THE PROPERTIES OF THE MAGNETIC SHAPE MEMORY ALLOY ACTUATOR

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Abstract
Components made of alloys with a magnetic shape memory (MSMA) are not commonly used in industrial systems or prototype solutions. The reasons behind this include the cost and implementation difficulties attached to MSMA alloys synthesis technology. The article presents the results of a prototype actuator in which the active element is a rod made of Ni-Mn-Ga alloy and with dimensions of 2x1x20 mm.

INTRODUCTION

Shape memory alloys (SMA), which constitute a group of smart materials that change their crystallographic structure under the influence of temperature [1], have been the subject of study for several decades now. Recently, considerable attention has been focussed on alloys with a magnetic shape memory (MSMA), [7]. The technical application potential of these alloys arises from their ability to deform in a range of 3 to 8%, at frequencies of up to 1 kHz. The first experimental actuators, in which the active element is an MSMA alloy, have already been created. The literature contains no information about the commercial applications of these alloys. Their drawbacks are low compressive stress limits, at which the shape memory effect persists, and the need to produce a magnetic field with an induction of 1 to 2 T [6].

This paper presents the results arising from the characteristics of one of the above-mentioned experimental actuators, the operating principle of which is based on the phenomenon of magnetic shape memory (MSM). The actuator generates movement as a result of changes in the linear dimensions of the MSMA material, with dimensions of 20x2x1 mm and made of Ni-Mn-Ga alloy subjected to further surface treatment. Although such treatment reduces the maximum deformation of the MSMA element, it improves its mechanical properties in comparison with a ‘pure’ alloy [3].

2. MSMA ALLOY OPERATING PRINCIPLE

The operating principle of the MSMA alloy is explained by the example of the most common Ni-Mn-Ga alloy. In a high-temperature state, that alloy remains in the non-deformed phase of the austenitic structure, which is characterised by the regular shape of an elementary cell. The shape of the elementary cell in the high-temperature phase is shown in Fig. 1a, while the tetragonal structure of the cells in the low-temperature phase, which is the martensitic structure for option 1, is given in Fig. 1b.

During cooling, the sample must be subjected to constant compressive stress \( \sigma_{xx} \) in direction [100], subject to the condition: \( \sigma_{sv} < \sigma_{xx} < \sigma_{b} \) (\( \sigma_{sv} \): compressive stress conditioning the tetragonal structure of the martensite formation in Option 1, the sides of the elementary cell \( a > c \); Fig. 1b, \( \sigma_{b} \) – blocking stress).
Exceeding stress limit $\sigma_b$ will result in the lack of shape memory effect and, at a stress $< \sigma_{xx}$ shaping of the martensitic structure in one option, does not occur.

Maintaining such a synthesis regime for the Ni-Mn-Ga alloy leads to the formation of elements comprising, in their entire volume, the martensitic structure in Option 1 (Fig. 1b, Fig. 2).

During cooling, a martensitic transformation occurs in the alloy and magnetic domains are formed, the magnetic polarisation direction $\mathbf{M}$ of which is consistent with the direction of compressive stress $\sigma_{xx}$.

Three variants of the martensitic structure can coexist in the low-temperature phase. The principle of the magnetic shape memory is based on bi-directional transitions between Option 1 and Option 2 of the martensitic structure (Fig. 3).

Placing the MSMA alloy in magnetic field intensity $H_y$ (Fig. 3) and perpendicular to the compressive stress $\sigma_{xx}$, causes, in the microscale, an increase in the second variant of the martensite contents ($a, c$: dimensions of the elementary cell sides; $\varepsilon_x, \varepsilon_z$: elongation of the sample, dependent on the magnetic field). Domain walls are moved and the migration and re-orientation of twins takes place.

Options 1 and 2 co-exist and increasing the magnetic field intensity $H_y$ causes an increase in the number of Option 2 cells, at the cost of Option 1. The deformation of the re-orientation in the microscale leads to the sample elongation. The MSMA principle is based on the magnetically forced re-orientation of the martensite variants.

