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USAGE OF SHAPE MEMORY ALLOYS IN MECHATRONIC EDUCATION

Summary. Shape Memory Alloys are very interesting and can be used in various applications in many different fields of life. The most important are in medicine, military, security systems, transport and many others. In some applications usage of SMA's just increase their performance and some of applications are impossible without SMA's. Actuators using this technology have several advantages and will be developed in the future. New applications are being supposed to appear every year and number of them will probably increase for a long time. One is for sure – modern engineer should know such material and should be ready for using it. The way to achieve this purpose is education. Walking robot „Bolec" and other educational devices, propelled by Muscle Wires, let students to learn basics of this modern technology. Author's experiences show that this subject meets students interest and engagement especially when student can touch it and use it on his own way during projects and laboratories. „Bolec" – made by student – is the best example of student's creativity and learning will.

STOPY Z PAMIECIĄ KSZTAŁTU W EDUKACJI MECHATRONIKI

Streszczenie. Stopy z pamięcią kształtu są bardzo interesującym materiałem z powodzeniem wykorzystywanym w wielu dziedzinach życia. Najważniejsze pola zastosowań to: medycyna, wojsko, zabezpieczenia, transport i wiele innych. W pewnych zastosowaniach stopy z pamięcią kształtu poprawiają działanie układu, inne zaś nie mogłyby bez nich działać. Siłowniki zbudowane na bazie tego materiału mają szereg zalet i na pewno będą się nadal rozwijać. Liczba aplikacji tych stopów zwiększa się z roku na rok Jedno jest pewne – dobry inżynier powinien znać te materiały i umieć je zastosować. Robot kroczący „Bolec" i inne edukacyjne urządzenia, napędzane przez sztuczne mięśnie, pozwalają studentom zapoznać się z podstawami tej nowoczesnej technologii. Doświadczenia autora wskazują, że tematyka ta spotyka się z zainteresowaniem studentów, zwłaszcza wtedy, gdy mogą oni dotknąć i użyć materiału na swój sposób podczas zajęć laboratoryjnych lub projektowych. Robot „Bolec" – wykonany przez studenta – jest najlepszym przykładem kreatywności i chęci nauki.

1. INTRODUCTION

Shape Memory Alloy (SMA) is unique material able to change its shape due to temperature rise or fall. This phenomenon is called Shape Memory Effect (SME) and can be observed (with different strength) in many alloys. In 1962 William J. Buehler at the U.S. Naval Ordnance Laboratory (NOL) investigated the shape memory effect in the alloy of nickel and titanium. He named this alloy briefly "NiTiNOL" (from **NI**ckel - **TI**tanium - **N**aval **O**rdnance **L**aboratory) and patented its technology. It has several interesting properties causing that it can be used in many untypical applications. NiTiNOL was worked out at the end of XX Century and nowadays is being sold under commercial name Flexinol. Increasing number of applications shows that it can be useful in almost all fields of life. Special abilities makes it to be very attractive especially in robotics and mechatronics.

2. PROPERTIES OF SMA

The shape memory effect is caused by temperature and stress dependent shift in the material's crystalline structure changing between two different phases called martensite and austenite. Martensite, the low temperature phase, is relatively soft whereas austenite, the high temperature phase, is relatively hard. The change of state follows as a result of the heating or cooling of the alloy. During state change the phenomenon of the temperature hysteresis appears. Hysteresis width (T1 in Fig.1) is defined as the difference between the temperatures at which the material is 50% transformed to austenite upon heating and 50% transformed to martensite upon cooling. This difference of temperatures can reach (20-30)° C.

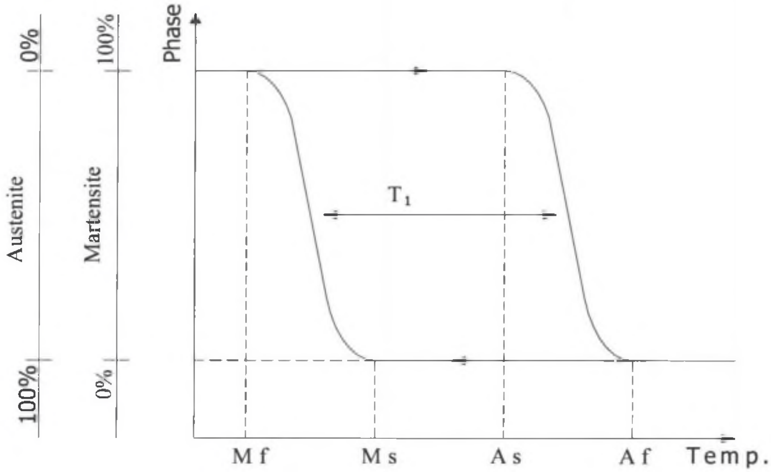

Fig.1. Hysteresis of SME
Rys.1. Histereza efektu pamięci kształtu

If any NiTiNOL part (Fig. 2a) is annealed at 540°C and is allowed to cool below the phase transition temperature (Mf), the crystalline structure will change to martensite (Fig. 2b) without shape change. Now, if the part is plastically deformed (Fig. 2c), for example by bending, and then reheated above the phase transition temperature (Af), it returns to its original shape. This phenomenon is material property and is called one-way shape memory effect (Fig.2.).

