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Actuators and Drivers Based on CuAlNi Shape Memory Single Crystals

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Our research reported here is concerned with the development of physical aspects of shape memory linear actuators and drivers made from CuAlNi single crystals. Our study is focused on reactive stress generation and reversible deformation in the clamped CuAlNi single crystals due to martensitic transformations during thermal cycling. The crystals can reproduce force generation in heating to 560 K for many times, and one time in heating to 700 K with the maximal stress 350 MPa. The theoretical model and calculations of linear actuators that use shape memory single crystals is discussed and we also demonstrate real model of an actuator based on these crystals.

Keywords actuators and drivers, shape memory alloys, stress generation

1. Introduction

Development of shape memory actuators and driver is due mainly to progress in shape memory (SM) materials. Single crystals have great potential in this application and surpass polycrystal alloys in all their features. They demonstrate absolutely reversible deformation above 10%, high level of generated stress, the possibility to operate at a wide temperature range, etc. Still there are no industrial technologies at present to produce SM single crystals en masse. We have developed a new, far more productive and highly accurate technology that improves on the design of actuators and drivers.

2. Shape Memory Single Crystal Fabrication

The single crystals Cu-13.4 wt.% Al-4.0 wt.% Ni were grown in the form of rods, 1 to 10 mm in diameter with axis orientation in the [100] direction. The crystals were treated: (1) heating to 1223 K, for 20 min, (2) quenched in room temperature water, (3) stabilized by aging at 373 K for 1 h. The resulting alloy has following characteristic transformation temperatures: M_s = 341 K and M_f = 330 K (direct transformation) and A_s = 343 K and A_f = 356 K (reverse transformation). To initiate the shape memory effects the crystals were elongated at a room temperature. After unloading the shape memory strain was 9% (Ref 1, 2).

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3. Force Generation

Force generation due to reactive stress in deformed SM crystal is the basic feature of any SM actuators (Ref 3, 4). In this study, we present the temperature dependence of the reactive stress. In the experiment, the crystal was initially pre-stressed to approximately 30 MPa. This preliminary loading prevents machine backlashes and compensates for thermal expansion effects at the stage of heating the specimen. Specimen were heated and cooled at a rate 1-2 K/min. Reactive stress generation was registered as a function of temperature (*T*). Figure 1 shows how the experiment was actually run (see insert) and demonstrates a plot of the reactive stress in heating-cooling cycle for the single crystal specimens. The dash and solid lines show, respectively, results of the two experiments: (1) heating to 560 K and then cooling to a room temperature (dash line) and (2) heating to 680 K and cooling to a room temperature (solid line).

During heating we observed a monotonic increase of reactive stress (stress generation) in both the experiments. In the first experiment, the stress generation had begun at 400 K and was stopped at 560 K when the reactive stress reached 280 MPa. At that time the slope of the $\sigma(T)$ curve began to decrease. In the second experiment, force generation stops at 680 K and reactive stress reaches 370 MPa. In the temperature range 560-680 K the slope of the stress generation decrease continuously and at 680 K the reactive stress drops to 70 MPa (see Fig. 1, A $\rightarrow$ A′). This drop of the reactive stress is initiated by decomposition of alloy solid solution.

Surprisingly enough, the reactive stress increased during cooling (see Fig. 1, A′B). and only below 480 K it begins to decrease, reaching zero at 400 K (Fig. 1, BC). Then it again increases to 150-160 MPa (Fig. 1, CD).

This complex behavior may be the result of several successive martensitic transformations with different kinetics

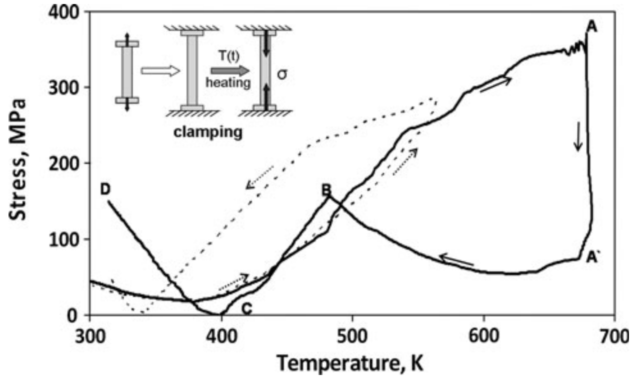

Fig. 1 Temperature dependence of the reactive stress in Cu-13.4% Al-4.0% Ni single crystal under thermal cycling experiments: 300-560 K (1) and 300-680 K (2) (dash and solid lines, respectively). Upper left the scheme of experiment

