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ISSN 0543-5846
METABK 54(1) 169-172 (2015)
UDC – UDK 669.77/78:669.24:620.16:368.083.4=11

APPLICATION OF SHAPE MEMORY ALLOY (SMA) AS ACTUATOR

Received - Primljeno: 2014-03-10
Accepted – Prihvaćeno: 2014-07-25
Preliminary Note – Prethodno priopćenje

This paper deals with actuators based on shape memory alloys. The testing device has been developed for experimental verification of shape memory alloy actuator testing. Static characteristic shows the hysteresis of this material. Also dynamic properties have been explored through the step response characteristic. Application of the material as actuator in engineering system is shown.

Key words: shape memory alloy, actuator, step response, measurement

INTRODUCTION

Shape memory alloys (also referred as SMA) are materials that “remember” their original shape and return to it when heated, even if apparent residual deformation was introduced below a certain temperature. The original shape can be set easily by heat treatment. The SMA crystallographic structure changes between two phases, the low temperature (martensite) and the high temperature (austenite) phases. Nitinol is SMA material, which is an alloy of nickel and titanium (discovered in Naval Ordance Laboratory in the sixties of the twentieth century). Phenomenon of SMA also occurs in more than 20 alloys. Thermal activation of the SMA can be easily driven by electrical current via Joule heating. Cooling can be realized via heating radiation into surroundings. Other methods of cooling can be used: forced air, heat sinks, peltier elements and liquid coolants [1-4].

SHAPE MEMORY ALLOYS AS ACTUATORS

SMAs are useful for such things as actuators which are materials that “change” shape, stiffness, position, natural frequency, and other mechanical characteristics in response to temperature. The SMA actuators are made as wire, spring or ribbon shape. It is able to produce extreme forces from the viewpoint of volume to force ratio.

As an actuator, the one-way SMA (one-way shape memory effect) element can only provide force/displacement in one direction. For example, a wire that compresses when heated does not expand without external force when the alloy cools down. This is disadvantage of the one-way SMA actuators. A bias (return) mechanism must be used if the actuator has to be returned to the original (cold) shape after the heating phase [5].

Gravitation bias force (Figure 1) is the simplest way. If possible, a load force can be used as bias force. The load force has to be large enough at all times, otherwise the actuator remains in the austenite position, even if the heating is deactivated.

Spring bias force (Figure 1) requires space, increases the weight of the actuator and the mechanical design becomes more complex. It must be also noted that the net (useful) output force decreases, because the force of the bias mechanism opposes the force of the SMA element.

Another way is the antagonistic arrangement of two one-way SMA actuators (Figure 1). This provides output force to both directions, but the heating and cooling of opposing elements must be arranged properly [5].

Two way shape memory effects also exist and there is no need to solve bias mechanism. Consequently the displacement is not as high as in one-way SMA actuators.

SMA actuators are very popular because of their several advantages [6]: compact actuator with high ratio power/mass; easy activation with low voltage power supply; silent operation of actuator; material of actuator is biocompatible.

Also there are several limitations, which have to be accepted in product design: low stroke (displacement approx. 5 % of its length); long reaction time and low operation frequency. It depends on the way of heating and cooling; complicated control of displacement, because of existence of nonlinearity and hysteresis in their characteristic.

The hysteresis is a significant characteristic of the heating and cooling behaviour of shape memory alloys. Hysteresis and nonlinearities cause problems with position control of SMA actuator. Heat losses during the phase transformation phases (owing to internal friction or structural defects) cause hysteretic behaviour of SMA as shown in Figure 2. In [7] has been presented a mathematic model of the SMA behaviours as equation:

$$\frac{dR}{R} = \pi_e \cdot d\sigma + K_\varepsilon \cdot d\varepsilon + \alpha_{RT} \cdot dT \ [7] \qquad (1)$$

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where, R is resistivity, π_e - piezoelectric coefficient, σ - stress, K_z- coefficient of shape sensitivity, ε - strain (deformation), α_{RT} - coefficient of thermal expansion, T - temperature.

