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BARTOSZ MINOROWICZ*, AMADEUSZ NOWAK*

FORCE GENERATION SURVEY IN MAGNETIC SHAPE MEMORY ALLOYS

Transducers used in all kinds of devices convert electrical input signal into a non-electrical, usually mechanical output such as: strength, speed, displacement, flow rate or pressure. Different kinds of electric motors and solenoids are commonly used as electromagnetic transducers. In this paper authors present materials with magnetic shape memory, which are a new group of smart material, and are subject to a number of ongoing research in the world. They change own properties (length, internal stress), under an influence of an external magnetic field. Authors placed in an introduction, a theoretical description of material, lists of their most important features, and also described production process and principle of operation. In order to perform research, a demonstration electromagnetic transducer was designed, which is distinguished by magnetic induction in air gap of 0.7 T. Study contains an analysis of the basic nonlinearity of this material, which is hysteresis, made to sinusoidal control signals of fading amplitude for both polarities of input current. Next, authors attempted to adjust strength of closed loop system where measured force was a feedback signal.

Key words: magnetic shape memory alloy, dSPACE, closed loop, force

1. INTRODUCTION

Mechatronic devices are present in every area of human life nowadays. With sophisticated control systems for operating in a closed loop with feedback signal, they are distinguished by a high precision of operation. Measuring systems and executive systems (actuators), indicate a great importance in these devices. Electromagnetic devices are commonly used in machines design, but after the laboratory age, a whole group of actuators based on smart materials (piezoelectric or SMA), are being implemented into industry and practical applications. The article presents the material with a magnetic shape memory, which after years of laboratory tests on the crystallographic network and the production processes are beginning to be used as a part of the electromechanical transducers [2, 6, 7].

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* Mgr inż. – Institute of Mechanical Technology, Poznan University of Technology.

2. MAGNETIC SHAPE MEMORY ALLOYS

Magnetic shape memory alloys materials were first described in 1996 by Ullakko [8] at MIT (Massachusetts Institute of Technology) in USA. During the next years, scientists were focused on improving production process and at the same time first attempts in using these materials in actuators design were done. MSM materials are distinguished by high operating frequencies, similar to those achieved in the magnetostrictive material Terfenol D and large deformation of up 10 %, which was previously reserved only for SMA (thermally activated). A combination of these two properties makes MSMA ideally suited for construction of mechatronics devices [1].

Unfortunately it has drawbacks that severely limit its use. The most unfavourable phenomenon’s include the occurrence of hysteresis, high sensitivity of material to temperature (maximum elongation decreases with increase of temperature, martensite changes into austenite), and the first cycle effect. What is more relative permeability changes with intensity of magnetic field. At the beginning it equals 65 and varies down to 2 at the maximum extension state. As a result of this magnetic property MSMA elements are distinguished by rectangular cross section with large disparity in length of its sides thus the magnetic field passes through the shorter one. Disproportion is introduced intentionally in order to reduce the size of coils which generate magnetic field in circuit, as well as to lower energy consumption.

The maximum elongation is obtained for a magnetic induction in alloy, which equals 0.65 T, however recently a Finnish company Adaptamat presented the next generation material, which has the magnetic induction decreased to 0.3 T for maximum elongation state.

Among materials exhibiting properties characteristic for MSMA, the most popular is Ni_2MnGa alloy. A crystal lattice of this full Heusler alloy takes the form $L2_1$ (fcc – face centred cubic), in high temperature. The secret of obtained properties is hidden in the production process of the alloy. Unlike conventional SMA, during the process of the sample cooling, compressive stress is applied, which must be greater than the stress initiating the growth of required martensite variant but lesser than the blocking stress. Thanks to that, after the cooling process, in the sample’s structure there is only one variant of martensite in which easy axis of magnetization is parallel to the direction of applied compressive stress (Figure 1) [1, 3, 4].