3. CONSTRUCTION OF THE EXPERIMENTAL ACTUATOR

The main component of the actuator, the diagram of which is shown in Fig. 4, is a magnetic circuit composed of two coils, connected in series and wound on to the central parts of sections of an $E$ type perminvar core. The coils are supplied by current source intensity $I$. When energised, the coils activate the magnetic field. The magnetic circuit is set up in such a manner as to ensure that the magnetic field intensity in the gap between the central parts of the $E$ sections, which is intended for the placement of the MSMA material, will be sufficient to deform that material. The magnetic field in the gap causes the re-orientation of martensite variants and, at the same time, the elongation of the MSMA material. The
displacement actuated is transmitted to a movable piston. Displacement of the piston $s$, observed outside the actuator, causes spring compression. The energy stored in the spring ensures the piston return movement. It should be noted that the MSMA material shortens itself after the magnetic field intensity is reduced. The material is not used for the return, or drawing back, of the piston, owing to its mechanical properties. The moving piston-spring-MSMA-element system should be selected in a manner that will prevent the contact between the piston and the MSMA element from being broken.

![Diagram of the actuator, with MSMA elements](image)

**Fig. 4.** Diagram of the actuator, with MSMA elements

### 4. TESTING THE ACTUATOR

The actuator tests focused on determining its static and dynamic characteristics. During the tests, the MSMA element was loaded by the spring with elasticity ratio $k$. The test results showed a considerable effect of friction in the cinematic pair $pl$ class, comprising a linear Teflon bearing and a moving piston. This phenomenon is particularly visible at a slow-changing (<5 Hz) current forcing with a sawtooth wave shape.

In the actuator tests, linear piston displacement $s$ was measured as a function of current intensity $I$. As the entire actuator coil was supplied from a current source during the experiment, an attempt was made to determine the relationship between the magnetic induction inside the gap, without the MSMA element, as the function of current $I$.

Since the magnetic induction can be linked to the magnetic field intensity in equation (1)

$$B = \mu_0 \mu_r H$$  \hspace{1cm} \text{[T]} \tag{1}

where $\mu_0$ – vacuum magnetic permeability in [H/m], $\mu_r$ – relative permeability, $H$ – magnetic field intensity in [A/m].

According to the producer, the relative magnetic permeability of MSMA alloys varies in a broad range of 1.5 – 40. Given the simplified formula for the magnetic field intensity as:

$$H = \frac{nI}{l}$$  \hspace{1cm} \text{[A/m]} \tag{2}

where $n$ – number of coils, $I$- current intensity in the coil and $l$- magnetic distance length,

for determined $n$, $l$, $\mu_0$, $\mu_r$ values, the relationship $B = f(I)$ can be given. For coil supply current intensity $I$ from the range $0$-$5$ A, the correlation (3) was experimentally determined for the magnetic circuit.

$$B(I) = aI + B_r$$  \hspace{1cm} \text{[T]} \tag{3}

$$a = \frac{n\mu_r}{\mu_0}$$

where $a$ – a constant of $0.1101$ [H/m²] for the magnetic circuit being tested and $B_r$ - remanence, here $0.0074$ [T]. The magnetic circuit was tested for increasing and decreasing values of current intensity $I$. This part of the experiment proved that, for a perminvar core, the hysteresis can be omitted and the $B(I)$ correlation can be regarded as the linear function. For current intensity $I > 5$ A, the magnetic circuit achieves a saturation state. The experiment described constitutes the testing of a complete actuator.

A testing workstation was set up, as per the diagram shown in Fig. 5. The workstation was assembled on a structure allowing the alteration of the displacement sensor distance in relation to the actuator being tested, in order to allow devices of different geometries to be tested. The basic measuring component of the workstation is the laser displacement transducer. A DC power supply and a controlled U/I converter were used to supply the actuator coil with the required current intensity. The DC motor drive was used as the U/I converter, operating as a voltage-controlled current source of linear characteristic in the range under study, $I = f(U)$. The drive has a PWM output with carrier frequency $49$ kHz and a voltage output in which the actual rms output current intensity can be measured. Such a power supply solution for the actuator coil allows high current increase rates to be achieved. The actuator power supply control and data acquisition systems were built using LabView hardware and software or PLC controller [2].

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The assumption adopted for determining the static characteristic of the element being tested was the measurement of the displacement value $s$, depending on the intensity of the current supplying the coil $I$. The static characteristic of the actuator was established by exciting the coil with a sawtooth wave current for selected frequencies. The maximum amplitude of current intensity $I$ did not exceed 5 A. The actuator response to the supplying of the coil with a current peak was also studied. During the experiment, the temperature of the MSMA element was monitored. The temperature measurement is ensured by a thermocouple installed in the lower portion of the magnetic circuit gap. The temperature value was not recorded. To ensure identical conditions, all the experiments were carried out in a temperature range of 298 – 303 K. At around 330 K, the MSMA material used exceeds the Curie temperature and is no longer ferromagnetic, losing its shape memory functionality until it cools.

