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Position regulation of magnetic shape memory actuator

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Materials

ABSTRACT

Purpose: This paper presents materials with magnetic shape memory. These materials are a new group of smart materials, which distinguished by large deformations (up to 10%), and relatively high operating frequencies. Authors used in research samples made of Ni2MnGa alloy in order to find out of their capabilities in transducers design applications and for better understanding their nonlinear behavior.
Design/methodology/approach: For research purposes, authors designed laboratory electro-mechanical transducer, which works in spring retuned operating mode. This transducer is connected with dSPACE system used for regulation and data acquisition process. Coils were connected with programmable DC power supply.
Findings: This design of transducer was for Authors a first attempt of practical application of MSMA. Results help in: modelling process of hysteresis for future open loop regulation, finding out optimal working conditions and scope of available operating parameters. Changes will be applied in next transducers design e.g. shape of magnetic circuit and these transducers will have more compact design.
Research limitations/implications: Step responses of material are much worse than values given by manufacturer, because response of controllable power supply is up to 0.1 s. Another problem were stiffness of transducer and repeatability of obtaining results, but since modifications it has been successfully eliminated.
Practical implications: Implemented in the examined transducer operating mode is identical to the principle of operation of an electromagnetic transducers used in design of electro-hydraulic and electro-pneumatic cartridge valves. In these valves solenoid moves a spool and after a power cut due to the spring tense, it returns to base position. Future work will focus on their replacement by a transducers designed with the use of MSMA.
Originality/value: In this paper design with detailed description is presented. It can be treated as guidelines for other scientists who would like to design similar transducers. The article is the base for further research.
Keywords: Smart Materials, Magnetic Shape Memory Alloy, Transducer, dSPACE

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1. Introduction

Transducers are a very important part of every mechatronic device, their purpose is to convert an electrical input signal usually for non-electrical output (displacement, force, flow rate, pressure) [1]. Electromagnets are commonly used, but in the last 20 - 30 years transducers designed by using smart materials have appeared. What is more scientists found a lot of practical applications for them. Nowadays their market share and range of applications are constantly increasing [2,3]. All applications where smart materials replaced classical solutions, improvement of the operating parameters such as positioning accuracy can be easily found [4,5].

Smart materials change their properties under the external stimulus which can be: electric field (piezo based materials), temperature (Shape Memory Alloys), and magnetic field [6,7,8,9]. In a latter case, to the group of magnetostrictive materials and magnetorheological fluids, magnetic shape memory alloys (MSMA) were joined in last decade. These new materials are compared very often with magnetostrictive materials and they have many features in common with them. The main difference is a magnitude of maximum deformation (0.2% for Tb0.3Dy0.7Fe1.9 vs. up to 10% for 7 layered MSMA [10]), at very close operating frequencies. Area of application could also be similar and a vibration sensor described in [2], could be designed based on MSMA without changing major rules of operation.

Authors present in this paper, design of laboratory electro-mechanical transducer and propose closed loop position regulation. At the end experimental results were attached. Summing up this publication, future direction of development were described, because it is a new material which before practical application still requires a large amount of research.

In addition to the obvious advantages, drawbacks should also be mentioned: hysteresis caused by internal friction, a first cycle effect and sensitivity to operating and ambient temperature, which significantly affects the properties of the material.

2. Magnetic shape memory alloys

2.1. Difference between TSMA and MSMA

Shape memory materials have been known in science and engineering since the mid-twentieth century. Then in the early 1960s, scientists developed material called Nitinol with a maximum deformation of 8% [11,12]. SMA are commonly used in technology and medicine nowadays. Shape memory effect in these materials has been “programed” during a manufacturing process and it is triggered by heating material to a temperature at which whole martensite phase transforms into austenite [13]. Until the discovery in 1996 by Ullakko at Massachusetts Institute of Technology in the USA effect of the magnetic shape memory, Nitinol and similar materials were single representatives of this group of materials. For this reason, it is necessary to split shape memory alloys into two new groups, where criterion is source of external stimulation: thermally activated materials (TSMA) and activated by external magnetic field (MSMA) (Fig. 1.).

