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# Behavior of NiTi-SMA and CuMnAl –SE smart system with optoelectronic command

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Smart materials like Shape Memory or Superelastic Alloys present some advantages in their applications as active elements for medical o orthotics. In this article is proposed a finger type driving system based on active elements like shape memory and superelastic alloys. The active element (SMA, stoichiometric NiTi) can be introduced in textile material with role of fixation and experimented for different bone conformations. The superelastic element (CuMnAl shape memory alloy) is used as recovery element during the cooling of the SMA wire. An experimental set-up was used in order to heat/cool the active element for behavior analyze of SMA element in time. The heating of the intelligent element was fulfilled through Joule effect or by hot air to analyze the activation and cooling periods. These elements are electrically activated with an optoelectronic system. The recovery stage of the system is sustained by a superelastic element made of CuMnAl obtained through classical induction melting.

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## 1. Introduction

Nitinol shape memory alloy are used in many medical applications (dentistry, orthodontics, cardiovascular, orthopedics etc.). Skeletal muscles are multi-functional actuators of human motor system with functions of actuating, energy-storing and self-sensing. In the last years many laboratories have conducted and are still conducting research on imitating the form and function of skeletal muscles. In this sense actuator devices (such as electric motors, hydraulics and pneumatics) and smart materials such as SMAs have been put forth as "artificial muscles". Conventional actuator devices, such as DC motor [1] and hydraulics [2] are hard to imitate skeletal muscles because of their low power density and large volume. Pneumatic artificial muscles [3], such as the "McKibben Muscles", can imitate the performance of natural muscle, but they are noisy and require a separate pump to provide the energy. In addition, the actuators mentioned above cannot imitate the self-sensing capability of skeletal muscles without additional sensors. First step in designing of an artificial muscle is the identification of the properties request in order to imitate a real biological one. The dynamic activity permits the movement of the segment body in space and the static activity permits the maintaining of the body position and the rest position [1]. In the scientific literature are a high variety of models proposed to describe the mechanical properties of skeletal muscles [3-5]. According to Hill model the skeletal muscles architecture can be simplified to three major components, figure 1,: contractile element (CE), parallel element (PE) and the element in the series (BE). CE represents the muscle fibers that generate the active contraction force. SE represents the tendons and PE element is the elastic recovery part that connects the extra solicitation of CE element and minimizes the danger of muscle lesions.

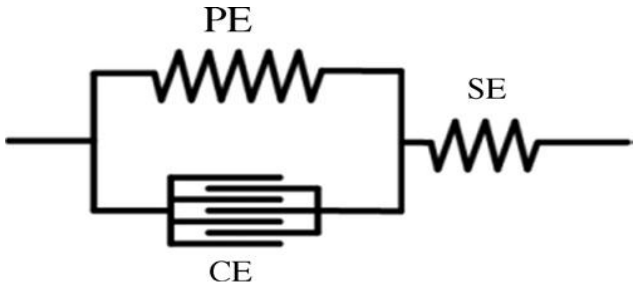



*Fig. 1. Schematically model of a muscle with three component elements*

Mechanical properties of skeletal muscles can be describe by analyze of relations between the force and rate and between force and length of skeletal muscle architecture length.

As CE element a shape memory alloy (SMA) NiTi can be used. Using a different number of SMAs wires put in parallel the artificial muscles can realize a needed contraction force with variable values. For example an experimental model can use 16 SMAs wires with a individual diameter of 0,15 mm and a rest length of 258 mm, Fig. 2 a).