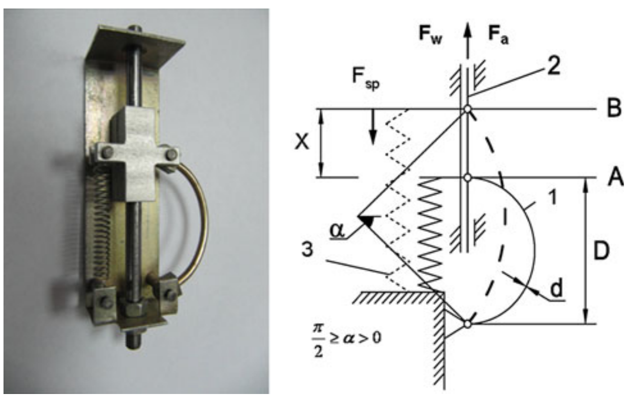

Fig. 2 Shape memory actuator with single crystal (left); functional scheme of the linear actuators (right); bend element (1), plunger (2), and spring (3)

and temperatures. It can also be connected to superposition of two opposite effects, i.e., shape memory effect and transformation plasticity (Ref 5).

In cooling from 560 K (Fig. 1, dash line) the reactive stress gradually decreases. Due to transformation hysteresis the curve shift toward lower temperatures, that is related to the curve of heating (Fig. 1, dash line, the increasing part). Reactive stress then disappears at 340 K. That is considerably lower than in the second experiment. If the cooling continues, the reactive stress increases to the initial 30 MPa In both the experiments, the specimens remained intact in spite of the high stress in the thermal cycles.

We showed that for multiple use of specimen, the maximum temperature should not exceed 560 K, with a maximal stress σ = 280 MPa and $d\sigma/dT$ = 1.7 MPa/K. At high temperatures the martensitic structure of specimen could decompose. Still it is possible to use the specimen, but only once. In that case, the stress can be as great as 350-370 MPa at ~700 K.

4. Designing of Cyclic Linear Actuators and Its Mathematical Model

The design and principle of use of cyclic linear actuator is shown in Fig. 2. This linear actuator with one SM crystal (bent

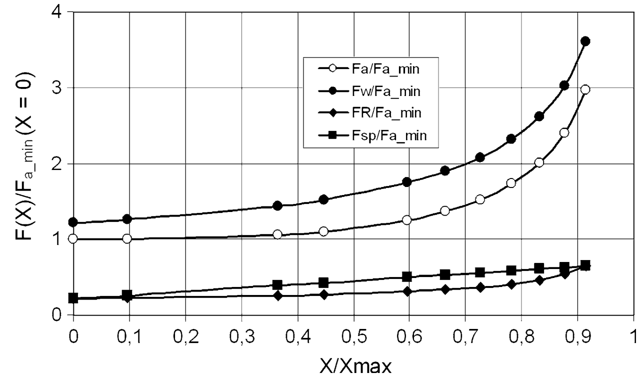

Fig. 3 Forces F_a, F_W, F_{SP}, and F_R presented as functions of displacement X

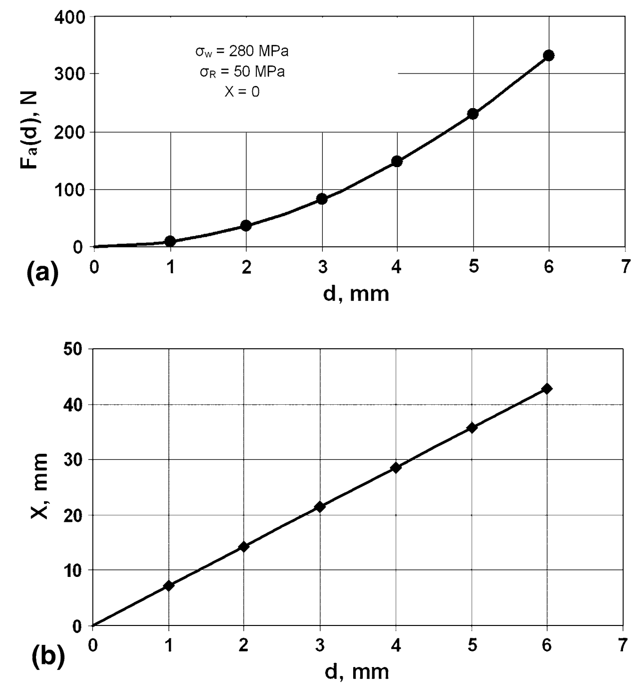

Fig. 4 Force F_a (a) and displacement X (*b*) versus the diameter of the crystal

element) and one spring does useful work only in a single direction.

