Characterization of MSMA-based Pneumatic Valves

Stanislaw Flaga* [1], *Janusz Pluta*, *Bogdan Sapinski

The deformation range, forces and frequency of the Magnetic Shape Memory Alloys (MSMAs) render them suitable for applications in electro-mechanical transducers, used to control pneumatic valves. A fast-operating electro-mechanical transducers can be designed, whose driving elements should not execute any motion, as they do in valves available to date, and which should get deformed instead. Utilising the deformation of an element made from the MSMA, the active element of the valves may be shifted, thus changing the flow orifice. MSMA-based valves can become a new group of electric valves, featuring improved dynamic behavior and better resistance to external vibrations.

Keywords: *pneumatic valves, MSMA.*

Introduction

The study explores the potential applications of the magnetic shape memory alloys (MSMAs), one of the latest smart materials, in pneumatic electro-valves. Typically, such valves comprise two main units: one- or two-stage pneumatic amplifier and an electro-mechanical transducers. The transducer acts as a simple controller (positioner) and its mobile driving element, when acting upon the active element of the pneumatic amplifier, causes the change of the orifice's surface area. In two stage valves (indirect action valves) the transducer interacts with the active element in the amplifiers first stage. Most transducers used in electro-valves have a mobile driving element.

New advances in materials engineering allow an electro-mechanical transducer made of the MSMA to be designed, whose driving element should not perform any motion but get deformed instead. Utilising the deformation of an element made from the MSMA, the active element of the valve can be shifted to change the area of the flow orifice. The actuating element should be designed such as to ensure the sufficiently wide deformation range.

In the light of current tendencies in electro-pneumatic control, it seems merited to develop an electro-pneumatic valve in which the orifice's surface area should be varied using a fast-acting adjuster (positioner) made from the MSMA.

In the context of potential applications of smart materials in valve adjusters (positioner), of particular importance is the variability range of geometric parameters of elements made from the MSMAs under various frequencies of deformation. The admissible compressive strength is of major importance, too. These parameters largely determine the variability range of the flow orifice's area in valves under the specified flow conditions.

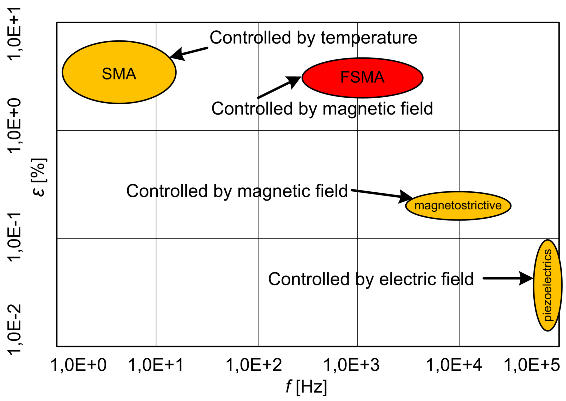

Fig. 1: Critical strains ε for admissible operating frequencies f of selected smart materials.

Fig. 1 [3] compares the critical ranges of strain ε for the admissible operating frequencies f of certain smart materials: shape memory alloys (SMA), piezoelectric elements, magnetostrictive materials and MSMA [1]. The critical operating frequency of the MSMA element is by two orders of magnitude larger than in SMA materials [4], for comparable relative strain levels.

[1] *Ing. Stanislaw Flaga, PhD., Ing. Janusz Pluta, PhD., Ing. Bogdan Sapinski, Prof.*, AGH University of Science and Technology Krakow, Department of Process Control , stanislaw.flaga@agh.edu.pl, janusz.pluta@agh.edu.pl, deep@agh.edu.pl
(Review and revised version 15. 09. 2011)

The properties of the magnetic shape memory alloy Ni-Mn-Ga were first reported in 1996. A great deal of attention has been given mostly to Heusler - type alloys, their general composition being given as Ni-Mn-Ga. Their main drawback seems to be the relatively low levels of admissible compression strength, ranging from 4 to 10 MPa. The most characteristic parameter of MSMAs is the blocking stress σ_b, when its value is exceeded, the shape memory effect ceases to operate.

The sole manufacturer of the Ni-Mn-Ga alloys (the Finnish company "AdaptaMat") attempted to utilise the alloy in vibration generators. Research is now underway on MSMA alloys containing the admixtures of iron. Their shape memory features are supposed to be most favourable, the induced strain levels approaching 10 % and the admissible compressive strength is about 40 MPa, so their parameters are similar to those of the most popular SMA alloy - NiTinol, containing nickel and titanium.

Operating Mechanism of MSMA

Currently MSMAs are not manufactured on the industrial scale. Apart from most precise control of its chemical composition, the manufacturing technology involves a specialised heat treatment combined with mechanical working. The MSMA effect is demonstrated using the example of the Mi-Mn-Ga alloy [2].