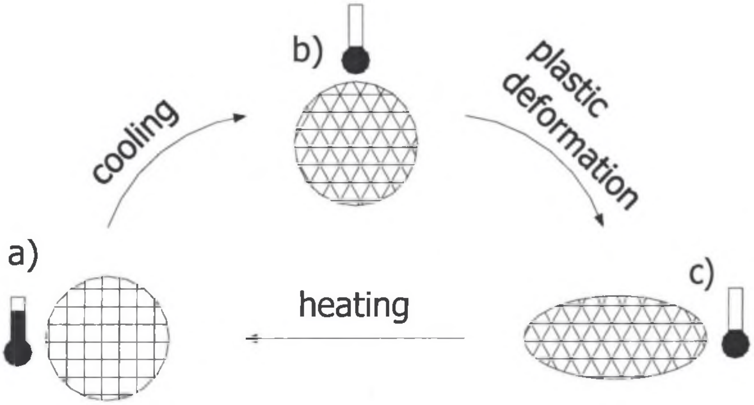

Fig.2. One-way shape memory effect
Rys.2. Jednostronny efekt pamięci kształtu

There is also a phenomenon called two-way shape memory effect (Fig.3.). Its main feature is that during a change of crystalline structure from austenite to martensite (during cooling) a sample of material also changes its shape. The material is as if it had remembered two shapes and becomes transformed between them without part of external stresses but only due to a change of temperature. However, the two way shape memory effect is no longer material property, but is acquired in technological process, which is called training. It consists of serial repetition of the following procedure:

- Max. 3% bending in martensite;
- Heating over austenite transformation temperature (material recovers its primary shape);
- Cooling to martensite.

After many repetitions, finally we get shape memory alloy capable of recovering a pre-set shape upon heating above its transformation temperatures and returning to an alternate shape upon cooling.

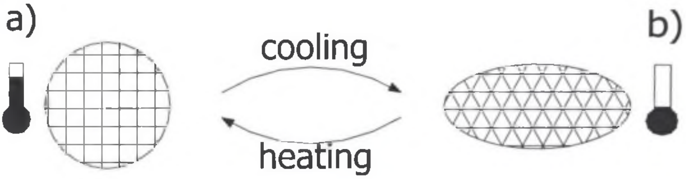

Fig.3. Two-way shape memory effect
Rys.3. Dwustronny efekt pamięci kształtu

3. BASIC PROPERTIES

In industrial applications only AlCuZn and NiTi alloys are used. The latter one, known as NiTiNOL (or Flexinol), is used most often. Beside the above mentioned effect it has several additional properties as e. g.:

Superelasticity - in some temperature range (Ms<T<As) NiTiNOL shows its unusual elasticity and as soon as the stress is removed it returns to its original shape. The reason for this is that in this temperature range the material is over its normal martensite temperature.

Relatively constant force during decompressing in quite wide range of deformation (few %).

Biomechanical and biological compatibility - unlike steel or Titan, NiTiNOL has non-linear mechanical characteristics like natural tissues: hair, bone or tendon. This causes that NiTiNOL is ideal prosthetics material. Even though it includes more Nickel (considered as toxic) than steel it is safe because in NiTi alloy intermolecular bonds are stronger and the alloy is covered with a layer of TiO2 so less Nickel is released. Experiments confirm that NiTiNOL is chemically more stable and more resistant to stain than stainless steel.

Magnetic properties - NiTiNOL is non-ferromagnetic with a lower magnetic susceptibility than stainless steel.

The following tables present basic physical and chemical parameters of NiTiNOL (Tab.1.) and Flexinol wires (Tab.2.)

Table 1

Elementary properties of NiTiNOL

Activation start temperature	68°C
Activation finish temperature	78°C
Effective transition temperature	70°C
Relaxation start temperature	52°C
Relaxation finish temperature	42°C
Annealing temperature	540°C
Melting temperature	1300°C
Heat capacity	0,322 J/g°C
Density	6,45 g/cm^3
Energy conversion efficiency	5%
Max. deformation ratio	8%
Recommended deformation ratio	(3 – 5)%
Young's Modulus	28 GPa