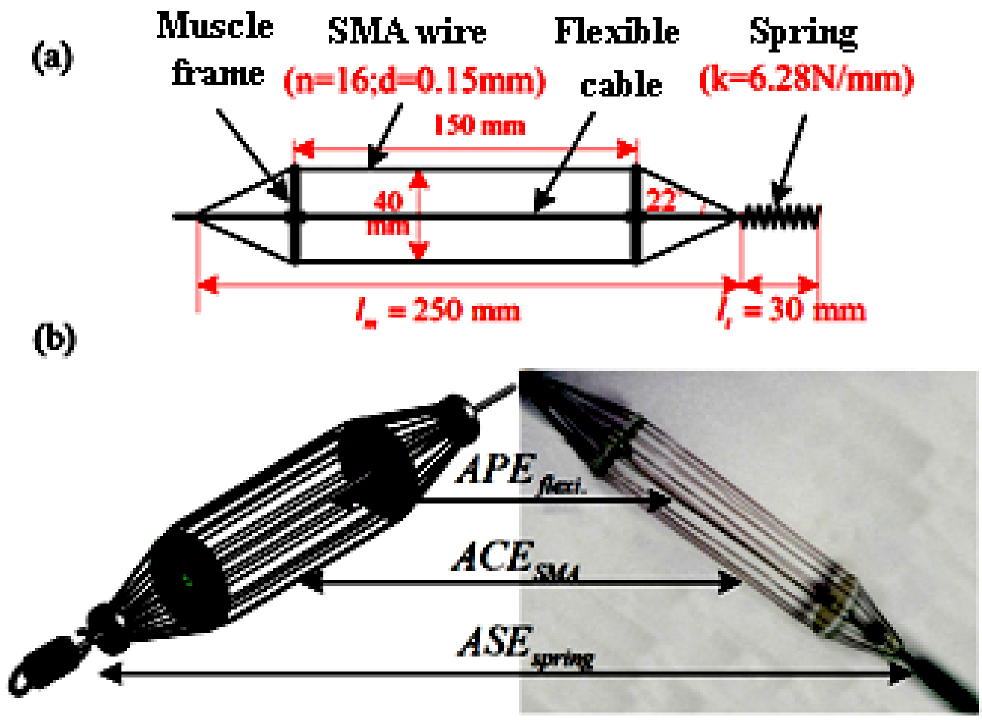



*Fig. 2. Schematically representation in a); CAD modeling and b) image of skeletal muscle [1]*

An artificial muscle with a total length of 280 mm can assure a contraction maximum force of 169 N and the maximum contraction length of 20 mm [4]. In order to maintain similar performances of biological muscles for the report force-rate during the imitation process of real muscles we have to use an anti overload which is added in parallel with the CE element [4, 5]. The constitutive elements get an A letter from artificial in new skeletal muscle sketch, Fig. 2.

The flexible body includes a flexible cable and two circular isolator plates which compose the muscle frame. When the length of element ACE is smaller than the rest length than the flexible cable is in a relaxation state with a passive equally zero force. In case that the ACE element is stretched near the rest distance the cable is gradually lying till a tensions state where the element manifests similar properties to arch wire.

The passive force of APE element increase quite fast high rigidities of the cable and the active ACE force decrease correspondently. This way the ACE element is protected by overload. More, this muscle format has the role of cooling are expansion for each SMA wire in order to improve the response rate of element ACE. Similar to skeletal muscles the artificial one must have a series of tendons as ASE element.

There are two main functions of the tendon element: the transmission of force for manipulation and to storage the energy for the research directions based of prosthesis. The biological tendon can be considered as an arch with different stiffness's.

In case of spastic patients which are initially treated to reduce the high muscle tone, the fundamental movements that must exist in an assistive system for their rehabilitation therapies are extension and flexion of all joints of the hand [5].

Thinking that the system designed should fit relatively easy onto hands with different degrees of spasticity, in some cases mounting the hand on the device may be difficult for patients who experience different degrees of pain when moving their hand or for those whose muscle tone is very high and offer much resistance when trying to extend the fingers.

With this in mind, the design of the mechanism for extending the fingers should provide facility to be mounted on the hand, different degrees of extension for different degrees of injury, possibility of treating fingers together or individually, and a friendly design to make the patient feel confident when using the device.

