# THE DEVELOPMENT OF SHAPE MEMORY ACTUATORS FOR ANTHROPOMORPHIC UPPER LIMB PROSTHESES

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Abstract. The single crystal Cu-Al-Ni alloys became generally commercialized. It can be observed that response time of any single crystal Cu-Al-Ni-based shape memory alloy (SMA) actuator is greater than the necessary when it is used for human prosthesis. Moreover, the electrical SMA actuator type with better performance than the thermal one is very problematic for this type of crystal due to its low electrical resistance. However, the construction of thermal single crystal Cu-Al-Ni-based SMA actuator can be improved to reduce this disadvantage when compared to the famous Ni-Ti SMA alloy. As option to reduce the time of response of single crystal Cu-Al-Ni-based SMA the heating procedure was developed and tested. To elaborate the heating conditions, the chemical composition of martensitic and austenitic single crystals, Cu-Al-Ni alloy samples were examined. The executed experiments clearly demonstrated the advantage of the preheating phase. The response time of the SMA prototype actuator was reduced to considerably adequate values when compared to those usually used as actuators in human prosthesis.

*Keywords. Single crystals, Shape memory alloys, Dynamic of hand prosthesis actuator, Heating methods.*

## 1. Introduction

The development of prosthesis for upper limbs with anthropomorphic characteristics of the human hand is a very important in prosthesis design. But the practical realization of proposed sophisticated kinematical models (Cunha, 2000) is difficult if based on any conventional actuator. One of new types of actuators is based on SMA that have the ability to recover from plastic deformation, which is sustained below critical temperature, by heating (Otsuka, 1999). The actuating force in any SMA actuators is the result of a dimensional change via solid-state transformation in alloys whose exhibit the shape memory effect, Fig.(1). Nowadays the Cu-Al-Ni single crystal alloys as force SMA element are very attractive.

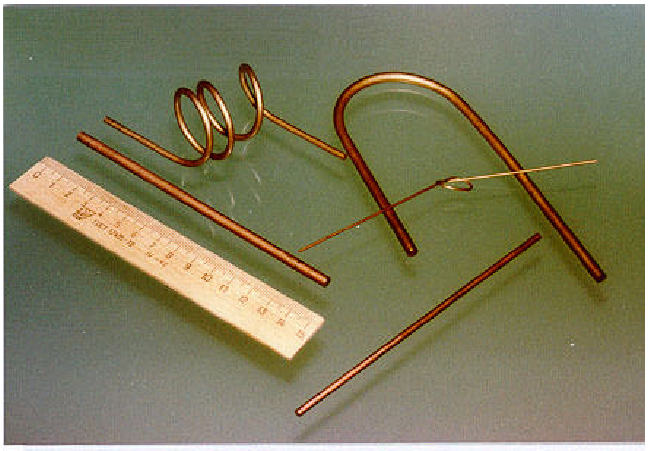

Figure 1. Samples of SMA Cu-Al-Ni single crystal alloys.

SMA Cu-Al-Ni single crystal actuators can be designed to operate in tension, compression or torsion and produce linear or rotary motion (Bhattacharya, 1994). Generally they have simple design, do not require mechanical reduction or any kind of sophisticated mechanism for displacement, and have greater output force/volume ratio (Priadko, 1997). There are examples of the use of Ni-Ti SMA actuators on prosthetic hands (Pons, 1999, Soares, 1997). Although the principle of SMA actuator control is simple, its dynamics is quite limited. Generally, the cooling part of thermal cycle defines the limiting speed of any SMA actuator. This is the traditional approach and it leads to more energy consuming prosthetic power modules. As alternative to the complete cooling cycle the prosthetic actuator can be established in a preheated state (Santos, 2002). Not only cooling time, but heating as well will be reduced (Cunha, 2003). Some new aspects of the dynamic of the Cu-Al-Ni single crystal SMA actuators with preheating were investigated.

**2. Materials and me thodology**

One scaled model of a future prosthetic actuator based on single crystals Cu-Al-Ni alloy fabricated in Institute of Robotics and Cybernetics of St. Petersburg, Russia was elaborated, Fig.(2).

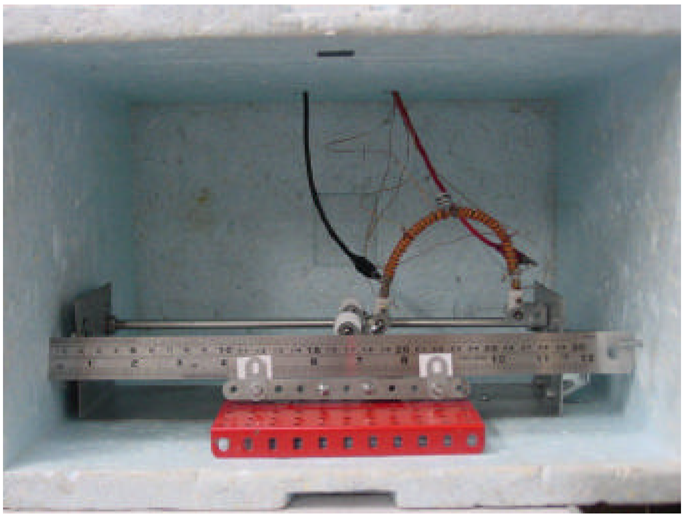

Figure 2. SMA experimental actuator.

