Magnetic Shape Memory Actuators for Fluidic Applications

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Abstract: Magnetic Shape Memory (MSM) actuators represent a new type of smart electromagnetic actuators where the MSM material elongates and contracts in a magnetic field. The MSM material has the ability to change its size or shape very fast and many million times repeatedly. Based on internally designed and produced Magnetic Shape Memory materials, the ETO GROUP has developed its new MAGNETOSHAPE® technology that offers mono-, bi-, and multistable actuator solutions that have potential to serve various fluidic applications, from pneumatics to hydraulics, stationary or mobile. In this paper, we present an overview of the current state of the MAGNETOSHAPE® technology and its future impact on fluidic applications.

Keywords: magnetic shape memory, electromagnetic actuator
Target audience: Mobile Applications

1 Introduction

Increased product requirements with respect to functionality, durability, and energy efficiency lead to more and more complex systems and design processes. These, however, have to be fulfilled at competitive system and life-cycle costs. In consequence, individual parts and subsystems have to comprise increased functionality and efficiency themselves. The broad class of smart materials, including prominent examples such as piezo ceramics or shape memory alloys as well as less known dielectric elastomers or magnetic shape memory alloys, offer ideal preconditions to fulfil such requirements. Therefore, they have a great potential to play an important role in future actuation technologies for fluidic systems.

Magnetic Shape Memory (MSM) actuators represent a new type of smart electromagnetic actuators where the MSM material elongates and contracts in a magnetic field. Typically, the MSM material is a monocrystalline Ni-Mn-Ga alloy, which has the ability to change its size or shape very fast [1] and many million times repeatedly [2, 3]. Some alloys are known, which are able to achieve a magnetic field induced strain of up to 12% [4]. Magnetic Shape Memory actuators exhibit unique advantages such as fast switching with large work output. They can be designed as multistable actuators with near-zero current consumption in any stable position. The phase transition temperature of the MSM material between the low temperature martensite and the high temperature austenite limits the application temperature in current alloys to about 60°C, but future improvements are expected [5].

Based on internally designed and produced Magnetic Shape Memory materials, the ETO GROUP has developed its new MAGNETOSHAPE® technology that offers mono-, bi-, and multistable actuator solutions that have potential to serve various fluidic applications, from pneumatics to hydraulics, stationary or mobile. Fast switching bistable actuators can help to enable digital hydraulics or high-durability high-frequency pneumatic valves. Multistable so-called push-push actuators with two MSM units working antagonistically can potentially replace proportional actuators and do not consume energy when holding intermediate positions.

However, the new technology requires modified approaches in the complete design process. For example, standard magnetostatic FEM simulations techniques have been adapted to take into account the magneto-mechanical coupling and the magnetic anisotropy of the MSM materials [6, 7]. Furthermore, specific control approaches are under development in order to enable fast and precise positioning for fluidic as well as non-fluidic applications.

2 Magnetic Shape Memory Material

The most widely known MSM materials are off-stoichiometric Heusler type Ni_2MnGa alloys, but also Fe-Pd, Co-Ni-Al and Ni-Mn-Al alloys have been proposed [8-10]. In the present study we will concentrate on MAGNETOSHAPE® Ni-Mn-Ga alloys. The MSM effect takes place when the material is in the martensite phase, therefore its crystal structure is of prime importance. Three different martensite structures have been identified, namely the 5M and 7M, both modulated ones, and the non-modulated T martensite. Which of the structure predominates depends on the chemical composition and thermal treatment of the alloy. So far, the 5M structure has proven the most suitable for actuator applications because of the low twinning stress and high work output. In the past years the mechanical stability [11, 12] and work output [13, 14] of these materials have been considerably improved, and new actuator designs have been proposed [15-17]. Also new manufacturing processes have been applied towards industrialization of the production technology [18, 19].