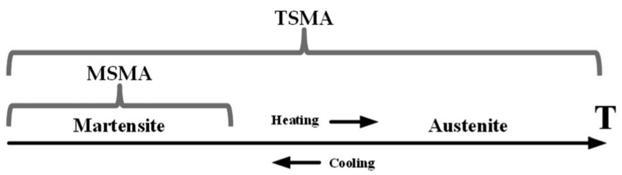

Fig. 1. Comparison of operating temperatures in TSMA and MSMA

MSM materials owe their advantage over TSMA due to much higher operating frequencies. This is because of fact that the thermal processes are distinguished by high thermal time constants. In this comparison it is important to mention about maximum generated force per one square millimeter. In MSMA there is possibility to achieve magnitudes from 6 up to 10 N, on the other hand for alloy Dy 90 described in [11], this force is much higher and equals 135 N. MSM materials are produced as rectangular samples with one side noticeably shorter. Magnetic field passes parallel to this side and thus air gap width, which plays a key role in the design of magnetic circuit, is limited to a minimum. TSMA are mainly produced as wires and mostly their deformation is realized by current flow causing them to warm up. The problem can be fast return to its original shape as it should be then rapidly cooled, which is a very difficult design issue. Therefore TSMA, if required on the basis of the proposed solutions, are disposable such as presented in [11]. A fast response time is achieved by a capacitor, which is connected to both ends of the wire.

2.2. Production process and principle of operation

Obtaining phenomenon of magnetic shape memory in alloys is also closely related to a production process. The greatest deformation and satisfactory properties are distinguishing for an alloy consisting of: nickel, manganese and gallium in composition Ni_2MnGa. This composition makes the alloy belongs to the group of full Heusler alloys. At high temperatures, the austenite lattice takes form of cubic $L2_1$ structure. The material is at constant compressive stress during the cooling stage, which value must meet the following conditions: be greater than minimum specified stress initiating a required martensitic structure formation but be less than stress which blocks this phenomenon. Through such a procedure, after cooling, is obtained one martensite variant, instead of randomly scattered structure of martensite variants. Martensite is present in range of 250 to 330 K. When temperature rises, maximum strain decreases, above 330 K shape memory effect does not occur, due to back conversion into the austenite phase (Fig. 2) [14,15,16].

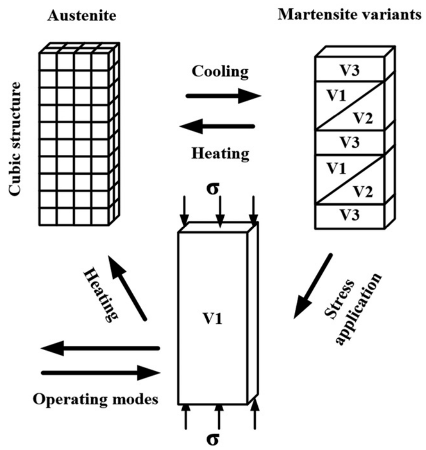

Fig. 2. Production process of MSMA

Easy axes of magnetization in MSMA magnetic domains are parallel to direction of applied compressive force. The process of compressing and cooling causes a further shortening and magnetic anisotropy of the material. Crystals sides have different lengths a and c = 0.94a. Thus prepared material is subjected to a magnetic field rotated by 90 degrees with respect to an easy axis of magnetization. This causes a nucleation and growth of the martensite variant 2 with movement of magnetic domains, reorientation and migration of twins - the increase of variant 2 at the expense of 1. It is called: magnetic field inducted martensitic variant reorientation. This is schematically shown in Fig. 3. Relative magnetic permeability varies from 65 (in H0), down to 2 (maximum elongation state) [14,15,16,17].