At first in the high-temperature stage, a MSMA element is in the phase of non-transformed austenite structure (high-temperature) characterised by regular forms of unit cells and tetragonal cell structure during the low-temperature phase - martensitic structure in variant 1. During the cooling stage, the sample is subjected to constant compression stress σ_{xx} applied in the direction [100] (Fig. 2), whilst the condition is retained that $\sigma_{sy} < \sigma_{xx} < \sigma_b$, where σ_{sy} compressive stress triggering the formation of variant 1 of the martensitic structure; the sides of the elementary cell being $a > c$. under the specified flow conditions.

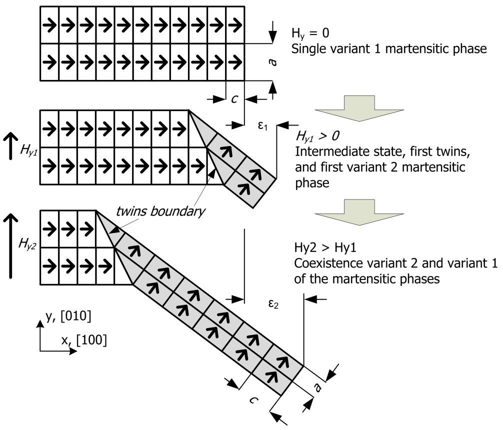

Fig. 2: Variations of the MSMA sample dimensions after reorientation of the variant 1 and variant 2 of the martensite in the magnetic field with the strength H_y.

Exceeding the critical value of the blocking stress σ_b causes the shape memory effect to disappear whilst maintaining the stresses below σ_{sy} causes that martensitic structure will not be formed in a variant 1. Maintaining the strict regime during the synthesis of the Ni-Mn-Ga alloy will finally yield a sample comprising the martensitic structure in its entire volume in variant 1. During the cooling stage, apart from the martensitic transformation, magnetic domains are formed with the directions of magnetic polarisation M coinciding with that of the applied compressive stress σ_{xx}.

In the low-temperature martensitic phase three variants of martensite are available. The shape memory effect involves the two-directional transitions of the martensite structure between the variant 1 and 2 (Fig. 2).

Placing the MSMA in an external magnetic field with the strength H_y (Fig. 2) and arranging it orthogonally to the applied compressive stress σ_{xx} axis causes an increase of the variant 2 of martensite, in micro-scale ($\varepsilon_1, \varepsilon_2$ - elongation of the sample related to the magnetic field strength). Domain walls are re-located and reoriented, accompanied by twin migrations. Variants 1 and 2 will coexist whilst an increase of magnetic field strength causes variant 2 to enhance at the cost of variant 1. Thus formed deformations of macroscale reorientation lead to sample elongation [1].

Properties of MSMA

The best known MSMA material is the alloy Ni-Mn-Ga and its various modifications have been recently investigated. Selected materials from this group are described, with the main focus on the induced strain in relation to the magnetic field strength. This relationship is of primary importance in the context of applications of MSMAs in fluid control elements.

Ni-Mn-Ga

The alloy containing nickel, manganese, gallium is described by the general composition formula $Ni_{2+x}Mn_{1-x}Ga$, where $0.1 < x < 0.3$. With this composition, the temperature of transformation of martensite variants in the presence of a magnetic field falls in the range (250, 330) K. The Curie temperature, at which the alloy Ni-Mn-Ga loses its ferromagnetic properties (ceases to be a shape memory alloy), falls in the range (340, 380) K. Depending on temperature and elemental contents, in the martensite phase three variants of martensite may be formed with the selected crystalline direction. The crystalline direction of variants is referred to as the easy magnetic axis, which is associated with magnetic polarisation. This direction shall coincide with the direction determined by shorter edges of unit cells. The sense of the magnetic polarisation vector might coincide with or be opposite to that of the easy magnetic axis and adjusts to the direction of the vector of the external magnetic field affecting the SMA material. The potential of achieving large magnetic field-induced strains is now investigated by materials engineers. The largest reported relative strains would approach 10 %. It was found out that they were also associated with the elemental composition of the alloy. The largest admissible compressive stress was found to be about 2.8 MPa.

The magnetic field strength H, inducing the material's response: i.e. its deformation was about 400 kA/m. The maximal deformation is reported for $H \cong 650$ kA/m [2].

Co-Ni-Ga

The martensite transformation in the cobalt, nickel and gallium alloy proceeds in the temperature range (202, 350) K. Studies of relative strains of the samples in relation to magnetic flux density B reveal that for $B \cong 0.8$ T, the sense of the strain is reversed. In each direction the magnitude of relative strain is approximately equal to 2.5 %. This material features lower magnetic anisotropy and better plasticity than Ni-Mn-Ga. This material features lower magnetic anisotropy and better plasticity than Ni-Mn-Ga.