Magnetic and mechanical measurements in MSM materials are carried out in order to identify the magnetocrystalline anisotropy, saturation magnetization, twinning stress, strain and stress output, as well as the efficiency. These are the most important parameters used also to design actuator devices. In Figure 1 the magnetization curve of a Ni-Mn-Ga single crystal, measured in a Permagraph, is presented. Initially, in the first magnetization cycle the increase of magnetization is slow and nearly linear, suggesting that the magnetization process is controlled by magnetization rotation (magnetization along “hard” magnetic axis). At a certain field, which may vary between 90 kA/m and 300 kA/m, the magnetization suddenly rises and then levels off. At this stage the “easy” magnetic c-axis of martensite is aligned parallel to the field, and the material elongates. From the area between “hard” and “easy” axis the magnetocrystalline anisotropy can be deduced. This has been measured for 5M martensites at around $K_u=2.3\times10^5$ J/m^3. From the same curve the saturation magnetization is determined between 60 emu/g and 68 emu/g. Large magnetocrystalline anisotropy and saturation magnetization are pre-requisites for the magnetic shape memory effect.

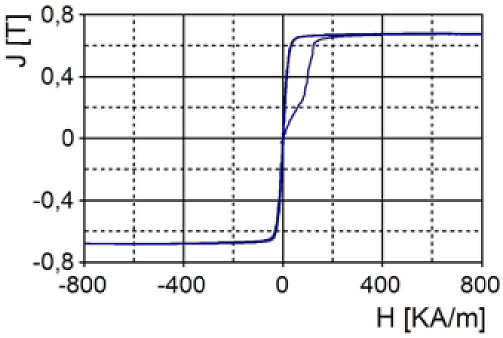

Figure 1. Magnetization curve of a single crystal Ni-Mn-Ga alloy

Strain versus field curves for MAGNETOSHAPE® Ni-Mn-Ga materials are summarized in Figure 2. The magnetic field induced strain (MFIS) of the material is measured when a constant pre-stress is applied on the sample. It is seen that the full 6% MFIS is achieved when a pre-stress of up to 2 MPa is applied. Even at a pre-stress of 3 MPa a 1.8 % MFIS is recovered. Accordingly, the work output (stress × stroke) achieved from a MANGETOSHAPE® material exceeds that of piezoceramic materials.

In Figure 3 the stress-strain curve of MAGNETOSHAPE® MSM materials is presented. In the presence of the magnetic field the sample elongates and the produced stress is continuously measured. At the maximum elongation the stress becomes zero and then the sample is compressed mechanically to its initial state. From the plateau of the return curve the twinning stress of the material is deduced. The efficiency of these materials, as measured by the ratio of the magnetic field-induced work output to the work needed to mechanically return the sample to its original shape, is very high and was measured in some cases even above 90%. It should be mentioned here that low twinning stress materials are generally desirable, however they do not a priori give the highest work output required for actuator materials [3].

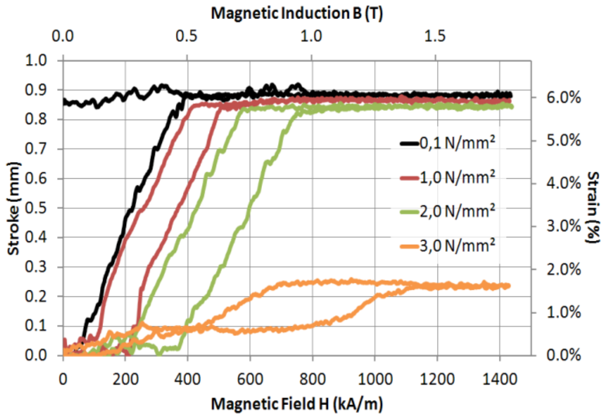

Figure 2. Strain versus field curve in a MAGNETOSHAPE® Ni-Mn-Ga sample measuring approximately $2\times3\times15$ mm^3.