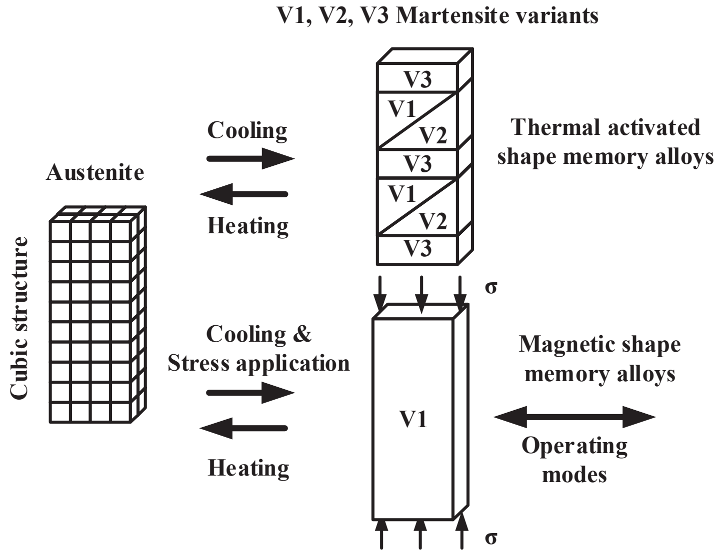

Figure 1. Production process of MSMA and SMA

Five possible modes of MSMA's operation can be distinguished. The operation mode in which the elongation is carried out by external magnetic field, that passes perpendicular to the length of material, parallel to the shorter side, while the sense of magnetic field vector may by optional. The return of material is carried out by external force e.g. by the spring, which should be pretensioned. A disadvantage of this solution is that compressive force varies with spring deflection. Nevertheless this is the most frequent operating mode described in the literature and it is called "spring returned operating mode". Easy adaptation to the design of electromechanical transducers makes it popular. The most preferred mode is the fifth one, however it is very hard to produce returning magnetic field due to the low magnetic permeability of the material, which strongly increases the size of the magnetic circuit. Other types of operating modes do not have actuator applications but they can be used for other purposes such as energy harvesting, vibration damping and measurements [5, 7].

The Figure 2 shows in detail the spring returned operating mode described above. Increasing the magnitude of magnetic field beginning from $H_0 = 0$, causes a reorientation of the crystal lattice which is called magnetically inducted reorientation. Ni_2MnGa material changes its length because the process of reorientation of the crystal lattice is less energy-intensive than the reorientation of magnetic domains in the direction of the magnetic field lines. On a macroscopic scale, it translates into a visible deformation. It is caused by the magnetic anisotropy established in the production process and it determines the maximum size of a subsequent deformation what can be calculated from the equation $\varepsilon_0 = 1 - c/a$.