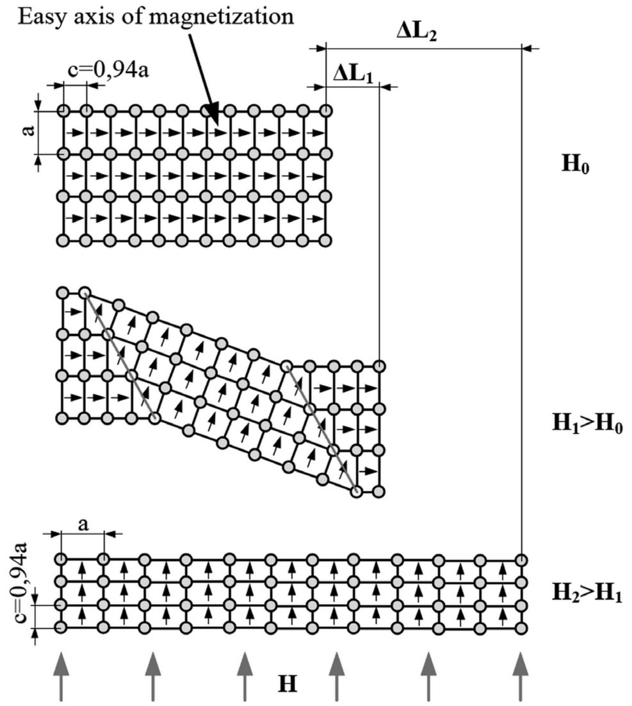

Fig. 3. Principle of operation of MSMA

2.3. Operating modes

Materials with magnetic shape memory in design of mechatronic devices may be used in one of the five available operating modes (Fig. 4.). The following modes apply only to transducers with one MSMA element; there is also the possibility to use more of them. These studies were carried out by [1,18,19] - these papers proposed design of push pull actuators.

In a first operating mode, an elongation of the material and return to original shape are implemented in a mechanical way, so there is no possibility of electrical control of actuator. Extension starts when external stretching force is greater than internal twinning stress. This mode is ideal for damping applications and these properties can be easily changed by modifying the chemical composition of the alloy.

In second mode, external magnetic field is used to generate elongation. Disappearance of the magnetic field does not cause return of sample to its initial shape; elongated material is in this form until an external force does not exceed value of twinning stress. Using a spring in this design of transducer is necessary to generate a compressive returning force, but in this case maintaining a desired position needs a constant coils supply. Presence of spring limits range of maximum elongation. One square millimeter of material cross-section can generate 2.5 N of force. Taking into account size of the spring this force is reduced approximately by half.

Third mode shows opposite of previous. The elongation is accomplished by a compressive force, returning of material is carried by a magnetic field from coils. Compared to the second mode it is much harder to achieve this mode in transducer design.

The next one mode is combination of previously presented variants. Elongation is performed by a tensile force and return by magnetic field. Due to fragility of MSMA it might be damaged during stretching.

The most preferred from the viewpoint of work and control of MSMA is last fifth mode, wherein elongation and return are implemented by magnetic field. This design needs two independent magnetic circuits. The biggest advantages in this case are full accessibility of generated force (in second mode, part of force was stored in the spring), and complete control in two ways of movement [4].