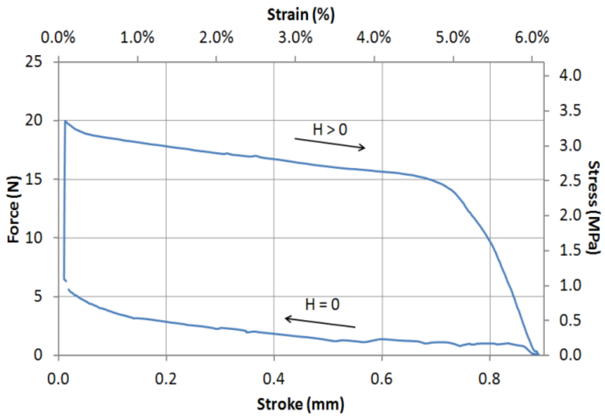

Figure 3. Stress versus strain curve in a MAGNETOSHAPE® Ni-Mn-Ga sample measuring approximately $2\times3\times15$ mm^3.

3 Magnetic Shape Memory actuators

3.1 MAGNETOSHAPE® spring actuator

The most straightforward MSM actuators principle is the spring actuator, which resembles a conventional electromagnet. In this actuator a pre-stressed spring is antagonistically applied on the MSM element. Once the coils are energized a magnetic field pervades the MSM element, which produces a magnetic stress perpendicular to the direction of the field. As soon as the amount of magneto-stress exceeds the pre-stress of the spring the element starts to elongate. After the current is switched off, the spring force returns the MSM element to its original shape. This is a well established and intensively studied solution which produces large stroke in combination with fast frequency response. The actuator, shown in Figure 4 demonstrates a stroke of 0.7 mm at high a frequency of 400 Hz and a response time of 1.6 ms (Figure 5) [20].

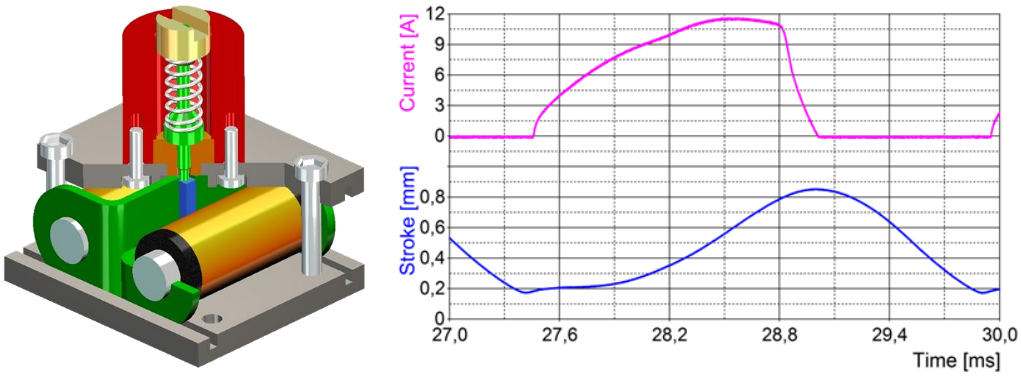

Figure 4: MAGNETOSHAPE® spring actuator (left) and stroke and current behavior (right)

A first prototype required about 10 A which has been reduced by improving the actuator design as well as the MAGNETOSHAPE® alloy to round about 3 A (Figure 5). In this case, an MSM element with minimum twinning stress will result in maximum work output, because the spring force can be minimal.

Figure 5: Improved MAGNETOSHAPE® spring actuator

3.2 MAGNETOSHAPE® Push-Push Actuator

In several applications it is desirable to hold intermediate positions without energy consumption. So-called push-push actuators (Figure 6) offer this behaviour [13, 14]. With two actuator units that are working antagonistically, this actuator type can replace proportional electromagnetic actuators. Both elements are controlled by two independent magnetic circuits which provide two independently controllable fields. Opposite to the spring actuator a MAGNETOSHAPE® element with higher twinning stress would be advantageous in this case, because this twinning stress defines the maximum external force under which the intermediate position remains stable.

Figure 6: MAGNETOSHAPE® push-push actuator.

3.3 MAGNETOSHAPE® Hybrid Push-Push

Instead of two antagonistically arranged MAGNETOSHAPE® actuator units one of these units can be replaced with other actuator types, especially with a conventional solenoid actuator for example. Since the MSM unit works only against the inertia mass of the reluctance actuator and the reluctance actuator only needs to work against the twinning stress of the MSM element, the hybrid push-push actuator will be fast, energy efficient and in potentially less expensive than a MSM push-push system.