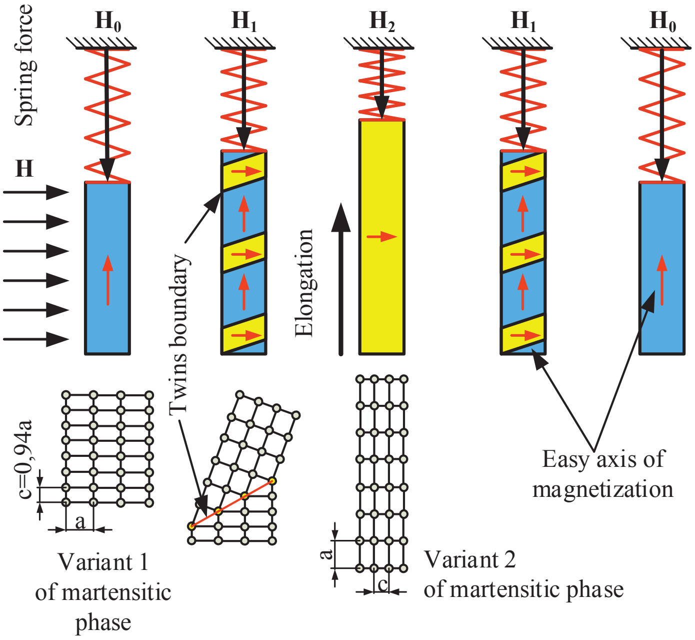

Figure 2. Spring returned operating mode

Reorientation of the crystal lattice occurs at borders called twinning boundaries separating different variants of martensite from each other. Increasing the magnetic field causes a conversion of one variant of martensite to another and a growth of its volume at the expense of the former. At a maximum elongation state the magnetic induction equals about 0.65 T, then decreasing of magnetic field combined with force coming from the spring makes reverse reorientation of crystal lattice to the initial state (variant 2 turns into variant 1). Without returning force MSMA reverse reorientation does not occur even if the magnetic field decreases to 0 again [3, 5].

3. DESIGN OF THE TEST STAND

The bench includes measurement and control system, which in this case was based on a dSPACE platform using Matlab Simulink software. The coils were energized with programmable DC power supply U_{nom} = 32 VDC and I_{nom} = = 10 A. It has analogue inputs and outputs that do allow users to control and measure current which passes through the coils. The last element is a test bench designed specifically for these Ni_2MnGa rectangular samples 1 × 2.5 × 20 mm. In order to produce a magnetic flux two coils were mounted in the test bench,

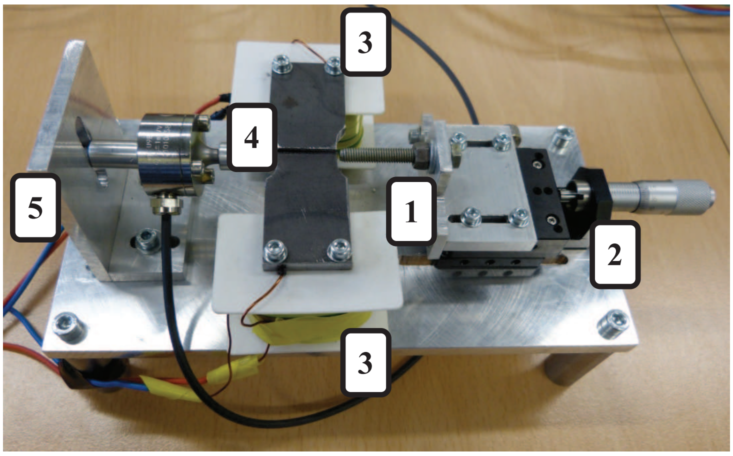

Figure 3. Test rig designed for MSMA samples investigation, 1 – blocking screw, 2 – table with micrometre screw, 3 – coils, 4 – air gap with MSMA, 5 – force transducer

with a maximum current for each of the coils equating 2.5 A. The value of the magnetic induction in the gap should be approximately 0.69 T, what has been examined using specialized probe with built-in Hall sensor (Figure 3).

4. DSPACE CONTROL PROGRAM

The test stand was connected to a high class dSPACE real-time computing system, which allows to perform multiple measurements as well as to control the device in real-time. The high performance of the system makes it complicated to implement control algorithms manually. Therefore the Simulink model diagram from Figure 4 was used to automatically generate a program code. dSPACE modular hardware output (block 1), is connected to a special controllable current supply, while information about actual current, voltage and force are gathered by an input unit (block 2). When using a special dSPACE ControlDesk program, modifications of some model parameters are possible. Several signal source types are implemented in the control program: manual control (light green blocks 3), pulse signal (cyan blocks 4), periodic signal with decreasing amplitude (cyan block 5), PID controller output (orange block 6). Only proportional and integral parts of PID regulator were used. Light green blocks are responsible for switching the source signal and manually controlling the DAC signals. Digital to analogue converter outputs are respectively scaled and saturated in range 0÷10 V. Similar values concern inputs (Figure 4).