Ni-Mn-Co-In

The MSMA effect occurs in the Ni-Mn-Co-In (nickel, manganese, cobalt, indium) alloys only in compression. The deformation effects at the room temperature were observed to be reversed by about 3 % due to the action of compression forces, when exposed to the magnetic field with the flux density about 4 T. Characteristics obtained by [1] when investigating the samples of single crystals of the $Ni_{45}Mn_{36.5}Co_5In_{13.5}$ alloy subjected to compressive stresses of 75 and 125 MPa show that the field with the flux density of 14 T has to be generated, which appears a very large value. The maximal strains obtained during those compression tests were 3.13 %, at the temperature 250 K and under the applied compression stress of 125 MPa. Unfortunately, the irreversible deformation effect of 0.26 % was reported, which was major drawback. A fully reversible stress-strain behaviour (2.92 %) was achieved at the temperature 200 K under the flux density 14 T and under the applied compressive stress 125 MPa.

Ni-Fe-Ga-Co

The alloy of nickel, iron, gallium and cobalt marks an attempt to synthesis the MSMAs containing iron. It was found out that the Curie temperature for this alloy tends to increase with an increased Co content. That fact is of key importance since the Curie temperature of the most popular Ni-Mn-Ga alloy is rather low, so the range of its potential applications is narrower. Like in Ni-Mn-Co-In, the magnetic field-induced strain in the sample subjected to compressive stresses is higher, too. For example, a sample subjected to compressive stress of 8 MPa would induce the further strain of 3.5 % under the action of the magnetic field. It is worthwhile to mention that at the compressive stress loading of 8 MPa in the absence of the magnetic field, the strain of 5 % would be induced. Testing done on the alloy Ni-Fe-Ga-Co reveals applications of this MSMA on account of the achievable strains further induced by the fixed compressive stress loading under the action of the magnetic field.

Applications

The range of produced strains and forces is sufficient to render the tuners made of MSMAs suitable for applications in pneumatic valves. The properties of MSMAs enable their applications chiefly in electro-mechanical transducers in proportional valves. Potential applications include flow-control or pressure-control devices, multi-functional valves, flow control valves and the like Fig. 4.

Proportional valves act as throttling elements and the control of their active elements provides for a variable flow orifice to maintain the fixed flow rate or pressure. Many proportional valves are based on conventional valves wherein a manual tuner or a conventional electromagnet is replaced by a proportional electromagnets. Proportional electromagnets (Fig. 3) are categorised as short- and long-stroke ones. Presently other electromechanical elements can be also used as tuners: momentum transducers and immersion coil transducers. The constructional difference between

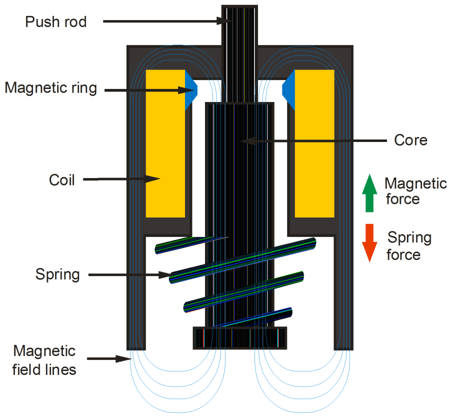

Fig. 3: Structure of a proportional electromagnet.

a tuner made of a MSMA material and a proportional electromagnet lies in the structure of the interior part, where the core is replaced by an element made of a MSMA. The core in a proportional electromagnet shifts its position when the current level in the coil should change, whilst that made of a MSMA will change its dimensions. In accordance with the recommendations set forth in the standard ISO 1219-1 a standard proportional electromagnet is represented by a graphic symbol (Fig. 4a). Further symbols in Fig. 4 represent the following types of electromagnets: those with the core position sensors (Fig. 4b), with an incorporated electronic control system (Fig. 4c) and those with the core position sensor and an electronic system (Fig. 4d). The examples of simple, typical throttling valves controlled by proportional electromagnets are shown in Figs. 4e and 4f, whilst Figs. 4g and 4h show valves with electromagnets equipped with an electronic control system.

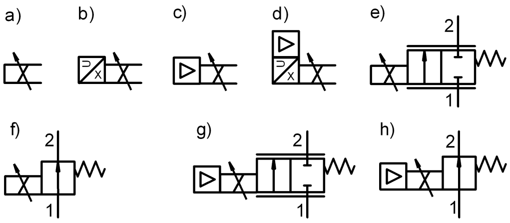

Fig. 4: Structure of a proportional electromagnet.