Table 2

Elementary properties of Flexinol for different wire diameters

Property	**Wire type**					
Wire diameter (μm)	25	37	50	100	150	250
Min bend radius (mm)	1,3	1,8	2,5	5,0	7,5	12,5
Linear resistance (Ohm/m)	1770	860	510	150	50	20
Recommended current (mA) [1]	20	30	50	180	400	1000
Recommended power (W/m) [1]	0,71	0,77	1,28	4.86	8,00	20,0
Max. recovery force (N) [2]	0,284	0,645	1,147	4,599	10,356	28,763
Rec. recovery force (N) [3]	0,069	0,204	0,343	1,471	3,236	9,12
Rec. deformation force (N) [4]	0.020	0,039	0,078	0,275	0,608	1,687
Min. contraction time (s)	0,1	0,1	0,1	0,1	0,1	0,1
Relaxation time (s)	0,1	0.2	0,3	0,8	2,0	5,5
Typical cycle rate. (cycles/min)	55	52	46	33	20	9

[1] In still air at 20 °C
[2] Wire stress 600 MPa
[3] Wire stress 190 MPa
[4] Wire stress 35 MPa

4. USAGE POSSIBILITIES

Most commercial applications of shape memory alloys can be grouped into three broad categories: **Superelastic Devices**, **Shape Memory Actuation Devices**, and **Martensitic Devices**.

The Superelastic SMA Devices are used for these applications, which demand the extraordinary flexibility and torqueability. SMA materials have the unique ability to absorb large amounts of strain energy and release it as the applied strain is removed. The elasticity of Ni-Ti is approximately ten times bigger than elasticity of steel.

The Shape Memory Actuation Devices use the shape memory effect to recover its shape upon heating above their transformation temperatures. Shape memory actuation devices can act without constraint to freely recover their trained shape, can be fully constrained so that they provide a force, or can be partially constrained so that they perform work. The transformation temperatures of the Ni-Ti alloy can be adjusted (by its chemical composition) to activate at the required temperature. Common actuation temperatures are human body temperature and boiling water temperature.

The Martensitic Devices use unique properties the Ni-Ti has in martensite phase. First, the martensitic phase transformation has excellent damping characteristics due to the energy absorption characteristics of its twinned phase structure. Second, the martensitic form of Ni-Ti has remarkable fatigue resistance. Finally, the martensitic phase can be easily deformed, but it will also easily recover its original shape upon heating.

5. SHAPE MEMORY ALLOYS IN MECHATRONICS

In Mechatronics SMAs are most frequently used as temperature-controlled actuators. Such actuator has a lot of advantages:

- It has a very simple structure – it is small and safe,
- It offers linear movement without any transmission needed in rotary machines,
- The stroke and force can be easily modified by the selection of the SMA element,
- It works clean, silently, makes no vibrations, no dust (there is no friction), no sparks - it does not need high voltage,
- It can be safely used in very flammable environments,
- SMA element can be easily controlled in range of small movements and accelerations,
- SMA elements offer very high power to weight (power to volume) ratio. It can lift about thousand more then its own mass.

Of course it is no ideal so there are some disadvantages of SMA actuators:

Low energy efficiency - the maximum theoretical efficiency of a Carnot cycle is about 10%. In reality, that efficiency is at least one order smaller than the theoretical Carnot value.

Limited bandwidth due to heating and cooling restrictions - shape memory actuators can be heated in different ways, radiation or conduction (thermal actuators) and by inductive or resistive heating (electrical actuators), and this is generally fast (about 0,5 s). The response speed is mainly limited by the cooling capacities.

Degradation and fatigue - the reliability of shape memory devices depends on its global lifetime performance. Parameters having strong influence on the lifetime are: time, temperature, stress value, deformation value, number of cycles, the alloy system, composition, the heat treatment, and the processing technology.

Complex control_ - shape memory alloys show a complex three-dimensional thermomechanical behaviour with hysteresis. Moreover, this behaviour is influenced by a large number of parameters. It follows that there are, in general, no direct and simple relations between the temperature and the position or force. Therefore, accurate position or force control by SMA actuators requires the use of powerful controllers and the experimental determination of complex data.

In spite of those limitations Shape Memory Alloys seem to be extremely interesting material difficult to replace with anything else.

6. EDUCATIONAL WALKING ROBOT

“BOLEC” – educational walking robot was made with low funds by student of Division of Mechatronics at Silesian University of Technology in January 2004. It is used in Laboratory of Mechatronics for demonstrating abilities of Shape Memory Alloys as actuators. It is interesting, showy, stimulating student’s fantasy device, very helpful in education process.

It is super light – its weight is about 35 g. It was made using light material called styropren, plastic and wires. Its bone is made from bicycle spoke. It is propelled by Flexinol Muscle Wires by specially projected controller. Bolec is not autonomic robot – it must be connected to power supply and to PC computer all the time. Light construction did not allow for carrying batteries. Bolec is fully programable and PC computer is used for controlling the movement of robot. The control program is written in QBasic and is very easy to understand and modify. Basic program lets it step forward and backward with speed of about 12 cm per minute, and also lets him turn left or right. Following pictures present its basic views (Fig.4) and its photo (Fig.5).