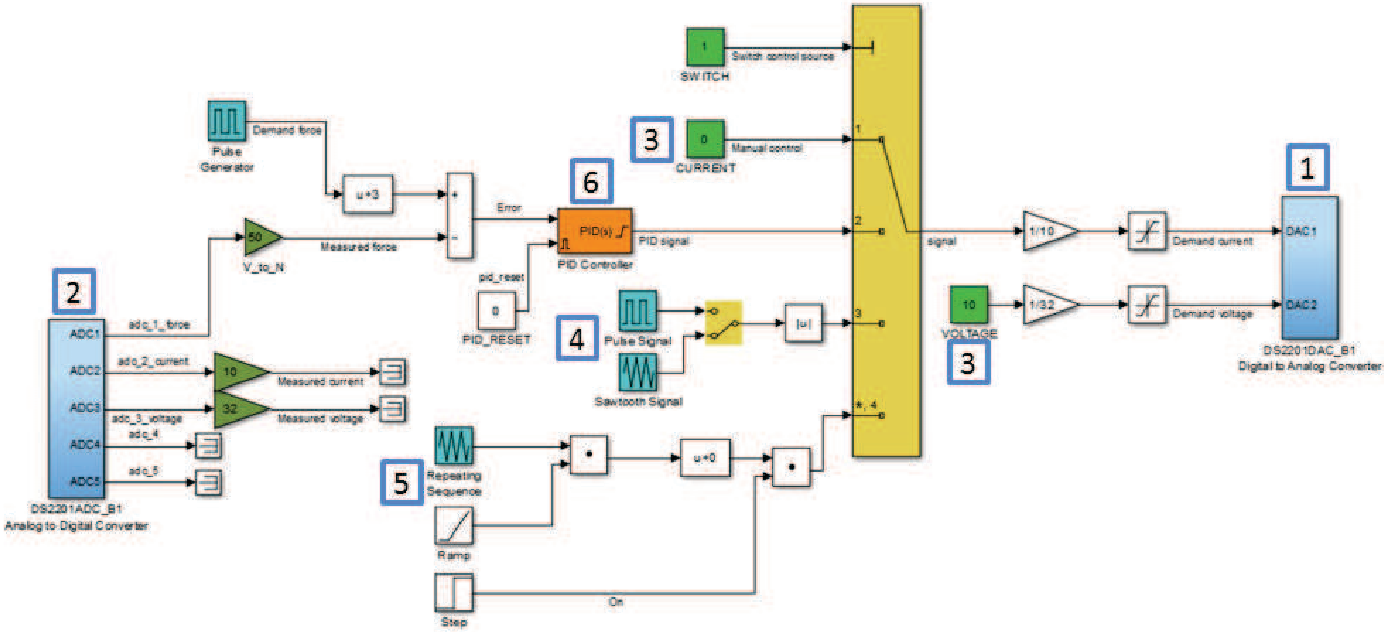

Figure 4. Matlab Simulink simulation model used to automatically generate program code

5. RESEARCH AND RESULTS

First, the results were registered for the sinusoidal signal. The DC power supply does not have a function of automatic change of polarization as a built-in feature thus an absolute value of control signal was used. In the picture Figure 5 curves were plotted for a signal decreasing from 5 to 0 A. In the next picture (Figure 6), input signal was decreasing asymptotically to 2.5 A.