Additionally, in the neuro-rehabilitation process of a hand, touching the palm of the hand when extending the fingers or the back of the hand when flexing them must be avoided because this would cause a reflex reaction opposite to the desired behavior. For this reason the proposed design consists on a fixed device which is coupled to the arm and hand of the patient in such way that it blocks the movements of the wrist.

Each finger is gripped by the distal end through a pair of Velcro strips, making the adjustment of the machine to each finger smooth. The fingers are slightly flexed in the initial position. Maximum flexion must be avoided as this might harm the patient.

In the case of thumb, only the abduction and adduction movements are covered since this is enough to keep this finger away from the central axis of the hand in order to provide more space for the movement of the other four fingers and re-teach the brain how to open the hand.

Finally, since the initial position of the device operates with flexed fingers, the force used to extend them is applied from below the hand.

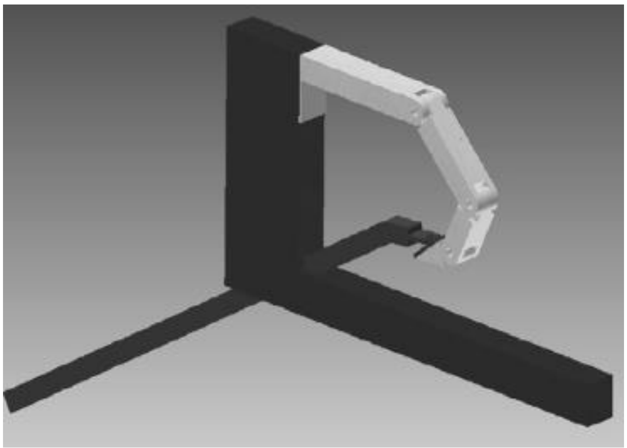


*Fig. 3. 3D model used to determine the inclination angle to extend each finger [5]*

To make this work with a single degree of freedom for each finger, such a force is applied at an angle of 30° to the coordinate plane of the hand. This angle was determined by simulation in Autodesk Inventor Professional building a 3D model of a finger and fixing it to a base, and then fixing a 3D model of a stick to the tip of the finger, Figure 3. To be able to apply force on the finger tip, a movement was programmed for the stick. While running simulations with different inclination degrees of the stick, it was found that an angle of 30° gave the best performance for the finger extension, giving a smooth movement and keeping all joints within range of motion.

In the real device, the force applied to the finger tips is generated by the Nitinol actuators and is transferred to each finger by means of aluminum rods that slide through bearings with low friction coefficient. In the case of the thumb, as the abduction and adduction movements are performed in a perpendicular plane to the flexion and extension of the other fingers, the mechanism must be different; therefore, a four bar mechanism crank rocker type was designed. The dimensions of this system were determined based on the size of the phalanges of the thumb, changing the pivot point between the meta-carpo-phalangeal and carpo-meta-carpal joints of the finger. To be able to use NiTi-alloy as an actuator of the thumb the crank was removed from the mechanism and the beam spread in order to place a Nitinol spring at each end of it.

The solid-state martensitic phase transformation which usually manifest in shape memory alloys (SMAs) is a diffusionless transformation type that can create interesting and useful properties, such as the shape memory effect, the two-way memory effect and superelasticity [6-8]. We present already the interest on shape memory for energy conversion and actuation so if we focus on superelasticity this phenomenon is characterized by a complex hysteretic stress–strain manifestation and it is particularly interesting for applications in impact absorption and damping [4]. Between the many shape memory alloy groups that have been reported in the literature the Cu-based SMAs are attractive because they can exhibit excellent shape memory characteristics at a substantially lower materials cost relative to the applications-dominant Nitinol alloys. In our faculty, Materials Science and Engineering from Iasi, we have a large experience on Cu-base shape memory alloys in different systems like CuZnAl, CuAlNi or CuMnAl [9-12].