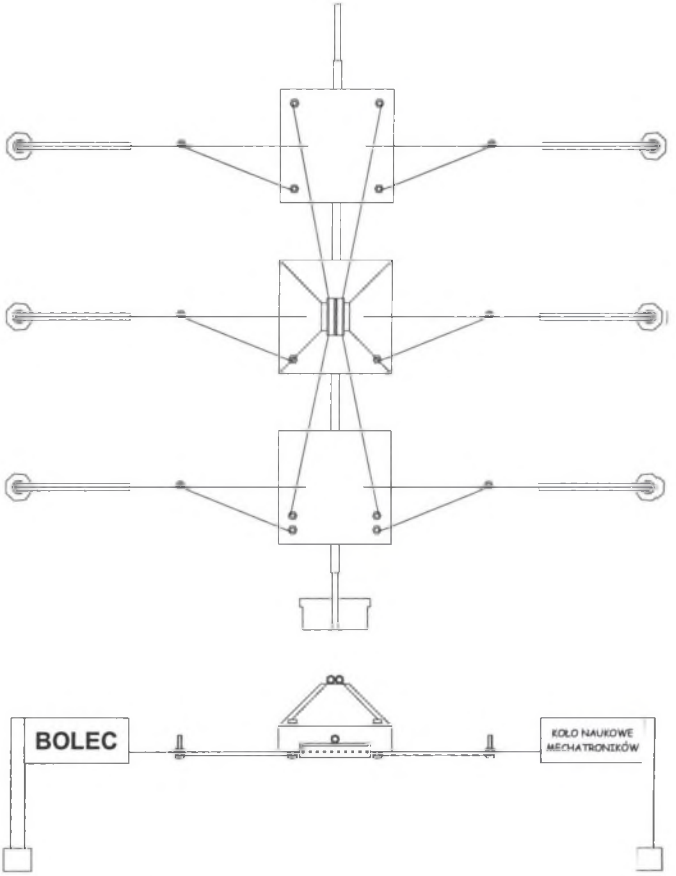

Fig.4. Front and upside view of “BOLEC”
Rys.4. Widok „BOLCA” z góry i z przodu

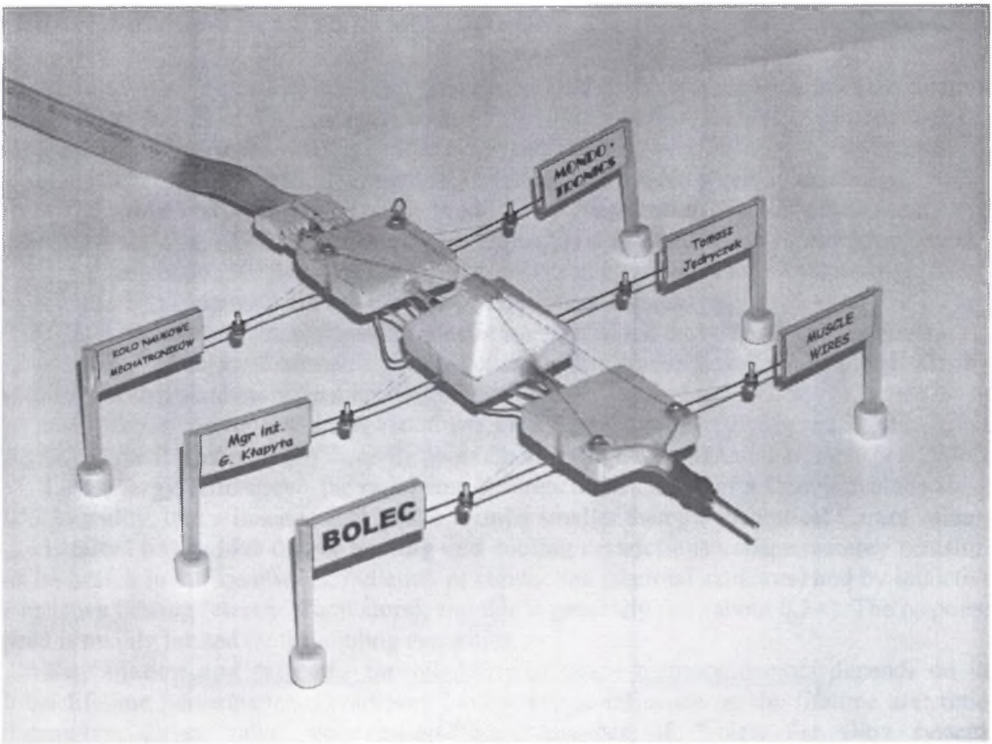

Fig.5. Walking robot "BOLEC"
Rys.5. Robot kroczący „BOLEC"

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