The shape of the hysteresis loop is not only alloy and processing dependent, but is also influenced by the application itself.

TEST MACHINE FOR SMA ACTUATORS

There is a standardized Test Method for Determination of Trans-formation Temperature of Nickel-Titanium Shape Memory Alloys by Bend and Free Recovery [8]. A pull test machine for measurement of SMA activity has been developed (Figure 3).

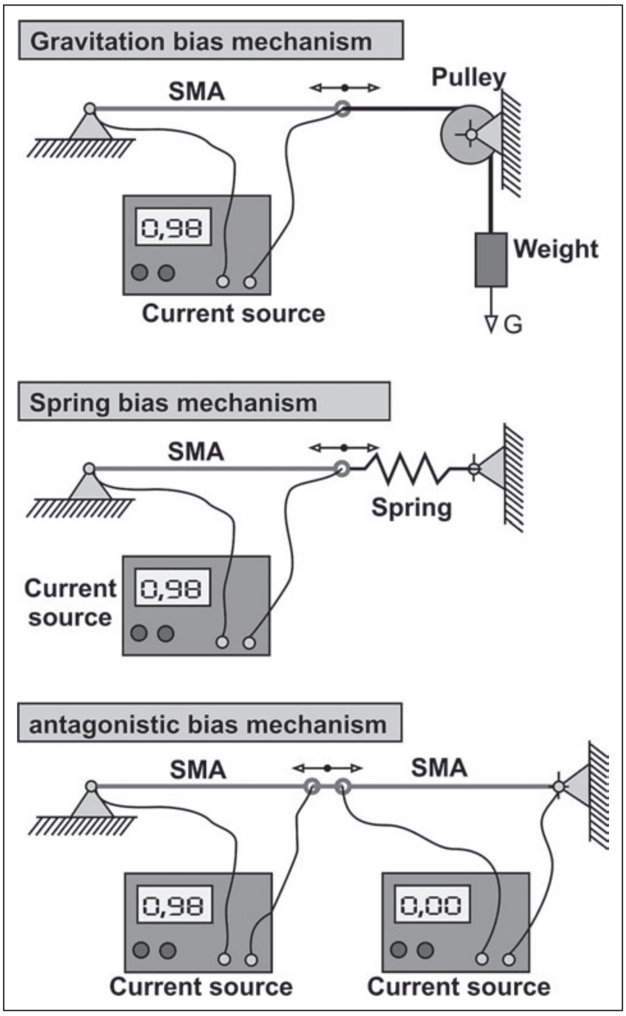

Figure 1 Bias mechanism for one-way SMA actuators

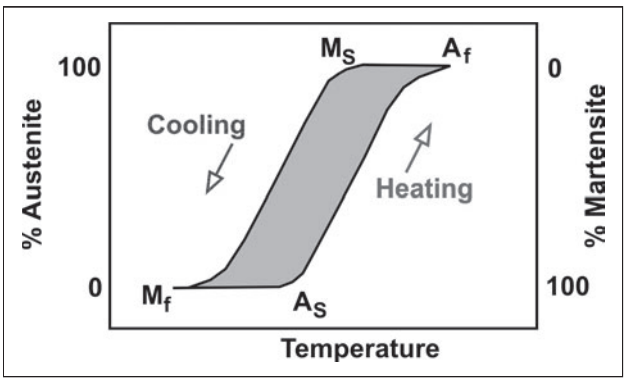

Figure 2 SMA actuator characteristic

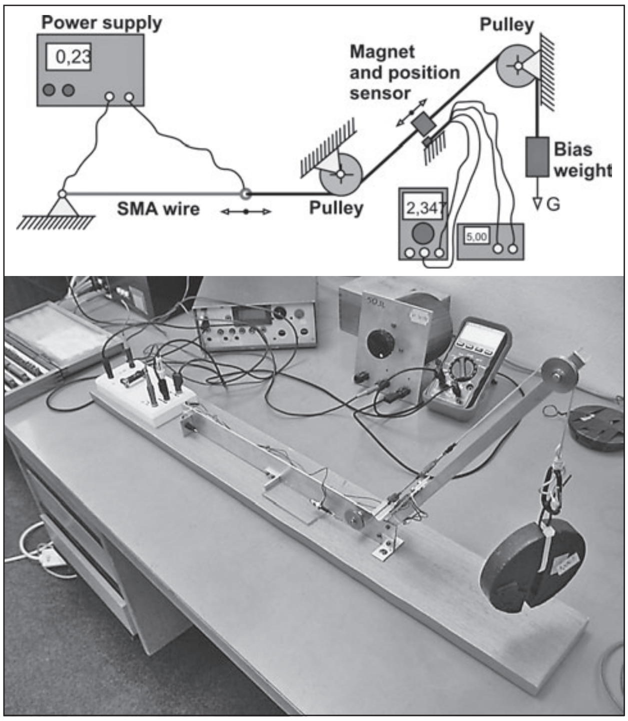

Figure 3 Test machine for SMA actuators

The SMA wire actuator is joined to the fix joint and to the movable joint, which is connected to nylon wire. The nylon wire is guided with two pulleys and bias weight is attached to the end of nylon. A permanent magnet is placed on nylon between pulleys for position sensing. Hall sensor with analogue voltage output is used for permanent magnet contact-less position sensing. Calibration of the sensor has been executed via usage of set of parallel gage blocks. The obtained calibration curve has been approximated with polynomial math model, which is useful for calculation of data obtained from position hall sensor.

