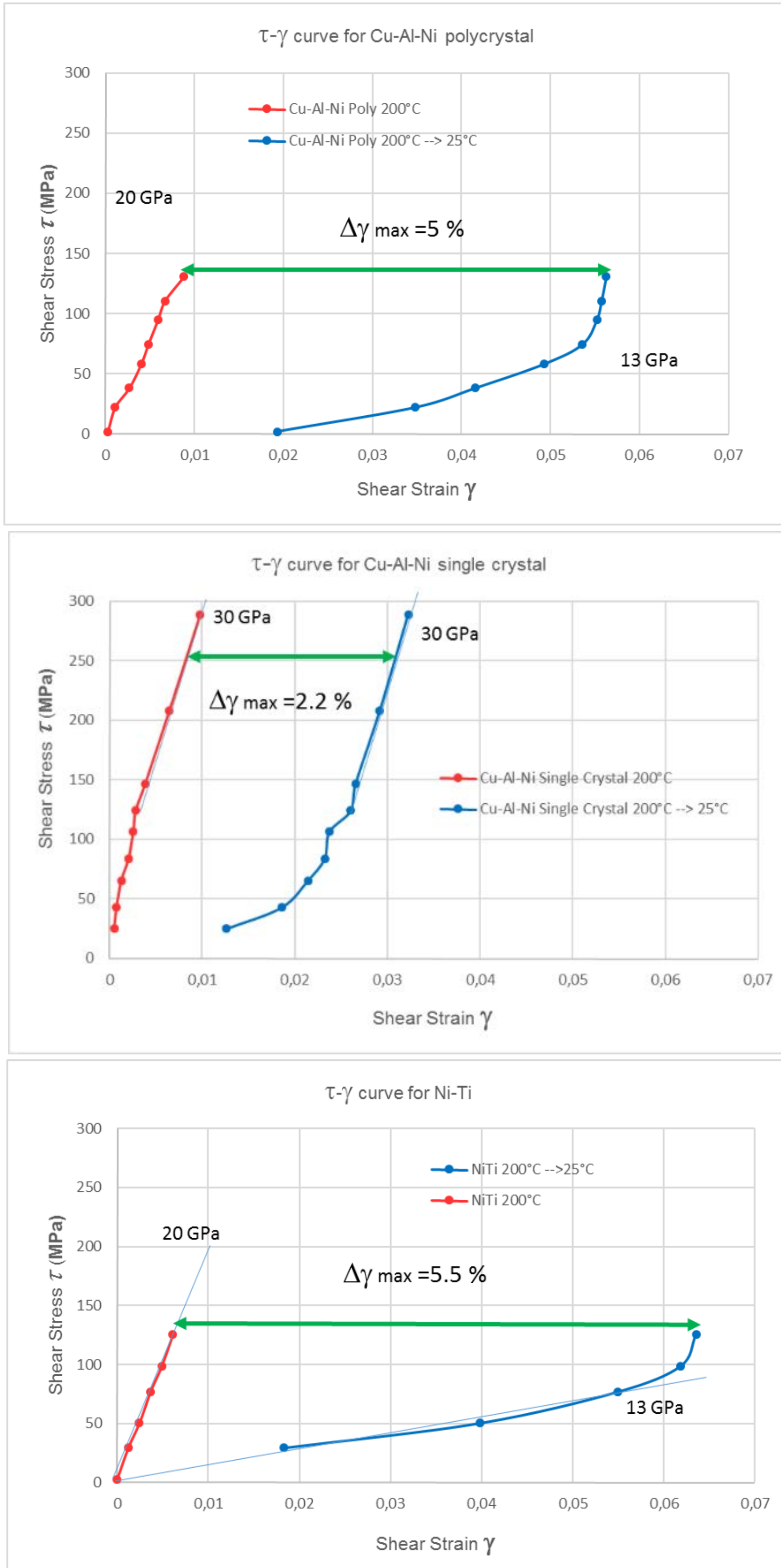
Ratio $d\sigma/dT$ of Ni-Ti (~6 MPa/°C) is higher than the ratio $d\sigma/dT$ of Cu-Al-Ni single crystal (~2.3 MPa/°C). That means for the same temperature range, and for the same power rate, activation stress of a Ni-Ti actuator will be approximately twice higher than the activation stress of a Cu-Al-Ni single crystal actuator. Furthermore, for the same stress, it takes about twice more heating for a Cu-Al-Ni single crystal actuator than for a Ni-Ti actuator.