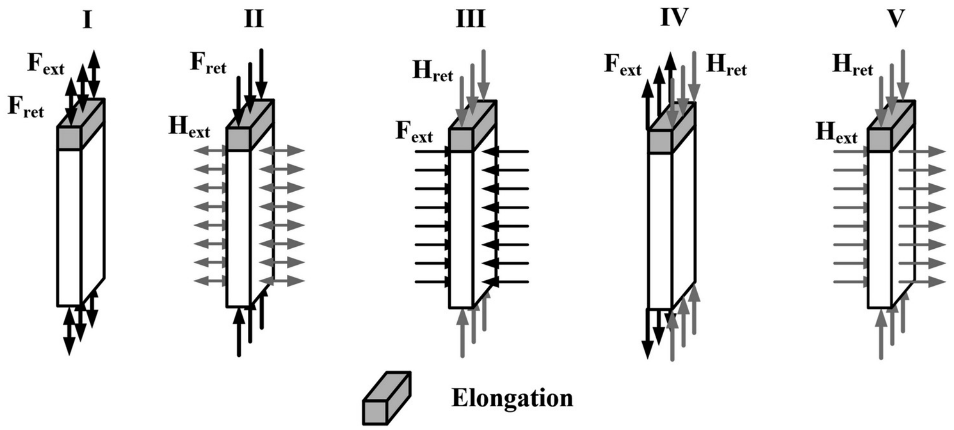

Fig. 4. Five possible operating modes

3. Research

3.1. Design of the test stand

Destiny of designed electromechanical transducer is static and dynamic examinations of samples made of Ni_2MnGa. Air gap width in magnetic circuit is adjustable and may vary from 1 to 2.5 mm. Dimensions of magnetic core were calculated for 1x2.5x20 mm^3 MSMA plates produced by Finnish company Adaptamat. In order to generate magnetic field two coils in parallel connection were used (300 turns each), theoretical calculated induction equals 0.7 T, which was confirmed in measurements 0.69 T for 5 A. Transducer meets all assumptions distinguished for second operating mode described above. Due to the fact that it is laboratory stand, there was possibility to add small table with micrometer screw to precise preload setting in whole range from 0 N up to blocking stress occurring in MSMA crystals. Maximum elongation is obtained for magnetic induction 0.65 T. Magnetic core is made of soft magnetic steel (Fig. 5). Table 1 summarizes the parameters of the test bench.

This is first version of transducer, now in preparation is next one with material sample 3x10x30 mm^3, theoretical maximum elongation equals 1.8 mm (6% of 30 mm). In this case magnetic circuit is made of ARMCO iron. Parts were heat treated after milling operations. This operation should decrease magnetic hysteresis and increase relative permeability, but this is not very important factor in magnetic circuit design due to very wide air gap which determines number of turns.

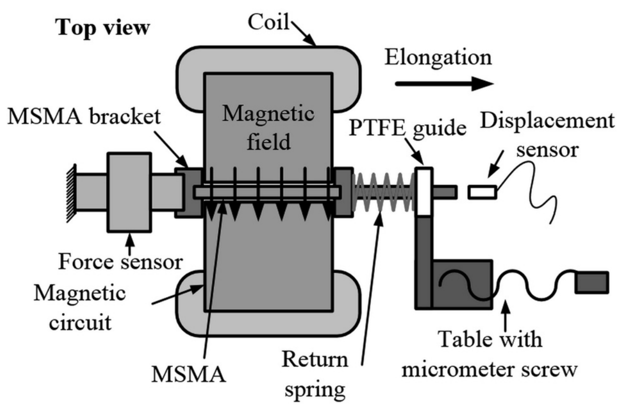

Fig. 5. Scheme of designed transducer

Table 1.
Test stand parameters

Parameter	Value [unit]
Sample dimensions	1x2.5x20 [mm]
Coils	2
Coil turns	300 [turns]
Max current for each coil	2.5 [A]
Air gap (adjustable)	1 to 2.5 [mm]
Magnetic induction	0.7 [T]
Return spring stiffness	0.43 [N/mm]
DC power supply	U_{max}= 32 [V], I_{max}= 10 [A]

3.2. Control program and test variants

Different testing variants required different control programs. Continuous modifying of the controller parameters was available by using a high class dSPACE real-time system, which allows implementing and developing very complex control algorithms without loss of the performance. The system is equipped by modular hardware input and output voltage analogue signal ports. Executive elements of the test stand were connected to the controllable current supplier. The supplier gives a possibility to measure its actual output voltage and current - it means on coils. Displacement laser sensor Philtec Fiberoptic D47 was connected to dSPACE ADC input. Special Simulink model was prepared to automatically generate program code. Fig. 6 presents schematic diagram of the program implemented on the dSPACE platform. Several different signals were used to control the MSMA material elongation; block number 4 switched a signal source to dSPACE output block no. 5. Manual signal (no. 6) was helpful in test stand calibration. Sinusoidal or saw-tooth periodic signals with decreasing amplitude are numbered 8 in the schematic. The last signal type is the one from PID controller (no. 3), which compares set displacement value (no. 2) with actually measured displacement (no. 1). dSPACE allows tuning PID parameters during work of the system and instantly checking the results. Data acquisition block number 7 is responsible for recording the measured values like displacement, current and voltage.