4 Advantages of Magnetic Shape Memory actuation for fluidic applications

4.1 High-cycle fatigue and fast switching

The effective stroke of conventional magnetic reluctance actuators typically is a few millimeters. The power density of such actuators is high and offers many possibilities as valve solenoids in hydraulic and pneumatic valves used in automotive and industrial applications. Typical examples are breaking systems or active camshaft systems in combustion engines. The actuator force depends on the distance between armature and core and increases exponentially (Figure 7) with deflection (i.e. shorter distance). This behaviour can be tailored using specific cone geometries, but typically at the cost of reduced efficiency.

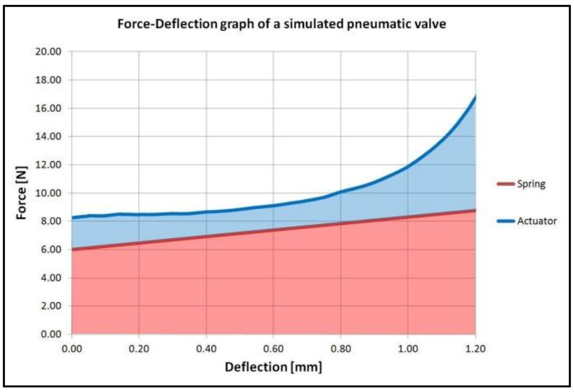

Figure 7: Simulated force-deflection behaviour of a pneumatic valve

The kinetic energy of the armature is highest at maximum deflection. In high cycle valve applications this may damage a valve seat, especially when high dynamics are required simultaneously. Consequently, high-speed solenoid valves with high durability (>1×10^9 cycles) come along with limited stroke.

MSM actuators offer considerable advantages in terms of high stroke combined with fast frequency response and potential for excellent high-cycle fatigue properties. In contrast to reluctance actuators, MSM actuators provide maximum force at zero deflection so that high acceleration can be realised. On the other hand force and kinetic energy approach zero when the maximum deflection is reached.

The MSM material itself has the ability to change its size or shape very fast [1] and many million times repeatedly [3]. ETO demonstrated that MAGNETOSHAPE® actuators can operate several hundreds of millions of cycles [20]. Figure 8 indicates that wear also appears in this type of actuator but after more than 400 million switching cycles the actuator is still functional. Taking into account that this is the result of a preliminary test only, it can be deduced that the MAGNETOSHAPE® technology has the clear potential for high-speed switching applications with multi-billion cycle requirements.

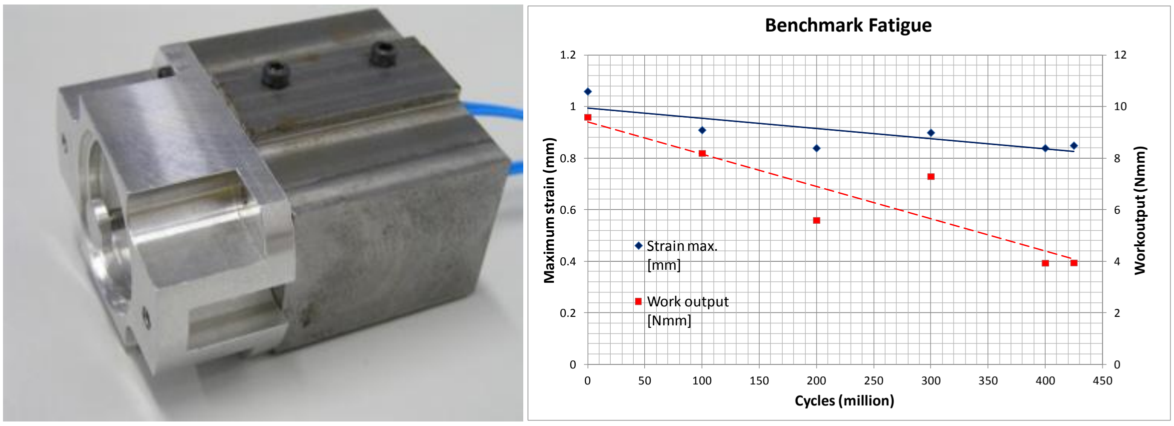

Figure 8: Behaviour of MAGNETOSHAPE® actuator over 425×10^6 cycles.