In the same time copper base shape memory alloy present few disadvantages like stress concentrations at grain boundaries and triple junctions that arise to maintain coherency of the transformation strains make the Cu-based SMAs prone to brittle inter-granular fracture [12]. Recent progress on Cu-base SMAs in microstructures where grains are less blocked has pointed towards a strategy to overcome the problems associated with grain boundary fracture.

In Cu-Al-Mn alloy case the martensitic transition occurs in a composition region far from the Heusler stoichiometry. For this composition range, the β-phase is only stable at high temperatures, but can be retained at low-temperature by means of suitable cooling. During this cooling the system develops an ordered $L2_1$ structure (Fm3m, Heusler symmetry) in two successive disorder-order transitions: $A_2$ (Im3m) → $B_2$ (Pm3m) at $T_{c1}$ and $B_2$ → $L2_1$ at $T_{c2}$ ($T_c$: Curie temperature) [6]. Upon further cooling it undergoes a martensitic transition at a temperature which is strongly composition dependent. This transition has a diffusionless nature which ensures that the atomic distribution of the $L2_1$ phase is inherited by the M-phase. It is worth noting that this feature is common to all Cu-based shape memory materials [7].

In this paper we propose two smart metallic materials to action as ACE and ASE elements. A shape memory alloy (NiTi) as the contraction active element, ACE, is proposed and analyzed and a superelastic smart material (Cu10Mn20Al), ASE, is considered and investigated.

## 2. Experimental details

Shape memory alloys require special equipments for investigation with temperature variation in order to evidence the martensitic transformation. The active element (CE) NiTinol is acquisitioned from NIMESIS, Frontigny France [8] and the hot shape was educated in the Shape Memory Alloy analyze laboratory located at SIM – Technical University “Gh. ASACHI” from Iasi. Analyze of the response of the material with temperature variation in time was realized using a thermostat experimental dispositive. Using different currents (from mA to A) we analyze the response of the shape memory element at stimulus for activate the transformation (M→A) through Joule effect. The reaction time of the active element till full constrain at heating and till full extension at cooling under different weights was registered. The maximum load that the active smart element can recover using different weights was determined and also determination of heat treatment temperature for establish the hot shape of the shape memory alloy wire was realized. The block diagram of the device is schematically given in [9]. The computer software code is designed to allow the data entered by the specialist doctor. In order to change manually the parameters, it is provided also a bistabile assembly that can replace the computer and the acquisition plate and which through the rotation of two potentiometers of 100 K can act upon the parameters of the led-s, the photo resistance and implicitly on the equipment parameters.

The superelastic material (Cu10Mn20Al) was obtained by classical melting in UltraCast furnace in Argon atmosphere [10]. The new material was analyzed using scanning electron microscopy (SEM VegaTescan LMH II – SE detector), X-ray energy dispersive analyze (EDAX Bruker Quantax) and differential scanning calorimetry (DSC Maya 202).

## 3. Experimental results

The paper addressed in experiments to two smart materials, one consecrate NiTi as active element and the other a new material, CuMnAl, with superelasticity as arch plate.

SMAs are metallic alloys that after plastic deformation return to its original shape when subjected to heating [7]. This is known as a shape memory effect. This material, within a given range of temperatures, can be plastic deformed to almost 10% of its length. Some alloys with a spring shape can become up to 0.14 m long and regain its original shape when heated [8]. These effects are called thermal shape memory elastic and elastic shape memory. Both effects are due to a phase change called thermo-elastic martensitic transformation. Potential applications of these two main behaviors can generate force, motion, or energy storage [9].

Nitinol covers a wide range of nickel-titanium alloys with different nickel to titanium ratios (Ni50.5Ti49.5). Given the specific composition, the characteristics will change. One notable characteristic is the temperature at which nitinol transitions between its martensite and austenite states. This will affect how useful nitinol is in certain situations. For example, in order to use nitinol as an actuator, the transition temperature must be above and differentiable from room temperature so that actuation can be controlled with the addition of heat. Specific samples of nitinol with transition temperatures below room temperature remain in the austenite form and thus can be used because of their rigidity.