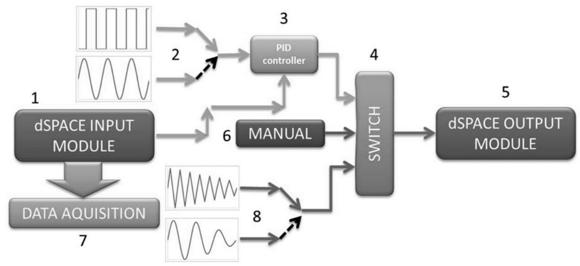

Fig. 6. Block diagram of the dSPACE control program

3.3. Results

Before closed loop regulation survey, hysteresis research were performed for sinusoidal input signal which amplitude was decreasing asymptotically to 2.5 A. Unfortunately, the DC power supply does not have automatic change of polarization as built-in feature thus two separate data records were done. In Fig. 7 were plotted these results. After this study, two conclusions could be written: direction of magnetic field, which passes through material does not change output value and large hysteresis loop exist (strong disadvantage of MSMA).

In Fig. 8 is shown a comparison of two states of sample, before and after activation of external magnetic field. The result is a macroscopic deformation which reaches approximately 1 mm. It is worth mentioning at this point that the material itself is a very brittle (due to its crystalline structure). In transducers applications it is necessity to provide proper guide otherwise sample can be easily damaged (e.g. break).

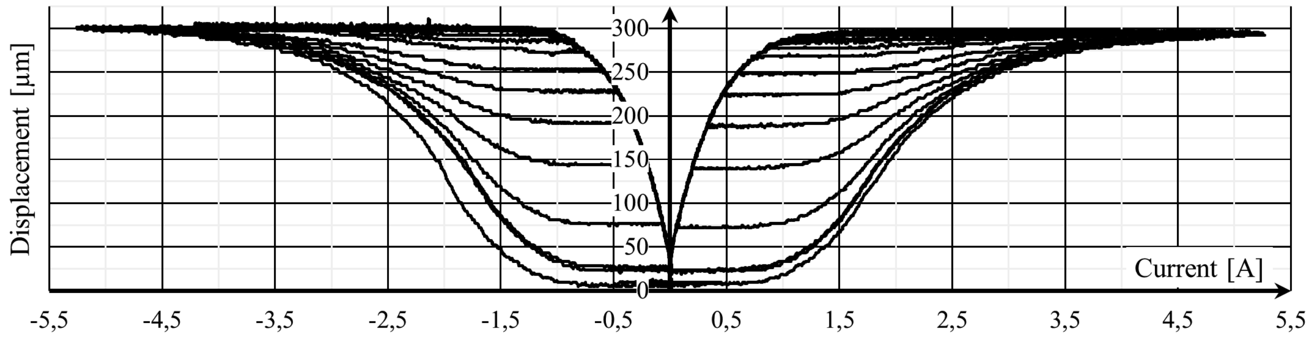

Fig. 7. Displacement vs. current for decreasing sinusoidal input signal

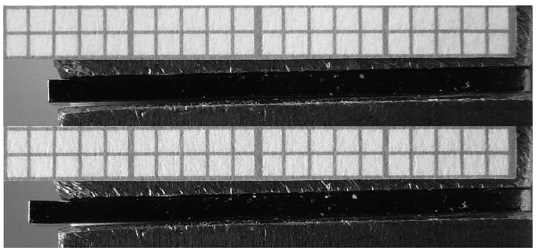

Fig. 8. Elongation of sample in magnetic field

In last part of research Authors attempted to use position signal as feedback for closed loop regulation. Three tests for different PID regulator coefficients were performed. Results are shown in Figs. 9 to 12.