In previous studies, the electrical (heating of the wire for Joule effect) and the thermal (heating of the wire for convection in a silica oil bath) SMA actuators with Ti-Ni-Cu-based composition were compared (Araújo, 1999). It was clearly demonstrated that the electrical SMA actuator is faster and it can offer the best dynamic results. In addition, its construction is simpler. The values of resistivity of single crystal SMA, 15,47-17,14 $\mu\Omega\cdot cm$ have been experimentally obtained. They are higher than the polycrystalline ones, probably because a small percentage of Fe was detected in the experimental samples. However, a low resistance of mentioned SMA discards the opportunity to directly apply the Joule effect due to heating. Consequently, the use of electrical single crystal Cu-Al-Ni-based actuator in prosthesis is more problematic, although it presents better performance.

To reduce the problem of the small resistivity, an alternative electrical SMA actuator was studied. In fact, current, in any conductor, is passed via its surface (Schmidt, 1979). Thus, if the battery poles are linked to different coaxially connected conductors, the resulting resistance must be increased because a current will pass through points on the surface. This way to increase the equivalent resistance was tested. Installed above SMA crystal, the simple stainless steel layer triplicates the resulting resistance. Of course, in this case, the electrical SMA actuator is being changed to another one of thermal SMA type actuator with thermal element incorporated, but its construction remains simple and uses the Joule effect. The thermal mode of heating for a single crystal Cu-Al-Ni-based SMA prototype actuator was established and a spiral of Ni-Cr was selected as an element for thermal heating. A cylindrical actuator with dimensions Ø3,98 mm in diameter and 194,52 mm in length, was heated by two serially connected electrical spirals of Ni-Cr 80-20 BS28 with an equivalent electrical resistance of 9.4 Ω.

To reduce heat dissipation, the actuator was installed in a thermally isolated box. Temperature was controlled through thermocouples installed in seven points: three of them in the SMA itself, one in the top of the heating resistance, one in the inside and the other outside of the thermal box. To adjust the initial point M0 used to measure displacement an additional weight of 100 g was applied. The other two points M1 and M2 were chosen such that the interval between M0 and M1 (40 mm) was reserved for the preheating and the interval between M1 and M2 (30 mm) left for allowing the performance of the claw. To compare the dynamics, the additional weight of 300 g and 600 g were applied. Initial temperature, speed and final temperature of preheating were adjusted. The initial temperature was varied between 22 and 42°C.

### 3. Results

Initially, the minimum necessary current to complete the phase transformation was established. For an assembled sample it resulted in 1.0 Ampere (A) region. Reducing this value resulted in an incomplete displacement between M1 and M2 points, indicating an unsuccessful phase transformation. Of course, the response time of about 150.0 seconds (s) for this current is not acceptable in prosthetic hand applications. The idea of preheating the sample was applied. Seeking the state close to the critical austenitic temperature without a complete phase transformation, the secure current and the corresponding appropriate temperature was chosen. Finally a 0.8A current reduces the preheating time to an acceptable preoperational value for prosthetic hand without a complete phase transformation. The initial point of the hysteresis curve was moved to the austenitic phase direction from 22ºC to 86ºC during preheating. After preheating, the actuator performance was significantly improved. In dynamic tests, the velocity value as function of preheating (initial) current, Fig.(3) and active (final) current, Fig.(4) to complete the displacement were experimentally obtained.

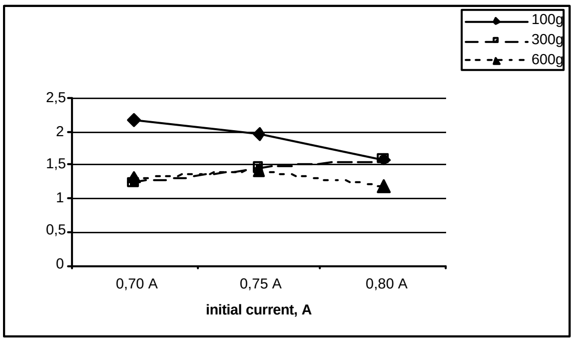


Figure.3. Velocity as function of preheating current.