Electrical behavior

We can heat by Joule Effect Cu-Al-Ni components to change the temperature of the material, as we can heat by Joule Effect Ni-Ti components. That involves taking into account the difference of resistivity between both materials.

Table 1. Comparison between Ni-Ti and Cu-Al-Ni resistivity

	Ni-Ti	Cu-Al-Ni
Electrical resistivity ρ (average between austenite and martensite) $10^{-6}\ \Omega.m$	0.9	0.12



(a) (b) (c)

Figure 6. Elements of comparison for (a) Ni-Ti and (b) Cu-Al-Ni polycrystal and (c) Cu-Al-Ni single crystal

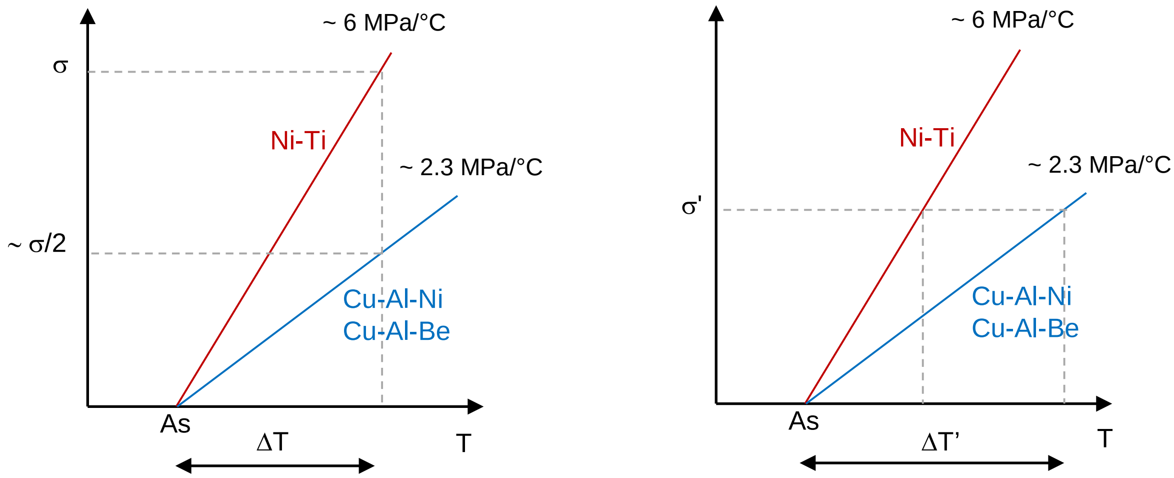


Figure 7. Comparison of Ni-Ti and Cu-Al-Ni σ-T slope and consequences on actuator activation (a) for a given temperature, (b) for a given stress.

$$\sqrt{\frac{R_{NiTi}}{R_{CuAlNi}}} = \frac{I_{CuAlNi}}{I_{NiTi}} = \frac{U_{NiTi}}{U_{CuAlNi}} \sim 2.7 \ to \ 3.5$$

For the same dissipated power:

$$I_{CuAlNi} \sim 3 \times I_{NiTi} \qquad\qquad U_{CuAlNi} \sim \frac{U_{NiTi}}{3}$$

Conclusion

Results obtained with the new CN-250X by Nimesis showed a very good stability during the thermal cycling in terms of shape recovery (8 to 10%) at 150 MPa for trigger temperature below 200°C. Higher temperatures (until 250°C) can be used for one-shot applications or for applications with a small number of cycles. Cu-Al-Ni single crystal wire seems to be able to be made into high temperature actuators (Figure 8), thermal safety devices, locking-unlocking devices, low shock mechanisms, and deployment mechanisms. Nimesis is now able to manufacture Cu-Al-Ni single crystal wire (diameter between 0.5 to 20 mm) in large quantity with a new patented industrial process, controlling the entire process from alloy casting to wire grinding. This allows supplying High Temperature SMA over the long term.

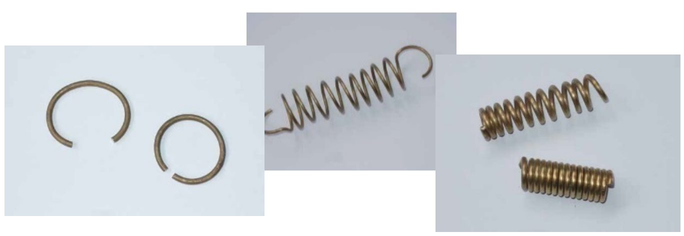


Figure 8. Examples of actuators made with Cu-Al-Ni single crystal wire

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