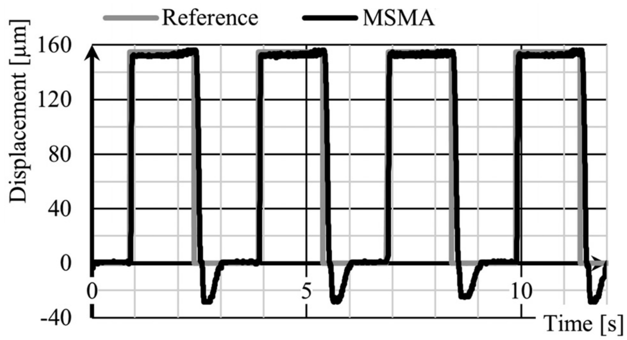

Fig. 9. Positioning of MSMA transducer, regulator P = 4, I = 140, D = 0.15

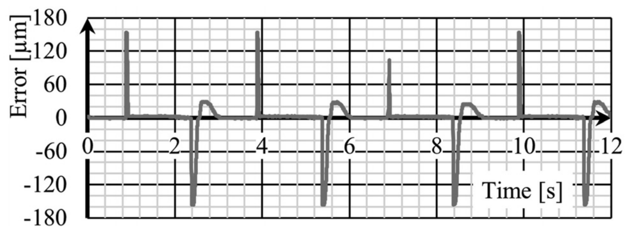

Fig. 10. Error vs. time for regulation presented in Fig. 9

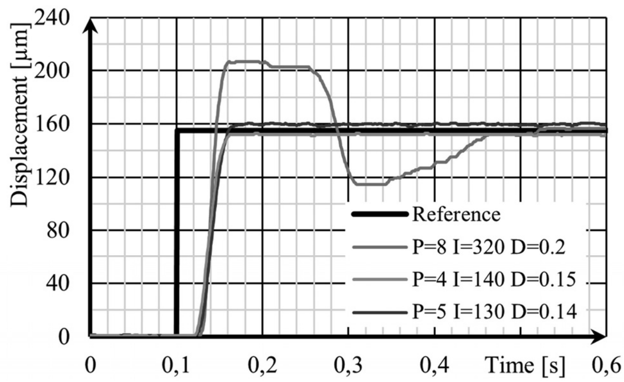

Fig. 11. Different regulation settings - magnetic field extension

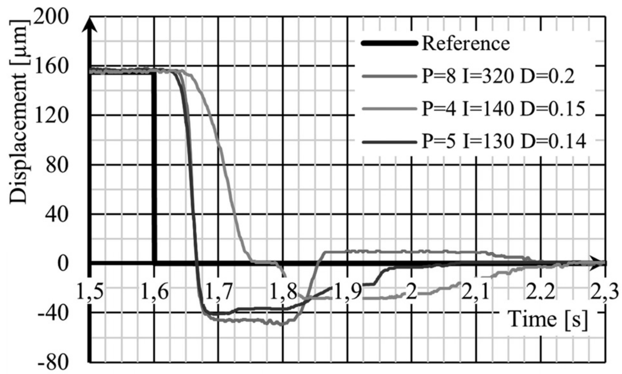

Fig. 12. Different regulation settings - spring return

4. Conclusions

The presented results focus on the closed loop regulation of MSMA elongation. The material as the part of actuator is able to be used in small size positioning systems, but still need further research. Some problems which occurred at first study phase were associated with mechanical construction of the test stand. The system was randomly destabilizing itself during closed loop control. Placement on more rigid base and adding PTFE guide beside the MSMA (which prevented from buckling), improved the stand and gave repeatable results, as shown in Figs. 9 and 10. Rest problems have reasons in the MSMA properties and operating mode number 2. Step responses for closed loop position regulation are different for elongation and reduction. Extending of MSMA is the process activated by the coils, when the return is done passively by the spring. Therefore it is easier to control while the material extends. Another problem is wide hysteresis, which additionally impedes set position achieving. Figs. 11 and 12 compare the step responses for different PID gain values. It is noticeable that better results are for elongation and even when the response is very good, the response for reduction is much different.

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