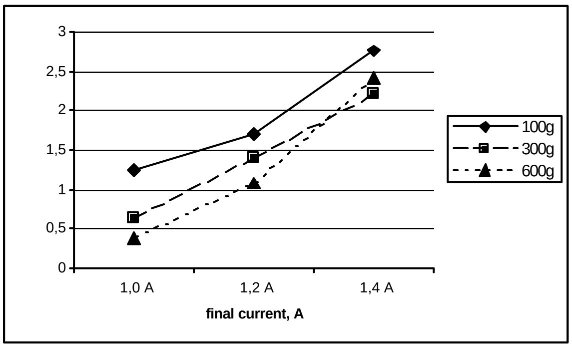


Figure.4. Velocity as function of active current.

### 4. Discussion

It can be observed that electrical SMA actuator type with better performance than the thermal is very problematic for any single crystal Cu-Al-Ni-based SMA actuator due to its low electrical resistance. This is the great disadvantage when compared to the famous Ni-Ti SMA alloy actuators. However, by preheating, the dynamic of thermal single crystal Cu-Al-Ni-based SMA actuator can be significantly improved. The executed experiments clearly demonstrated the advantage of the preheating phase. The response time of the SMA prototype actuator was reduced to considerably adequate values when compared to those usually used as actuators in human prosthesis (Pons, 1999). As shown here, the necessary final current to establish the preheating is quite acceptable for applications in human prosthetic design. Moreover, it is necessary to preserve and not dissipate this heat, which alters the own ideology of actuator design. The chemical analysis demonstrates a good way to optimize the preheating: displacing the hysteresis curve during the fabrication. This can be achieved if one compares the chemical composition of austenitic, Fig.(5), and martensitic, Fig.(6), samples.

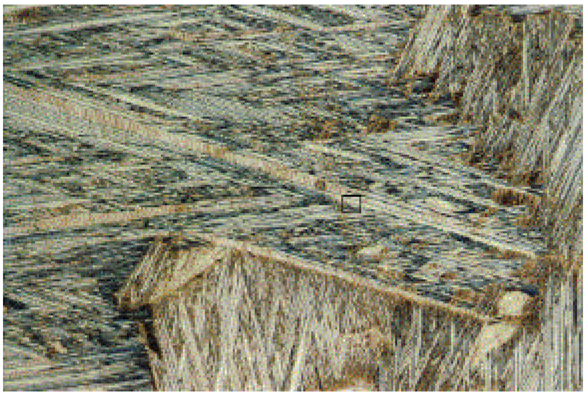

Figure 5. The martensitic sample

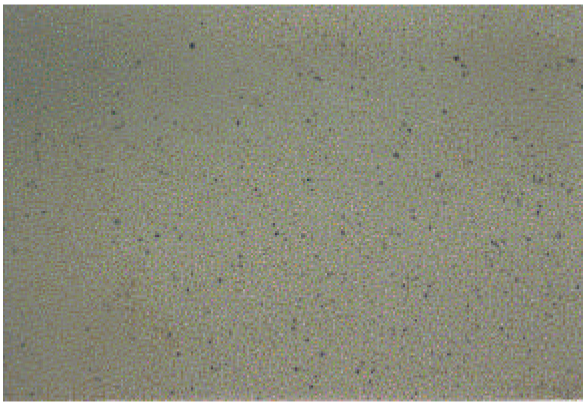

Figure 6. The austenitic sample.

Table 1. Experimental results for chemical analysis of austenitic and martensitic samples.

| Elements | Austenitic sample | | Martensitic sample | |
|---|---|---|---|---|
| | % mass | % atomic | % mass | % atomic |
| Cu | 83,29 | 72,15 | 86,13 | 75,60 |
| Al | 10,96 | 22,36 | 10,04 | 20,76 |
| Ni | 3,58 | 3,35 | 3,83 | 3,64 |
| Fe | 2,17 | 2,14 | -- | -- |
| Total | 100 | 100 | 100 | 100 |

Table 1 demonstrates that any varying the chemical composition might radically alter the properties of single crystal Cu-Al-Ni. It show the small percentage of Fe in austenitic sample if compare with martensitic one and the reducing percentage of Cu. Although the proprieties of austenitic and martensitic samples are completely different they have the same stress-strain curves as functions of temperature (Otsuka, 1999). But the curve of austenitic sample is dislocated to small temperature direction. It is the very interesting option for prosthetic actuator - the selection of percentage of Fe (or other element with the same effect). Not necessary to preserve the high preheating temperature, because it is possible to approximate the curve to ambient temperature. Apparently, the problem lays in exactly defining this percentage during the sample fabrication as a function of ambient temperature range and force developing for each model of prosthetic actuator.

## 5. Conclusion.

The results have shown the viability of application of single crystal Cu-Al-Ni-based SMA actuators in prosthetic construction. The preheating methodology reduces its response time and the economy of power supply did not significantly affected which is an aim of actuator design. In future works, it would be interesting to analyze the force/deformation relation as function of current variance for this type of actuator.

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