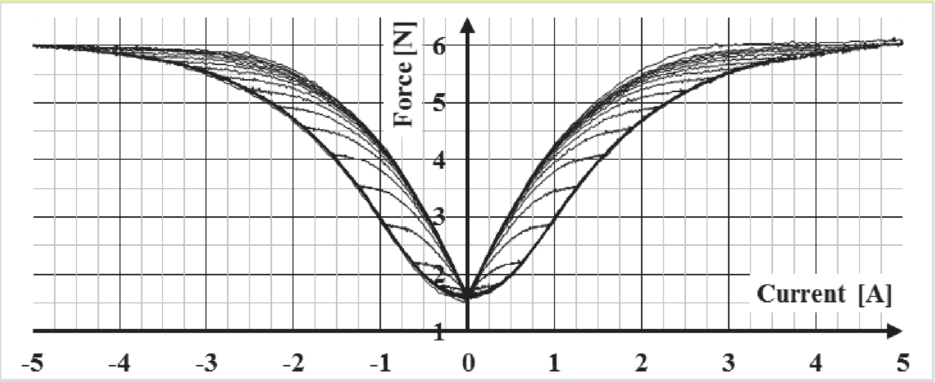

Figure 5. Force versus current for decreasing to 0 A sinusoidal imput signal

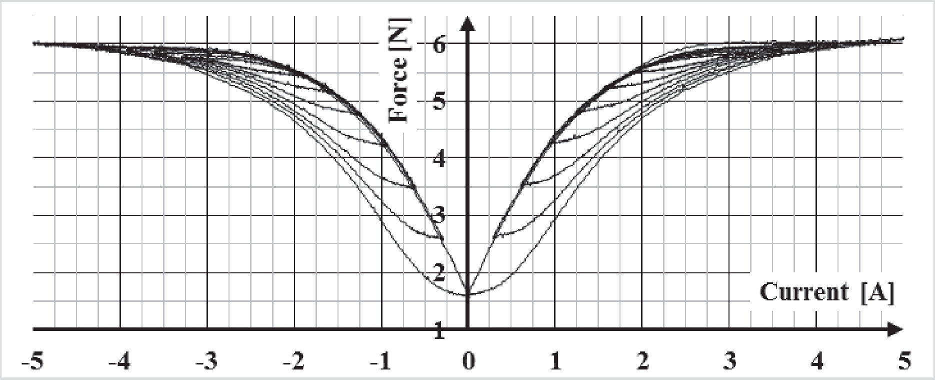

Figure 6. Force versus current for asymptotically decreasing to 2.5 A sinusoidal input signal

Tests were performed for both polarizations separately and then, obtained results were connected in one graph. In the graphs it can be seen that the polarization of current and consequently the direction of the magnetic field does not affect the achieved results. Characteristics of forces are even. One of disadvantages of these materials mentioned in the introduction was the effect of the first cycle, which is not shown here. This follows from the fact that the return to the original state requires application of additional external force, what is impossible in case of construction of the electromechanical transducer.

It is presented two step responses types. The first step (Figure 7) is from 3 N to 4 N of generated force. The second step (Figure 8) is the return from 4 N to 3 N. Both characteristics plotted for two PI regulators, which gain coefficients are presented on the right side. Results show that for lower integral coefficient responses differ not much. Increasing the value of integral gain causes significant oscillations when the MSMA material returns to its initial state. A possible cause of this might be that MSMA response is different according to the movement direction. Another reason might be the fact that during the elongation, the MSMA is buckling a little and the return takes longer time. Furthermore, elongation causes decrease of the relative permeability of MSMA which amplifies the

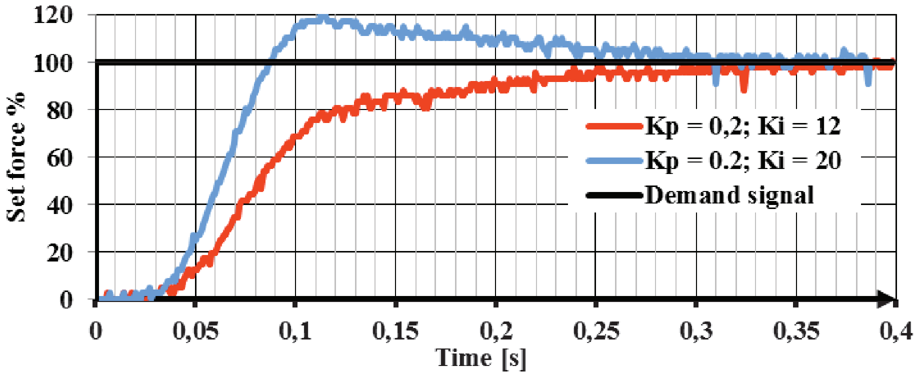

Figure 7. Step response of force for PI regulators with different coeff.; 0 % is 3 N and 100 % is 4 N