It operates as follows: During heating, (1) the bent element unbends and moves the plunger from position A to B, (2) the spring extends. Moving from 0 to X, the linear actuator can produce force F. During cooling, the spring returns the linear actuator to the initial position A.

Figure 2(b) shows the operational model of the linear actuator. It also shows our approaches to its calculation.

We assume:

1. The bent element is a cylindrical rod, of diameter d.
2. It is bent over a circle arc of diameter D. This corresponds to the angle 2α.
3. Strain ε in the bent element cross section is linearly distributed. It reaches maximum on the external surface of the bent element.

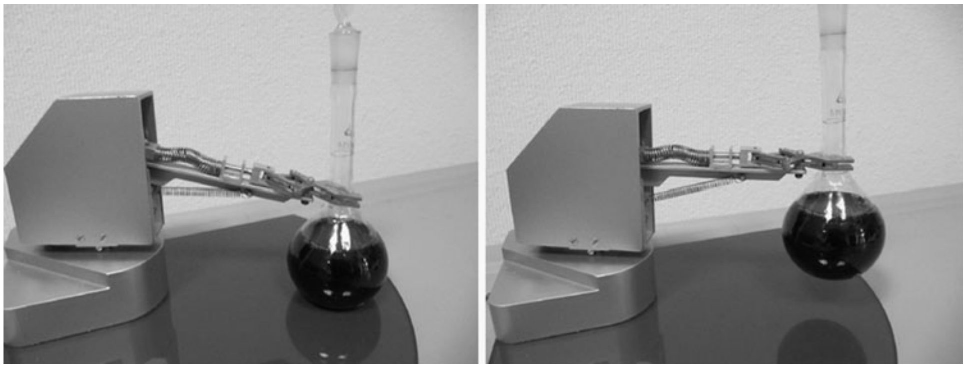

Fig. 5 Shape memory minirobot at work

4. The stress is distributed over the cross section according to the plastic hinge scheme (Ref 6).
5. At initial position ($X = 0$ and $2\alpha = \pi$) the maximal strain of the bend is $\varepsilon_0 = d/D_0$.
6. At the final stage the position of the plunge is maximal (X_{max}). This is achieved at $2\alpha = 0$. The construction of the device limits the movement of the bent element to 90% of maximal (i.e., $0.9X_{max}$).

During heating the bent element moves and generates force (F_W) (which corresponds to stress σ_W). To move it during cooling, we need force F_R (stress σ_R). The spring force F_{SP} must be greater than F_R.

What is outline above is described by the following (Ref 7–9):

$$X = \frac{d}{\varepsilon} \cdot \left(\frac{\pi}{2} \cdot \frac{\sin\alpha}{\alpha} - 1 \right) \quad \text{(Eq 1)}$$

$$F_R = \sigma_R \cdot \frac{d^2}{3} \cdot \varepsilon \cdot \frac{2\alpha}{\pi(1 - \cos\alpha)} \quad \text{(Eq 2)}$$

$$F_W = \sigma_W \cdot \frac{d^2}{3} \cdot \varepsilon \cdot \frac{2\alpha}{\pi(1 - \cos\alpha)} \quad \text{(Eq 3)}$$

$$F_{sp}(X) = F_R(0) + \frac{F_R(X_f^a) - F_R(0)}{X_f^a} \cdot X \quad \text{(Eq 4)}$$

$$F_a(X) = F_W(X) - F_{SP}(X) \quad \text{(Eq 5)}$$

These equations are used to calculate the activator's forces and displacements; F_W is the force of the bent element, F_R is the force needed to deform the element, F_{SP} is the force of the spring, F_a provides the useful work as shown in Fig. 3.

Figure 4 is an example of numerical calculation of F_a versus crystal diameter in the following conditions: maximum bending strain, $\varepsilon_0 = 8\%$, $\sigma_W = 280$ MPa, $\sigma_R = 50$ MPa.

Practical realization of our design and calculations are shown in Fig. 5. The device is actually a minirobot that moves a full flask is much heavier than the device.

5. Conclusions

We have demonstrated that CuAlNi single crystals can be effectively used for actuators and drivers.

Up to 560 K the crystals are successfully used in cyclic systems. At higher temperatures of' ~700 K they can be used only a single time. The suggested mathematical model enables one to calculate forces and displacement of these single crystal actuators.

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