4.2 Energy efficiency

A solenoid valve actuator with a fail-safe functionality manufactured by ETO for automotive applications has been compared with a MAGNETOSHAPE® spring actuator with similar force and stroke in terms of energy efficiency. As an overall result, both technologies are roughly equivalent meaning that none offers clear advantages in terms of energy efficiency. In order to provide the fail-safe behaviour both systems consume electric energy to overcome a mechanical restoring force (spring force) that ensures a defined closed or open valve position at zero current. Both technologies may make use of so called peak-and-hold approaches with increased current for switching and reduced current of holding a position. An intrinsic difference between the two technologies cannot be observed.

The situation is completely different, when a MAGNETOSHAPE® push-push actuator (both hybrid and conventional) is compared with a proportional actuator. Depending on the operation profile assumed (frequency of position changes, average holding position of electromagnetic reference actuator) the energy consumption can be drastically lowered. While the proportional solenoid permanently consumes electric energy to hold or change the position, the push-push actuator requires only a short pulse and therefore a very low amount of energy. Energy savings compared to a proportional solenoid can exceed 90%.

The energy-efficient holding function is intrinsically combined with high-speed operation and high-cycle-operation making the MAGNETOSHAPE® push-push actuator an attractive solution for any proportional control or multistable switching operation. As shown in figure 9, a positioning accuracy of less than 5 µm was achieved for a MAGNETOSHAPE® push-push actuator with a simple PID controller for strokes of about 0.5 mm. Recent results with a modified PI controller show that even the controller itself can be designed such that the energy consumption during control actions is further reduced making use of the intrinsic hysteretic properties of the MAGNETOSHAPE® material [22, 23].

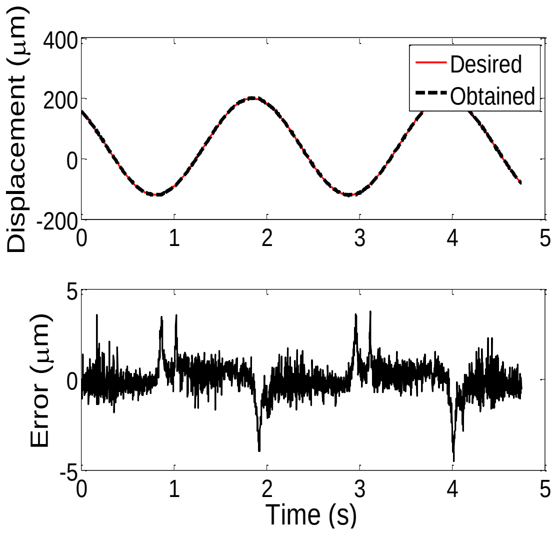

Figure 9: PID controller performance of MAGNETOSHAPE® push-push actuator.

5 Summay and Outlook

The magnetic shape memory technology is a relatively new technology developed over the past decade. Accordingly, the progress in materials and production process development, as well as in actuator design, is very fast. To date, MAGNETOSHAPE® MSM materials produced by ETO MAGNETIC GmbH define the world-wide benchmark in terms of quality, reproducibility, and effective work output for this class of material. This new level of maturity allows the development of novel actuators for fluidic applications using this technology.

The most relevant potential applications of the MAGNETOSHAPE® technology in the field of fluidics are high-speed switching valves with excellent high-cycle fatigue behaviour as well as multistable push-push actuators that offer zero current stability, which can replace proportional solenoid valves. Nevertheless, potential applications have to be carefully selected to match best the specific profile of the magnetic shape memory technology.

Future challenges remain in further improving the MAGNETOSHAPE® materials and manufacturing processes. Especially, the operation temperature limit should be increased above the current limit of about 60°C. Recent progress was made with new materials operating at 70°C [21]. Furthermore, the actuator design process of magnetic shape memory based actuators has to be improved further and made more flexible, while the specific nature of the magnetically anisotropic material with changing geometry over a deflection cycle has to be adequately taken into account.