MEASUREMENT OF SMA CHARACTERISTIC

Heating and cooling of the SMA actuator cause change of the SMA actuator free end position. Figure 4 shows this dependence of free end SMA actuator position on value of electric current, which shows high nonlinearity and hysteresis behaviour. The characteristic shown on Figure 4 has been measured with bias weight 1 /kg, which corresponds to maximum pull stress.

The dynamic characteristic of SMA actuator has been tested through the step response testing (Figures 5 and 6).

Excitation electric current is shown in Figure 5 and it has been controlled via microcontroller. Step response has been measured via measuring adapter with personal computer. Math model obtained from calibration process has been used for obtaining of the step response as time dependence of the free end SMA actuator position.

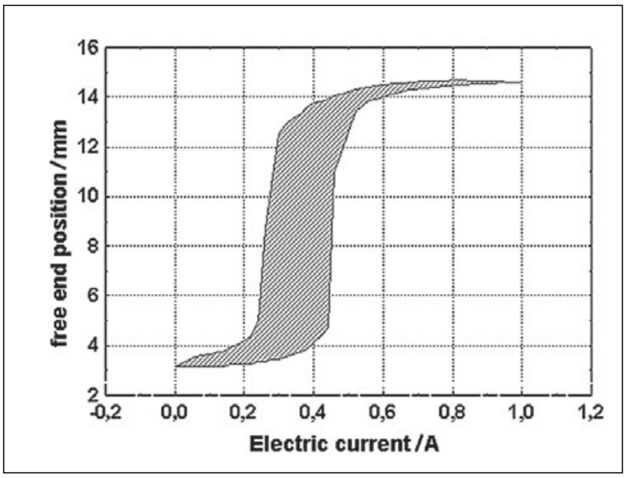

Figure 4 Dependence of SMA free end position on value of excitation electric current for heating