In Fig. 4 experimental results of the nitinol wire behavior is presented. The differential scanning calorimetry characterizes the transformation temperatures domain, austenite transformation points, on the heating process. Using an electronically power source (Electronics CO, DC Power Supply RXN-303D-II with 5V/30A) and a temporization device we heat, through Joule effect, the shape memory alloy in the transformation domain, Fig. 4 b).

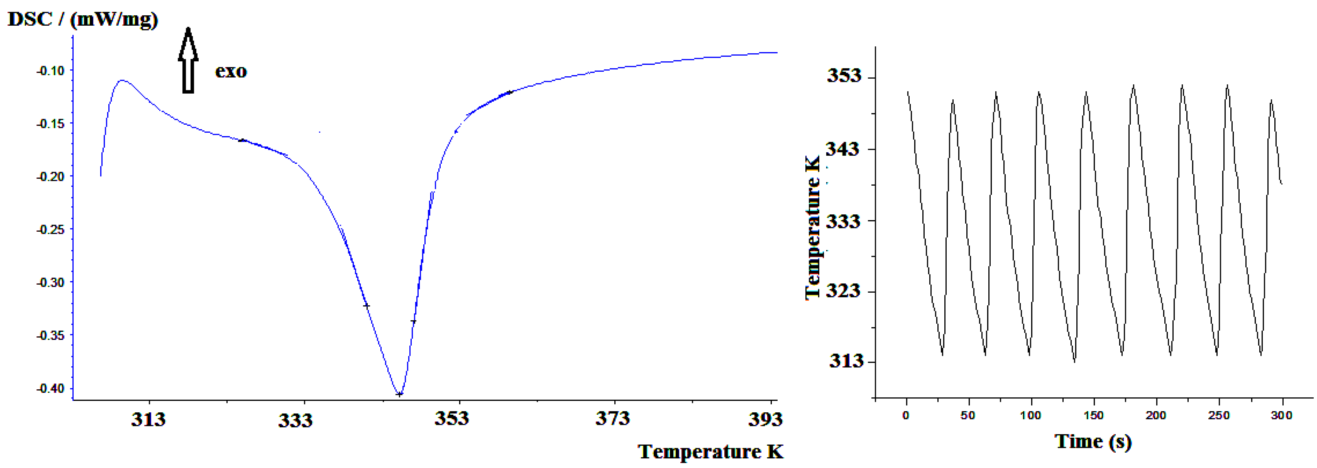



*Fig. 4. Active shape memory alloy experiments a) differential scanning calorimetry and b) temperature- time variation of the shape memory alloy*

From the experimental observations [10] a modification of the martensitic transformation domain occurs after 5000 cycles of thermo-mechanical solicitations of the material at the first arch coil.

In this case the mechanical solicitations of caching the spring using a screw and the experimental solicitations lead to a movement of the transformation temperatures points to a higher temperature. This fact can greatly influence the function of the active element and the applications of the shape memory alloys in actuation domain in long time usage terms.

From this experimental session, it was found that Nitinol springs by themselves take too much time to recover their shape, but it is possible to get a better response by cooling them and using a different configuration, in which there is a spring opposite to the other.

Also, it has been determined that a careful control algorithm can be implemented to decrease reaction times resulting in a more efficient design. Given this, nitinol wire can be implemented in any actuator design, allowing for customizable specifications giving nitinol actuation an edge to other methods for certain applications.

