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EXPERIMENTAL VERIFICATION OF THE SHAPE MEMORY ALLOY (SMA) SPRING ACTUATOR FOR APPLICATION ON IN-PIPE MACHINE

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Preliminary Note – Prethodno priopćenje

The paper deals with Shape memory alloy (SMA) spring analysis and its possibility for usage as actuator for in-pipe machine. In the paper the inner structure of SMA is introduced. Further, the experimental analysis of SMA contractor and expander was done. From the experiments was found that SMA spring has several disadvantages like long time of cooling and high electric power consumption. Using SMA spring as actuator for in-pipe machine has been obtained average velocity of in-pipe machine roughly 2 mm/min. Advantage of SMA spring as actuator is its good expansibility.

Key words: SMA, spring, actuator, Matlab

INTRODUCTION

SME–Shape Memory Effect was discovered in 60s on Ni-Ti alloy. This alloy was developed by Buchler and Wiley at the Naval Ordance Laboratory (NOL) and was named Nitinol. Shape memory materials are significant and growing group of intelligent materials. These are alloys, which at the phase transition temperature (or also transformation temperature) change their crystalline structure and shape. When heating above the transition temperature alloy gets to cubic structure and returns to the shape that had before deformation. We say that a body has the shape memory. At present is known more than 20 SMA alloys, in which there is the shape memory effect (for example, Ni - Ti, Cu - Sn, Au - Cd, Ni - Al, etc.) These alloys by their characteristics belong among unique materials with a wide application in flying, cosmic and regulatory, technology, medicine, and especially surgery, dentistry and orthopaedics and micro-electromechanical systems (MEMS), where are implemented micro-actuators, constructed of materials with shape memory [1-3].

SHAPE MEMORY ALLOYS AS ACTUATORS

The external manifestation of SME is shape change of body, which arises during heating and cooling. Heating these materials is performed by passing an electric current through an executive element and its control is relatively easy because the heat developed is proportional to the resistance executive element and the current, which passes by it. Cooling largely depends on the environment and factors such as temperature of environment or flowing around the actuator can be very difficult to control. Moreover, the cooling lasts more slowly than heating.

Physical basis for the explanation of the shape memory effect is diffusionless phase transition in solid state - martensitic transformation, whose course in SMA can be controlled by varying temperature or external stress. Phase existing at a higher temperature has a cubic crystal lattice and is called austenite. Phase obtained by cooling or by external forces is called martensite and has a crystal lattice with lower symmetry.

In Figure 1, ξ(T) represents the martensite fraction. The difference between the heating transition and the cooling transition gives rise to hysteresis where some of the mechanical energy is lost in the process. The shape of the curve depends on the material properties of the shape-memory alloy, such as the alloying and work hardening [4, 5].

Mechanical movement in SMA alloys is caused by changes in the crystal structure of metals, as can see in Figure 2.