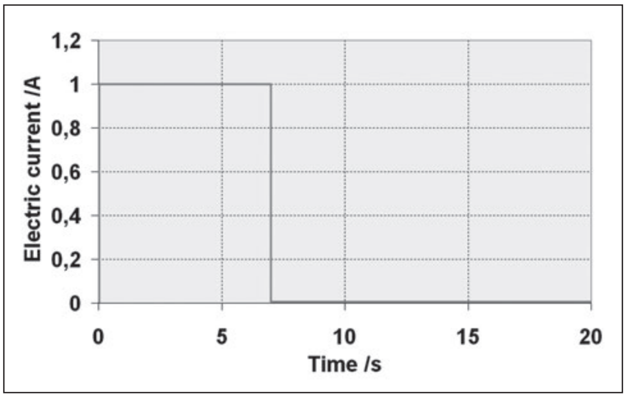

Figure 5 Excitation current pulse

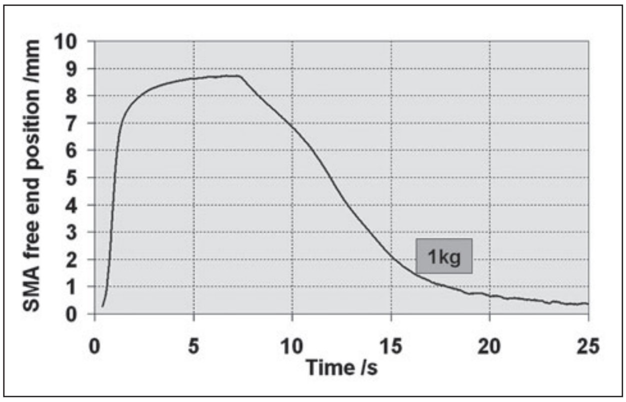

Figure 6 SMA actuator step response

It is possible to determine activation and deactivation time for SMA actuator which corresponds with the heating and cooling time. Figure 6 shows that the cooling is slower than heating.

Activation time can be also described as ratio of the energy necessary heating and electric power consumption used for actuator activation [9]:

$$t_a = \frac{E_h}{P_{el}} \tag{2}$$

Where energy necessary heating E_h and electric power consumption used for actuator activation P_{el} can be expressed in form:

$$E_h = c_v \cdot m \cdot \Delta T = c_v \cdot \rho_{Density} \cdot S_{NiTI} \cdot L \cdot \Delta T \tag{3}$$

$$P_{el} = I^2 \cdot R = \frac{I^2 \cdot \rho_{Re\,sist} \cdot L}{S_{NiTi}} \tag{4}$$

Where

c_v – specific heat constant, ΔT – temperature difference of crystallization phases, m – actuator weight, $\rho_{Density}$- density of the actuator, $\rho_{Re\,sist}$ – electrical resistivity of actuator, S_{NiTI} – cross section area of actuator, L – actuator length, I – heating electric current.

Activation time t_a can be expressed from the equations (2, 3, 4) in form:

$$t_a = \frac{A_{Material} \cdot S_{NiTi}^2 \cdot \Delta T}{I^2} \tag{5}$$

Where $A_{material}$ is material constant for SMA actuator.

Equation (5) shows that activation time depends mainly on its cross section and also on value of electric current used for heating. The length of actuator wire has no influence on activation time.

APPLICATION OF SMA ACTUATOR

Inchworm robot (Figure 7) based on SMA spring actuator (in the middle) is one of the possible applications. Mechanical design of in-pipe robot consists of SMA spring and steel spring. In-pipe robot has bristles with rectangular cross section with length 20 mm and thickness 1 mm. The bristles are from flexible material so that they may adapt to the inner pipe wall. Friction coefficient of in-pipe robot bristles plays a highly significant role for its locomotion through the pipe.

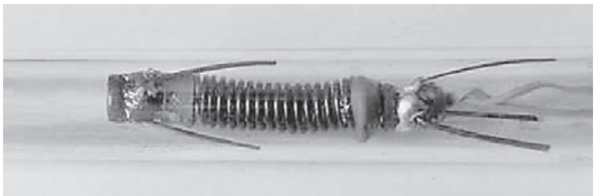

Figure 7 Realised in-pipe robot with SMA spring actuator

CONCLUSION

Shape memory alloy has a lot of advantages such as clean, silent and spark free operation, high biocompatibility and excellent corrosion resistance. They are also free of parts such as reduction gears and do not produce dust particles. Actuators based on this principle are very often used in robotic and mechatronic application [10-12].

Acknowledgement

This research was supported by grant project Vega No. 1/1205/12, APVV-0091-11, Kega 048TUKE-4/2014 and project FGV/2013/8.

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