References:

/1/ M. A. Marioni, R. C. O'Handley, and S. M. Allen, *Appl. Phys. Lett.*, vol. 83, pp. 3966-3968, 2003.

/2/ I. Aaltio, A. Soroka, Y. Ge, O. Söderberg, and S.-P. Hannula, *Smart Mater. Struct.*, vol. 19, 075014, 2010.

/3/ T. Schiepp, V. Detkov, M. Maier, E. Pagounis, and M. Laufenberg, *Proc. 4th Int. Conf. on Ferromagnetic Shape Memory Alloys (ICFSMA)*, Boise, Idaho, 2013.

/4/ A. Sozinov, N. Lanska, A. Soroka, and W. Zu, *Appl. Phys. Lett*, vol. 102, 021902, 2013.

/5/ E. Pagounis, M. Helmer, M. Maier, and M. Laufenberg, *4th Int. Conf. Smart Materials Structures Systems (CIMTEC)*, Montecatini Terme, Italy, 2012.

/6/ J. Kiang and L. Tong, *Smart Mater Struct*, vol. 19, pp. 1-17, 2009.

/7/ T. Schiepp, M. Maier, E. Pagounis, A. Schlüter, and M. Laufenberg, *Proc. 19th Conf. on Computation of Electromagnetic Fields (COMPUMAG)*, Budapest, Hungary, 2013.

/8/ J. Cui, T.W. Shield, R.D. James, *Acta Mat.*, vol. 52, 35, 2004.

/9/ M. Wuttig, J. Li, C. Craciunesku, *Scripta Mater.*, vol. 44, 2393, 2001.

/10/ L. Menosa, A. Planes, M. Acet, E. Duman, E. Wassermann, *J. Appl. Phys.*, vol. 93, 8498, 2003.

/11/ F. Xiong, Y. Liu, E. Pagounis, *J. Alloys Compd.*, vol. 415, 188, 2006.

/12/ I. Aaltio, Y. Ge, X.W. Liu, O. Söderberg, S.P. Hannula, *in Proc ICOMAT 2008, Santa Fe (NM)*, USA, 487, 2008.

/13/ L. Straka, H. Hänninen, A. Soroka, A. Sozinov, *J. Phys.: Conf. Ser.*, vol.303, 012079, 2011.

/14/ Magnetic Shape Memory, Brochure, ETO MAGNETIC GmbH, Stockach, 2013.

/15/ I. Suorsa, J. Tellinen, I. Aaltio, E. Pagounis, K. Ullakko, *in Proc. of Actuator 2004*, Bremen, Germany, 573, 2004.

/16/ T. Schiepp, M. Maier, E. Pagounis, A. Schlüter, M. Laufenberg, “FEM-SIMULATION OF MAGNETIC SHAPE MEMORY ACTUATORS” , *IEEE Trans. Magn.*, to be published

/17/ Patent Application: DE 10 2011 014 193

/18/ L. Sturz, A. Drevermann, U. Hecht, E. Pagounis, M. Laufenberg, *Phys. Proc.*, vol. 10, 81, 2010.

/19/ J. Brillo, H. Behnken, A. Drevermann, Y. Plevachuk, E. Pagounis, V. Sklyarchuk, L. Sturz, *Int. J. Heat and Mass Transfer*, vol. 54, 4167, 2011.

/20/ T. Schiepp, M. Laufenberg, E. Pagounis, *Proc. 3rd ICFSMA*, Dresden (2011), 147.

/21/ E. Pagounis, M. Helmer, M. Maier, M. Laufenberg, *presented at 4th International Conference, Smart materials*, structures, systems, CIMTEC 2012, Montecatini Terme, Italy, June 10-14, 2012.

/22/ Patent Application: DE 10 2013 110 131, unpublished.

/23/ L. Riccardi, B. Holz, H. Janocha, *Innovative Klein- und Mikroantriebstechnik Nürnberg (2013)*