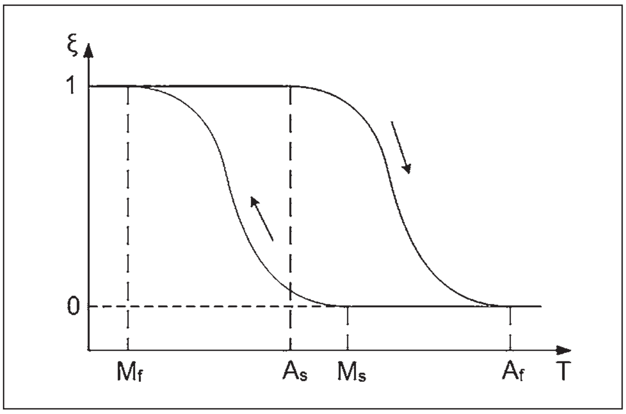

Figure 1 Curve of heating and cooling SMA alloys

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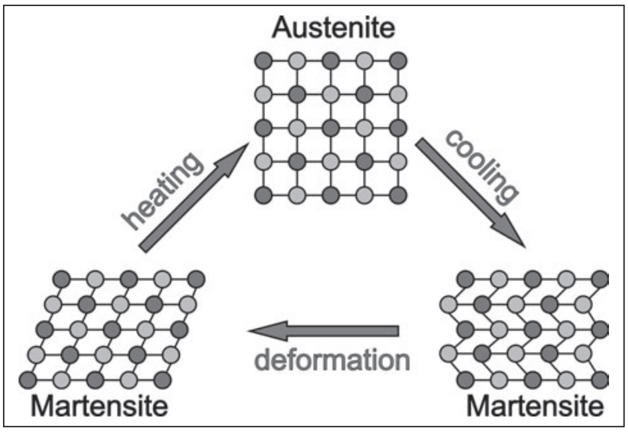

Figure 2 Changes in the crystal structure

The simplest function that describes the diagram in Figure 1 is Falke model that represents the polynomial dependence of extension **ε** and temperature T:

$$F(\varepsilon, T) = \alpha\varepsilon^{6} \cdot \beta\varepsilon^{4} + (\delta T - \gamma)\varepsilon^{2} + F_{0}(T) \qquad (1)$$

where α, β, γ, δ are material constants [1, 2].

Phase change is achieved by performing mechanical work or heating. The relation between stress and deformation we get by differentiation of function F according deformation [2]:

$$\sigma(\varepsilon, T) = \frac{\partial F(\varepsilon, T)}{\partial \varepsilon} \qquad (2)$$

This relation can be implemented into finite element method (FEM) as a very useful tool for modelling SMA. Expression of the mechanical properties of SMA is directly linked with the temperature change. That manifests by a change of stress in the internal structure of the material. This subsequently influences the deforming of a body. The Figure 3 shows the dependence of stress change during the transition states corresponding to a given temperature.

Individual parameters in the Figure 3 are: T is the temperature, σ is the stress, ε is the strain, σ_s^{cr} and σ_f^{cr} are starting and ending critical stresses at C_M martensitic transformations. M_f, and M_s temperatures represent a critical ending and initial temperatures of martensitic transformation. A_s and A_f temperatures represent critical initial and ending temperature of austenitic transformation [6, 7].

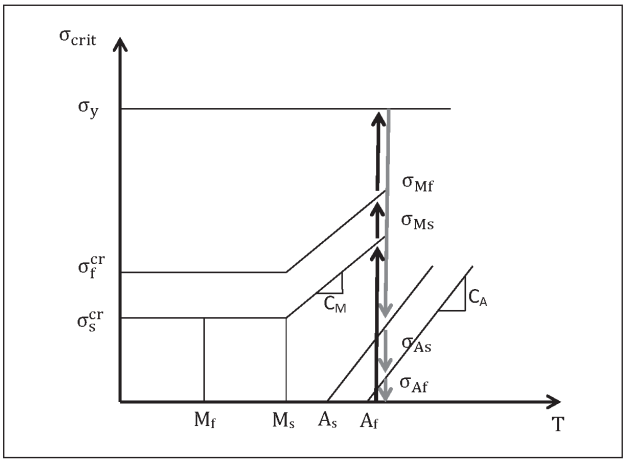

Figure 3 Mechanical property of SMA in critical stresses for transformation versus temperature [6]

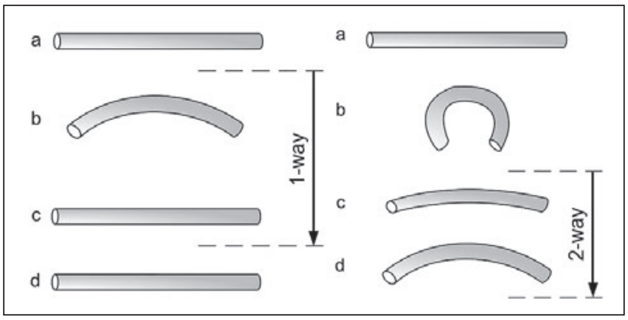

Figure 4 One-way memory effect and two-way memory effect, (a) starting from martensite, (b) adding a reversible deformation (1-way) or severe deformation with an irreversible amount (2-way), (c) heating the sample and (d) cooling it again

Shape memory alloys have different shape-memory effects. Two common effects are one-way and two-way shape memory. A schematic of the effects is shown below in Figure 4.