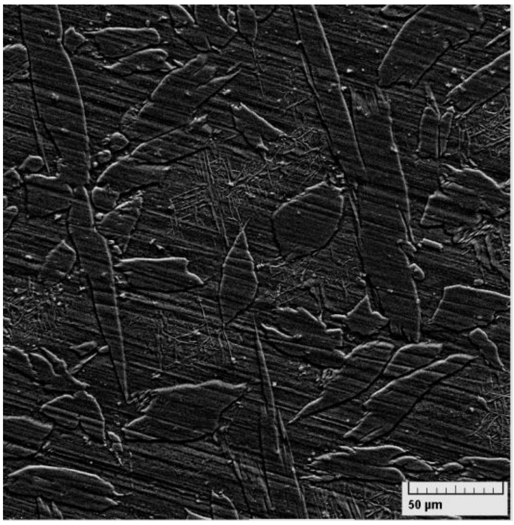
SMAs are subjected to fatigue when they are used in most of applications. Fatigue involves severe alterations in microstructure. Thermal and/or mechanical cycling originates new defects in crystal lattice and nucleation and growth of cracks that leads to the failure of components (classical mechanical fatigue, also called structural fatigue) [11, 12]. Like any other engineering material, this kind of fatigue is affected by microstructural properties of samples such as grain size, lattice defects, inclusions, surface quality and experimental setting parameters like temperature, type of loading, environmental conditions, geometry of specimen [13].

Moreover, irreversible changes in microstructure, in particular the formation of new dislocation substructures, influence functional properties of SMAs modifying characteristic temperatures and causing loss of memory, pseudo elasticity or damping capacity (this phenomenon is named shape memory fatigue or functional fatigue) [14, 15].

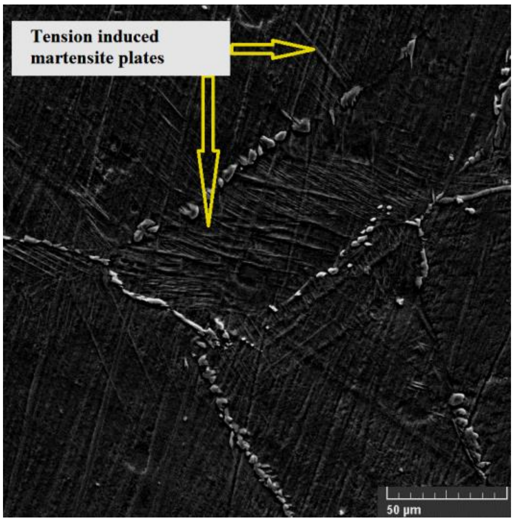
During working life, SMA actuators are subjected to thermal cycling under external load through the transformation range (thermo-mechanical cycling, TMC) and they are expected to complete the desired operation repeatedly without any deterioration in the strain response [16-19].

Some intelligent materials like shape memory alloys exhibit a nonlinear thermo-mechanical response associated with stress - induced transformations of their crystalline structure. These reversible (M→A) transformations lead to the special properties of superelasticity and shape memory effect. However the superelasticity and shape-memory effects are induced in shape memory alloys by reversible and diffusionless, solid to solid phase transformations. For nitinol alloys the structure transformation take place from a highly ordered austenitic (simple cubic, B2) crystal structure to a less ordered martensitic (B19', monoclinic) structure. The stress-induced austenite-to-martensite transformation is effected by the formation of martensitic structures which correspond to system energy minimizers. During heating the martensite to austenite (reverse) transformation, all variants transform back to the same parent phase.

In conclusion if the material is tested just above its transformation temperature to austenite, the applied stress transforms the austenite to martensite and the material exhibits increasing strain at constant applied stress, i.e. considerable deformation occurs for a relatively small applied stress.




*(a)*




*(b)*

*Fig. 5. S.E.M. microstructure of CuMnAl before a) and after b) lamination deformation*

When the stress is removed, the martensite reverts to austenite and the material recovers its original shape. In order to use this effect we obtain a superelastic material based on copper with an austenite structure at room temperature and transformation domain under zero degrees. Lamellar spring made by superelastic Cu10Mn20Al shape memory alloy present an austenitic state at room temperature, the microstructure of the alloy is presented in Fig. 5, a) as melted state and b) laminated state.