The MSMA alloys can be utilised to control pneumatic elements, such as direct-action proportional throttling valves. The transducer made of the MSMA is represented by the symbol given in Fig. 4a. The single-stage proportional throttling valves controlled by transducers made of MSMAs are shown in Figs. 5a and 5b (one-directional) and in Figs 5c and 5d (two-directional option). When two valves controlled by MSMA transducers are connected in parallel (Fig. 5a), we obtain a three-way direct-action proportional separator (Fig. 5e).

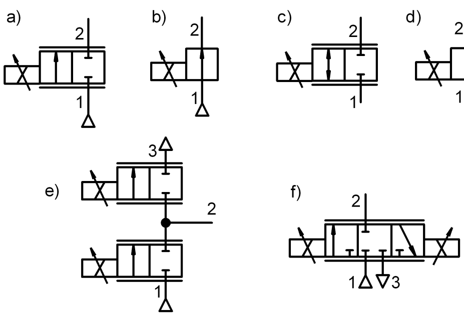

Fig. 5: Symbols of proportional throttling valves controlled by MSMA transducers.

A one-stage proportional pressure valve has a more elaborate structure, it is constructed as an assembly of two proportional throttling valves and of the pressure transducer (Fig. 6a). This device can be used as a proportional pressure controller (a reduction valve). Symbols in Figs 6a and 6d do not coincide with the traditional valve designations, yet they well demonstrate their structure and functional features. In accordance with the standard ISO 1219-1 this valve can be represented as in Fig. 6c.

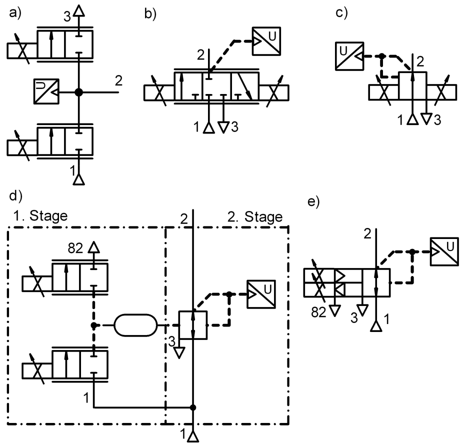

Fig. 6: Symbols of proportional pressure controllers controlled by MSMA transducer.

Electromechanical transducers made of MSMAs might be utilised to control the first stage (valve pilots) in the indirect-action reduction valves. In such valves a pilot system might incorporate a single-stage valve (Fig. 6a) combined with a pneumatic tank. The structure of the second-stage of the valve can incorporate currently available pressure valves with the pressure transducer at the output. The detailed structure of valve is shown in Fig. 6d in; its simplified version is shown in Fig. 6c. Typically, dynamic properties of currently manufactured valves fail to meet the expectations of today's engineers, chiefly because electromechanical transducers are now capable of very fast operation. MSMAs can help improve the dynamic behaviour of valves. Valves based on MSMA tuners do not comprise a mechanical spring, present in conventional proportional valves. Development of pneumatic valves superior to those currently available would give an opportunity to extend the range of potential applications of electropneumatic systems. As regards the applications of MSMA-controlled pressure elements, indirect-action proportional pressure controllers appear most promising. Controlled pneumatic valves based on MSMA can play an active role in further development of mechatronic systems comprising electro-pneumatic components).

Summary

The widest range of applications of valves incorporating MSMA pieces include electro-pneumatic proportional techniques. These valves can comprise the new group of electro-valves featuring improved dynamic properties and better resistance to external vibration. The response times of those valves can be decidedly shorter than in traditional valves with proportional electromagnets, to make a full use of state-of-the-art. That ensures better use of electronics and measurement technique possibilities. MSMA-based pneumatic valves may be employed among others in mining equipment e.g. pneumatic brakes used in hoisting machines in mines.

Acknowledgement

The research work has been supported by the Polish State Committee for Scientific Research as a part of the grant No. N N501 357339.

References

[1] S. Flaga and B. Sapinski, Properties of the magnetic shape memory alloy actuator, 10th Conference on active noise and vibration control methods, 2011, vol. 29, no. 1, pp. 84–85, ISBN 83-89772-70-1

[2] S. Flaga, D. Kata and B. Sapinski, Microstructure evaluation of Ni-Mn-Ga alloy, *Mechanics and Control*, 2010, vol. 29, no. 1, pp. 6–10.

[3] N. N. Sarawate, Characterization and modeling of the ferromagnetic shape memory alloy Ni-Mn-Ga for sensing and actuation, The Ohio State University, 2008.

[4] I. Dominik, Advanced controlling of the prototype of SMA linear actuator, *Solid State Phenomena*, 2011, vol. 177, pp. 93–101.