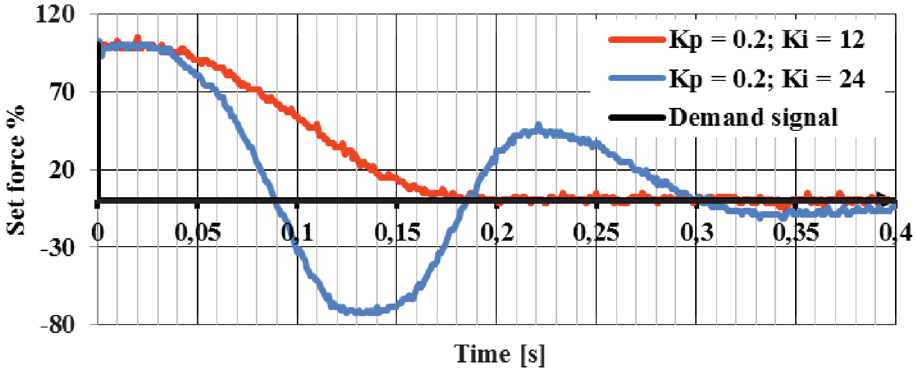

Figure 8. Step response of force for PI regulators with different coeff.; 0 % is 3 N and 100 % is 4 N

effect. Generally the change of relative permeability enlarges the nonlinearity of materials characteristics. It is under consideration is that magnetic stream elongates the probe but the return only removes the tension in material – the process does not works the same at both directions. During the tests, it could be noticed that sides of magnetic poles attract each other and deflect, what decreases the magnetic air gap between them and MSMA material. This is another reason of the permeability change in magnetic circuit, which had not been considered during the designing phase. Further investigations may base on improvement of the test stand, checking the influence of poles deflection on materials work and modelling of the MSMA behaviour in specific conditions.

6. SUMMARY

Basing on performed, tests it is confirmed that Magnetic Shape Memory Alloys are characterized by various nonlinearities. Major identified one is the hysteresis of the material. Initial tests of control in a closed loop were performed. Presented figures show the difference in step responses depending on the acting direction. Some of the problems might have their reason in the construction of the test stand, which will be improved before the next study phase. Response time in the dynamics tests strongly depend on DC supply activating time and built-in current regulator. In the next steps Authors are going to investigate and analyse displacement characteristics.

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BADANIA REGULACJI SIŁY W MATERIAŁACH Z MAGNETYCZNĄ PAMIĘCIĄ KSZTAŁTU

Streszczenie

Przetworniki stosowane w różnego rodzaju urządzeniach zamieniają elektryczny sygnał wejściowy na nieelektryczny, zwykle mechaniczny, sygnał wyjściowy typu: siła, prędkość, przemieszczenie, natężenie przepływu albo ciśnienie. W artykule przedstawiono materiały z magnetyczną pamięcią kształtu, które stanowią nową grupę materiałów inteligentnych i są przedmiotem wielu badań prowadzonych obecnie na świecie. Materiały te zmieniają swoje właściwości (długość, naprężenia wewnętrzne) pod wpływem zewnętrznego pola magnetycznego. We wstępie podano ich opis teoretyczny i cechy szczególne, a także opisano proces produkcji i zasadę działania. Na potrzeby badań skonstruowano demonstracyjny przetwornik elektromagnetyczny, który umożliwia uzyskanie indukcji magnetycznej w szczelinie powietrznej na poziomie 0,7 T. Analizę podstawowej nieliniowości tego materiału, jaką jest histereza, wykonano dla sygnałów sterujących o gasnącej amplitudzie i obu polaryzacji prądu zasilania. Następnie podjęto próbę regulacji siły w układzie ze sprzężeniem zwrotnym.

Słowa kluczowe: magnetic shape memory alloy, dSPACE, sprzężenie zwrotne, siła

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