EXPERIMENTAL VERIFICATION OF SHAPE MEMORY ALLOY SPRINGS FOR IN-PIPE MACHINES

SMA springs can be used in two variants: contractive and expandable (in case of application like in-pipe machines). To achieve a specific movement of micro machine inside the pipe, we have to consider not only the gradual cyclical movement but also the overall mutual interaction between micro machine and pipe. Said interaction depends not only on used actuators, geometrical shapes, and construction but also on the suitable control of the mechanism. In terms of locomotion, the most important elements of mechanism are its structural parts that directly interact with the surrounding environment and have a great influence on the movement. Such structural parts include actuators and tactile bristles. The role of SMA actuator is to excite propulsive movement forward. We therefore experimentally verified both SMA spring variants suitable for application in the in-pipe machine. In the first experiment, we have connected contractive spring made from Nitinol to voltage supply. Contraction of the spring was verified at different loads that affected the spring in form of various weights. After the connection of individual weights of the values between 50 grams to 500 grams (with raising of 50 grams), we have changed tenseness by one Volt until the tension in which it was possible to see contraction of spring.

At the same time, we have recorded the values of currents that passed through the spring. The dependencies of contraction displacements on change of currents for specific force application in the Figure 5 is shown. From these results can be concluded, that the characteristics have a linear character. It means that by using regression of values obtained, we construct a relationship

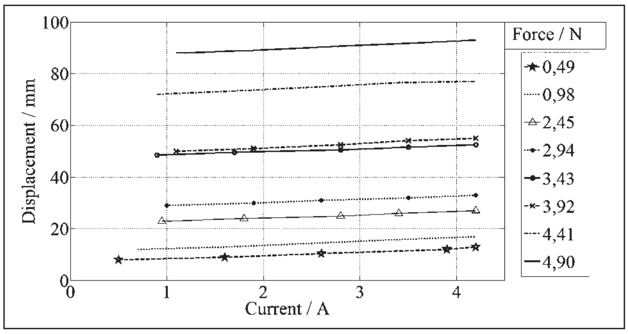

Figure 5 Characteristics of displacements in contractive process of Nitinol spring

by which we can determine the current of connection for specific shift. In the second measurement, was examined a spring from Nitinol, with an initial length of 26 mm. Unlike the first case, the measurement was implemented in such way, that traditional steel springs was placed into a spring of Nitinol. Steel springs have the following stiffness coefficients:

$k_1 = 309{,}13$;
$k_2 = 177{,}34$;
$k_3 = 351{,}67$;
$k_4 = 343{,}21$;
$k_5 = 308{,}82$.

There was achieved reversed counteract to Nitinol spring, while current passed through it. As in the previous case, there was also changed voltage but in the interval of 0 to 2 V (with a step range of 0,2 V). Simultaneously with the change in voltage, the current passing through spring and the displacement of deflection of spring were measured. The results of measurements are shown in Figure 6. From the graphs of dependence of displacement on the change of the current, it follows that Nitinol spring was able to stretch up to 9 mm maximal. The most linear character of dependence occurred when using a spring with $k_3 = 351{,}67$ coefficient.