Grains structure with $\alpha + \beta$ phase, Fig. 5a), is visible in the homogenized condition of the alloy; which is a pre requisite for martensite formation on quenching indicating that all the alloys have potential for exhibiting the shape memory behavior.

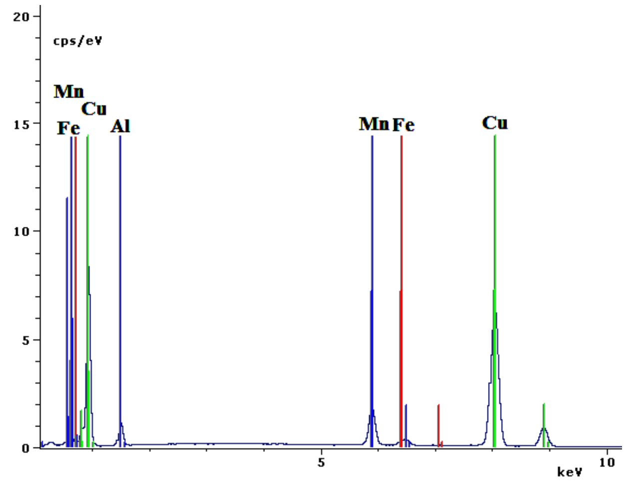
The martensite formation, Fig. 5b), is observed in most of the areas of the laminated samples however with different morphologies. The martensite that appears on the laminated microstructure is a stress induced martensite and is guilty for the super-elastic behavior of the material at room temperature. The superelastic behavior in Cu–Al–Mn alloy is strongly related to the crystallographic orientation as well as the grain size so the control of the orientation as well as the size of the grains is important for obtaining stable super elasticity [20-22].

The characteristic temperatures (Ms, Mf, As, and Af) and the hysteresis of the martensitic transformation mainly depend on the composition of alloy, the size and volume fraction of precipitates and in our experimental alloy case are under room temperature toward negative values.

Chemical composition of the shape memory alloy with superelastic behavior is presented in Table 1.

In such alloys the strain produced on stressing may be accommodated by favourably oriented plates of martensite, which grow during the further deformation (formation of stress-induced martensite) and/or by the growth of favourably oriented twins in the martensitic structure followed by growth of more favourably oriented martensite variants at the expense of other variants.

*Table 1. Chemical composition of experimental alloy CuMnAl with super-elastic behavior at room temperature*




| Chemical element | wt% | at% | EDAX error % |
|---|---|---|---|
| Cu | 79.41 | 69.16 | 1.7 |
| Mn | 10.19 | 10.26 | 0.3 |
| Al | 9.69 | 19.87 | 0.5 |
| Fe | 0.72 | 0.71 | 0.1 |

The super-elastic behavior in polycrystalline is different from that in a single crystal. The residual strain is always higher in polycrystalline materials than in single-crystal ones under the same load conditions. Unrecoverable deformation and damaging of super-elastic properties arise from the grain constraint.

## 4. Conclusions

Analyzing the results the authors comes to these conclusions:

- Shape memory alloys are highly used in new applications were an actuation movement is necessary in order to obtain mechanical work from different energy types.
- The artificial experimental model proposes for a biological muscle can benefit of the shape memory properties as shape memory effect and superelasticity for contraction operation and shape recovery.
- Through a careful analysis and testing of Nitinol wire, it was determined that an actuator could in fact be designed using Nitinol as the method of actuation. This actuator design can be made by following a step by step procedure that incorporates the results from the tests performed
- The new experimental alloy Cu10Mn20Al presents good superelasticity in austenite state at room temperature and respond for the necessity in the return movement of the active element. Off course it is necessary a very good design of the dimensions and the effect of the superelastic element in order to perform a proper work with the shape memory alloy element.

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