5. ANALYSIS OF THE RESULTS

First, piston displacement $s$ in response to the coil’s being energised with a current peak at intensity $I$, was recorded. As a result of this coil energising at current increase rate 125 A/s, linear piston velocity, loaded with the elasticity force, was achieved in the range of 0.15 – 0.30 m/s, as shown in Fig. 6. The static characteristic of the actuator may not be determined by measuring displacement $s$ on piston stoppage with a constant value of current intensity $I$. To the reasons for this include the friction in the cinematic relation piston-Teflon nut. First attempts to determine that characteristic were made by energising the coil with a current of symmetric sawtooth shape and frequency 1 Hz. An analysis of the actuator’s response to the energising of its coil with a current peak determined the delay as being ca. 1 ms. For such a delay value, it was assumed that, for a supply current frequency of below 10 Hz, for each intensity $I$, the displacement $s$ will be a constant value [4, 5].

![Fig. 6. MSMA actuator response to current peak forcing in the actuator coil.](image)

It was, however, proved that, for frequencies below 3.5 – 4.5 Hz, the friction in the cinematic relation of metallic piston and Teflon nut causes a stepping movement in the piston, as shown in Fig. 7.

![Fig. 7. MSMA actuator response; with the actuator coil energised with sawtooth current and frequency 1 Hz.](image)
For the actuator construction under study, it is noticeable that, for current frequency \(<4.5\, \text{Hz}\), it can only be used for operations of On/Off, which is to say full stroke /home position, type . For supply current frequency \(> 5\, \text{Hz}\), the piston movement becomes smooth and cinematic friction is observed in the entire stroke range. An example of piston movement, depending on \(10\, \text{Hz}\) current intensity, is shown in Fig. 8. It is noticeable that the piston stroke, or MSMA material elongation, begins at \(I \approx 2.7\, \text{A}\), which corresponds to a magnetic induction of approx. 0.3 T.

![Fig. 8. MSMA actuator response with the actuator coil energised with current signal](image)

Analysing the measurements of the displacement \(s\) as a function of the current energising the actuator coil with various frequencies, the \(s(I)\) characteristic was determined (see Fig. 9). It can be noted that for current intensity \(I\), increasing from 2.7 A to ca. 4 A on average, and for the values \(I\), decreasing from 1.7 A to 0.45 A, the correlation \(s(I)\) can be approximated with a linear function. Therefore, in the case of the increase and decrease of current intensity \(I\), the displacement \(s\) varies from 0.05 to 0.20 mm.

![Fig. 9. Actuator hysteresis loop measured with the coil energized with sawtooth current signal at frequencies 5 and 10 Hz](image)

However, the actuator construction described has some drawbacks. As a result of friction in the cinematic relationship of piston and linear bearing, the interface of MSMA and piston and the loose fitting of the MSMA element in order to allow buckling in the magnetic circuit, it was impossible to determine the dynamic characteristic of the actuator. The above phenomena lead to the occurrence of random resonance frequencies, which implies the necessity of introducing structural modifications.

### 5. CONCLUSIONS

The results described cannot be translated into the properties of the element made solely of the MSMA alloy. The parameters of an entire actuator in which the active component was made of Ni-Mn-Ga alloy have been presented. The test results of the actuator, without load, do not characterise the MSMA element alone. The element operated under the elastic load, piston inertia and friction force in the cinematic relationship, which resulted in a stepped piston movement at low frequencies of the actuator coil supply current.

The MSMA element in the actuator being tested was subjected to ca. 20 thousand deformation cycles. As a result of the first few thousand cycles, the maximum relative deformation was found to have decreased from 2.25 % to around 1.50 %. The experiments carried out do not explain that phenomenon. The tests described were performed with a stabilised maximum relative deformation (ca. 1.5 %). This observation raises the need for further comparative studies using other samples of the MSMA material, as well as studying the fatigue characteristics, in order to determine its life expectancy.

During the tests, imperfections in the structure presented were discovered, but it must be stressed that this was a pre-prototype stage. Based on the results, it can be concluded that it will be possible to use MSMA alloys as new actuators, particularly for generating linear movement.

The next step will be to determine the actuator’s limit loads and endeavour to modify its construction, with a view to increasing the operating stability at low supply frequencies.
REFERENCES

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