Previous experimental analyses are now necessary for designing of in-pipe machine based on SMA spring actuator. Let´s consider following sequence of locomotion. During the first phase the in-pipe machine is supplied by electric current. Due to current the SMA spring starts heat and front of the machine moves forward while rear of machine is static because of friction between bristles and pipe. During second phase the current is not flows through SMA spring and it starts cool. Due to cooling of SMA spring it lost their power and steel spring draw rear of machine to the front. By repeating of these two sequences the machine performs forward motion. Interesting are experimental results.

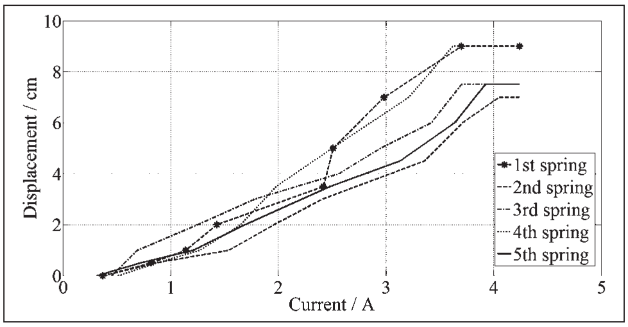

Figure 6 Characteristics of displacements in expansion process of Nitinol spring

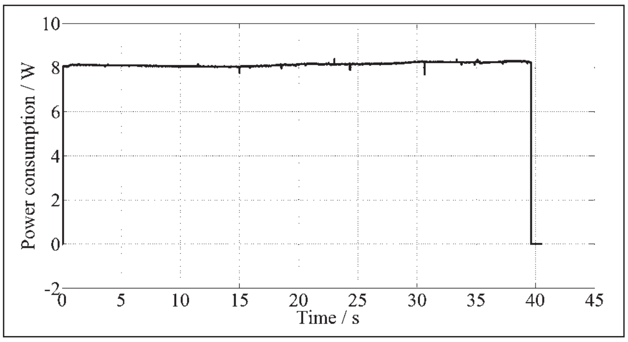

Figure 7 Electric power consumption necessary for SMA spring extension during the first phase of motion

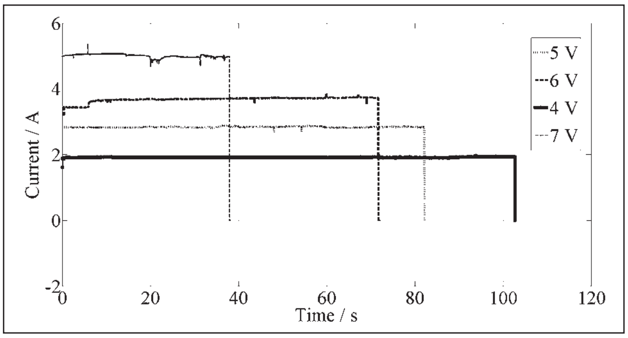

Figure 8 First phase duration caused by different value of voltage input

In the Figure 7 can see electric power consumption what is roughly 8 Watt. Considering that weight of machine is not higher than 9 grams, electric power consumption is too high. Next disadvantage is too high duration of first phase. In the Figure 8 the duration of first phase depending on electric current is shown. Using current 5 A we could obtain duration of the first phase roughly 38 seconds. This causes, that average velocity of in-pipe machine locomotion is 2 mm/min, what is very slow motion.

CONCLUSION

Advantages of SMA spring is well expansibility, simply control and relative high force generating in SMA spring by heating. However, using of SMA spring as actuator has rather more disadvantages than advantages. The heating and especially cooling phase takes a lot of time what causes slow working cycle. In the case of in-pipe machine it cases very slow average velocity, what is in our case only 2 mm/min. Next disadvantage is too high electric power consumption, which grew from 8 W to 30 W. Considering, that weight of whole in-pipe machine is no more than 9 grams, measured electric power consumption is too high.

Nevertheless these disadvantages, SMA actuators are suitable solution for some specific areas and they are often use in robotics and mechatronics.

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Note: English language: Ph. Marianna Dombrovská, Translation agency Zita Panková - A.Z.P. Slovakia